Wavelength Beam-Combined Direct Diode Lasers of Highest Spatial Brightness

Dissertation zur Erlangung des akademischen Grades eines Doktors der Naturwissenschaften (Dr.rer.nat.)

vorgelegt von

Haas, Matthias

an der

Universität Konstanz

Mathematisch- Naturwissenschaftliche Sektion

Fachbereich Physik

Konstanz, 2019

Konstanzer Online-Publikations-System (KOPS)
URL: http://nbn-resolving.de/urn:nbn:de:bsz:352-2-s4418cflc9q77
Tag der mündlichen Prüfung: 09. August 2019

1. Referent: Prof. Dr. Thomas Dekorsy

2. Referent: apl. Prof. Dr. Johannes Boneberg
Direct diode lasers are of great interest in many fields of today’s industrial laser materials processing. The striking advantages of such lasers compared to optically pumped solid-state lasers consist of a higher compactness and an enhanced electrical-to-optical conversion efficiency of up to 50% or higher. During the past decade low-brightness multi-kW direct diode lasers have successfully replaced lamp-pumped solid-state lasers in high-power metal processing applications such as brazing, cladding and welding. Quite recently, high-brightness dense wavelength beam-combined direct diode lasers have come of age which are potentially suited to serve all kinds of high-brightness kW-class laser metal processing applications like flat sheet metal cutting or remote welding, where, to this day, well-established high-power thin-disk or fiber lasers dominate the market. In this thesis, a novel external cavity architecture for dense wavelength beam combining of high-power broad-area laser diode bars has been investigated with regard to an efficient spatial brightness scaling towards the kW power level with minimal beam quality deterioration. The external wavelength-stabilizing multi-laser cavity is based on a single customized ultra-narrowband thin-film filter as dispersive optical element inside the resonator and enables spectral stabilization of hundreds of broad-area laser diode emitters at once, each at a unique wavelength. Subsequent spectral beam combination of the cavity output is performed by means of a diffraction grating and a cylindrical telescope which is used for linear dispersion-matching between the thin-film filter and the combiner grating. For the investigations, both commercial and non-commercial state-of-the-art high-power 9xx-nm broad-area laser diode bars are used which are equipped with micro-optical beam transformation systems enabling beam combining in the fundamental-mode fast-axis beam dimension of the broad-area laser diode bar emitters. The achieved experimental results are benchmarked with respect to wavelength beam combining efficiency and beam quality preservation against a well-known external cavity architecture for dense wavelength beam combining using a single intra-cavity diffraction grating for simultaneous wavelength stabilization and beam combining. Using the novel approach, cross-talk-free spectral stabilization of individual diode bar emitters with a spectral channel spacing below 200 pm is achieved over the total diode operation current range with low thermo-optically induced wavelength shift of about 1 pm/W. The wavelength beam combining efficiency in the external laser cavity is about 80% and mainly limited by power losses at both the thin-film filter due to the spectral filtering and the combiner grating due to the restricted diffraction efficiency and depolarized power fractions of the diode bar.
emitters. Detailed experimental and theoretical studies of beam quality preservation in the external cavity show that the resulting beam quality of the combined cavity output is affected by several mechanisms which deteriorate beam quality in the beam-combining axis. These are the residual spectral linewidth of the stabilized emitters, diode bar smile, beam distortion induced by the spectral filtering and the dispersion mismatch between the thin-film filter and the combiner grating. As a result, the achieved beam parameter product in the beam-combining axis at the 100-W power level is an order of magnitude larger compared to the diffraction-limited value of an individual unstabilized diode bar emitter, where still no thermo-optically induced beam distortions are present. On the basis of simulations of the resulting beam quality deterioration, the cavity and the combiner setup are optimized for optimal beam quality preservation. An impact of the wavelength stabilization on the beam quality in the non-beam-combining axis is not observable. The novel external cavity structure has been applied to a laser diode module consisting of ten horizontally stacked actively cooled 150-W broad-area laser diode bars in order to realize a high-brightness kW-class direct diode laser module which potentially serves as a building block for a 4-kW direct diode laser system. An output power of 1.1 kW is achieved corresponding to an electrical-to-optical conversion efficiency of about 40%. The combined output beam has a symmetrical beam parameter product of about $6 \text{ mm} \times \text{ mrad}$ in both beam axis. The 230 broad-area laser diode emitters of the laser diode module are spectrally stabilized within a bandwidth of 43 nm. Thermo-optically induced wavefront aberrations due to the heating of the thin-film filter and the combiner grating and furthermore an imperfect magnification of the dispersion-matching telescope are identified to be the reason for a degrading beam quality in the beam-combining axis in high-power operation which is not observable in individual-bar experiments, where an order of magnitude lower intra-cavity power and stabilized spectral bandwidth are present.
Kurzzusammenfassung

Publications

Parts of this PhD thesis have been published in the following scientific journal papers and conference proceedings:

**Scientific Journals**


**Conference Proceedings**


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List of Abbreviations

AOI  angle of incidence
AR   anti-reflection
BAL  broad-area laser
BPP  beam parameter product
BTS  beam transformation system
CCD  charged-coupled device
COMD catastrophic optical mirror damage
CTE  coefficient of thermal expansion
CWBC coarse wavelength beam combining
d.c.  duty cycle
DOP  degree of polarization
DWBC dense wavelength beam combining
e-o  electrical-to-optical
FA   fast-axis
FAC  fast-axis collimator
FF   filling factor
HR   highly reflective mirror
HWP  half-wave plate
ILASCO active isolated laser cooler
NA   numerical aperture
NPBS non-polarizing beamsplitter
OC   output coupling mirror
OPD  optical path difference
PBC  polarization beam combining
PBS  polarizing beamsplitter
p.c.  power content
PM  power meter
PRM  partially reflective mirror
QW  quantum well
QWP  quarter-wave plate
SA  slow-axis
SAC  slow-axis collimator
SBC  spatial beam combining
TE  transverse electric
TFF  thin-film filter
TFP  thin-film polarizer
TM  transverse magnetic
VBG  volume Bragg grating
WBC  wavelength beam combining
WDM  wavelength division multiplexing
Over the past 30 years, high-power lasers have come of age and are nowadays well-established processing tools for all kinds of highly productive metal processing applications. The laser can certainly be considered as one of the most disruptive high-tech enablers being brought to the metal processing industry in those years. In a few lines, the unique advantages of the laser against conventional metal processing tools are obvious. In modern body-in-white automotive manufacturing lines, it allows for force- and contact-free spot and seam welds. Combined parts themselves, such as pillars, are formed by tailored welded blanks which themselves are joined with high-power lasers as well. For such applications, the metal sheets being used are cut in a high-speed 2D laser cutting process. Over conventional metal cutting technologies, like water-jet cutting or punching, the laser has the advantage of providing burr-free edges without further edge treatment at highest productivity. For very recent applications like cutting of high-strength steels to lower weight and carbon dioxide (CO$_2$) emission of cars, conventional punching tools can not be used anymore, eventually leaving the laser as the only tool of choice. Besides the laser emission wavelength, which determines the material absorption of the incident laser power by the work piece, the output power and the beam quality of the laser beam are the most important laser parameters for metal processing applications, as illustrated in Fig. 1.1. The better the beam quality, the smaller the resulting spot size in the beam waist behind a focusing optics which leads to a high beam intensity in the focus. Typically, beam quality is quantified either by the beam parameter product (BPP), which is given by the product of the beam waist radius $\omega_0$ and the far-field divergence $\theta_0$ of the laser beam, or alternatively by the wavelength-independent beam quality factor $M^2$ [1]. Physically, the BPP describes the phase-space volume of the laser beam which, according to Liouville’s law, remains constant by the transformation of the laser beam by passive optical components such as mirrors or lenses in the absence of any aberrations. The lowest possible BPP, corresponding to the best achievable beam quality, is given by $\omega_0\theta_0 = M^2\lambda/\pi$ with $M^2 \geq 1$, where $\lambda$ being the emission wavelength of the laser beam. In case of the absolute minimum ($M^2 = 1$),
the laser exhibits a diffraction-limited Gaussian output beam which is achieved for laser operation at a single transverse resonator mode. A physical quantity which combines both the laser output power and the BPP \( BPP \) (\( BPP \): rotationally symmetric BPP; \( BPP_x, BPP_y \): BPP in the lateral or vertical beam dimension) represents the spatial brightness \( B \), given by

\[
B = \frac{P}{A \cdot \Omega} \approx \frac{P}{\pi^2 \cdot BPP^2} = \frac{P}{\pi^2 \cdot BPP_x \cdot BPP_y},
\]

which defines the optical laser power \( P \) per beam spot area \( A \) in the focus and solid angle \( \Omega \) in the far field [14]. Laser applications in the field of metal processing can be divided into three groups according to the spatial brightness which the laser beam has to meet [2]. Brazing and cladding are low-brightness applications which demand for a laser power between 0.3 kW to 10 kW with a BPP of larger than 100 mm \( \times \) mrad. Lasers with comparable output powers but significantly improved beam quality are required for moderate-brightness applications.
as for instance welding. First near-infrared high-power solid-state lasers which were capable to address these applications were lamp-pumped neodymium-doped yttrium aluminum garnet (Nd:YAG) rod lasers. Fiber-coupled multi-kW lamp-pumped Nd:YAG rod lasers with a BPP of 30 mm × mrad were realized and predominantly used for welding applications in the automotive industry [15, 16]. Metal cutting and remote welding are applications which demand for the highest brightness of the laser beam. Depending on the cutting process, the sheet material thickness and the desired edge quality of the cut, a laser power in the range of 1 kW to 10 kW and a BPP below 5 mm × mrad are required. The marked sweet spot in Fig. 1.1 indicates where presently the majority of laser cutting machines are sold by market-leading companies [17]. High-dynamic remote welding applications, using scanner optics in the laser processing head, require comparable spatial brightness to laser cutting in order to keep the size of the galvanometer-driven scanner mirrors small and to realize a significantly increased working distance of the laser output to the work piece compared to classical welding [18, 19]. Until the mid nineties, high-brightness laser applications have primarily been served with electrical discharge-pumped CO\textsubscript{2} gas lasers operating at output powers of multiple Kilowatts and providing almost diffraction-limited beam quality of about 3 mm × mrad (λ = 10.6 µm). At those times, nearly every 2D flat sheet cutting machine incorporated a CO\textsubscript{2} laser and its subsequent free-space beam delivering components. Since 2010, multi-kW diode-pumped solid-state lasers of equivalent spatial brightness have come of age to replace step-by-step these in a way old-fashioned working horses [20, 21]. The technology change was driven by different factors [16, 22, 23]. Compared to lamp-pumped solid-state lasers and CO\textsubscript{2} lasers, ranging at about 3% and 15% [16, 24], modern diode-pumped solid-state lasers provide electrical-to-optical (e-o) conversion efficiencies larger than 30%. In particular, high-power gallium arsenide (GaAs) based laser diodes, with an emission wavelength in the near-infrared spectral region from 900nm to 1000nm, paved the way for efficient optical pumping of ytterbium-doped laser gain media [25–28]. Due to the smaller quantum defect compared to most common neodymium-doped laser crystals in conjunction with the enhanced e-o conversion efficiency and more narrowband spectral operation of the pump diodes compared to gas discharge lamps, power conversion efficiencies of high-power solid-state lasers could be significantly improved. Relating thereto, lower induced heating of the gain medium simultaneously reduced thermo-optically induced beam quality degradation with scaling of the laser output power. Furthermore, the enhanced spatial brightness of laser diode pump sources compared to gas discharge lamps enabled the realization of pumping optics architectures for ytterbium-doped thin-disk and fiber lasers whose quasi-three-level gain media require excellent cooling conditions and high pump power densities [29–32]. As
a consequence of the mentioned facts, diode-pumped ytterbium based thin-disk and fiber lasers today represent the most prominent state-of-the-art high-power solid-state lasers which provide the highest spatial brightness \[33\]. Commercial and scientific high-power fiber lasers provide diffraction-limited beam quality of about \(0.3 \text{ mm} \times \text{ mrad} (\lambda = 1070 \text{ nm})\) up to 20 kW of output power \[12, 13, 34–37\]. Fiber-coupled thin-disk lasers are commercially available with output powers between 1 kW to 10 kW and a BPP in the range of \(3 \text{ mm} \times \text{ mrad}\) \[38, 39\]. Nowadays, edge-emitting broad-area diode lasers themselves have been developed to a maturity that, in conjunction with certain beam shaping, transforming and coarse wavelength beam combining (CWBC) optics, provide a spatial brightness which can compete with optically pumped solid-state lasers in the field of classical tactile welding applications. The striking advantages of direct diode lasers compared to optically pumped solid-state lasers consist of a higher compactness and an enhanced e-o conversion efficiency of up to 50\% \[40\]. In principle, higher e-o conversion efficiencies for direct diode lasers are accessible due to the direct usage of the laser diode output beams and the omission of power losses which are induced by the resonator and the laser crystal in optically pumped solid-state lasers. These features are the driving factor for direct diode laser technologies in the field of high-power laser applications.

Among the different types of diode lasers, arrays made up of edge-emitting broad-area laser (BAL) diode emitters (laser diode bars and stacks) are the most efficient, compact and reliable solid-state high-power radiation sources which is the reason why these devices are the most promising building block for realizing efficient high-power direct diode lasers. Several hundred Watts of output power have been demonstrated for an individual 10-mm wide BAL diode bar with an e-o conversion efficiency of up to 65\% \[41\]. Since the output power of an individual BAL diode emitter is limited to about 10 W and furthermore exhibits multi-transverse-mode operation in the lateral beam direction with a BPP typically larger than \(3 \text{ mm} \times \text{ mrad}\), the resulting spatial brightness of bare high-power laser diode bars and stacks are fairly low in the lateral and/or stacking dimension. As a consequence, direct diode lasers which are based on bare laser diode bars and stacks are not capable to directly address high-brightness laser applications even in the ideal case of maximal closely packed emitters in space domain and in the absence of any brightness degrading mechanisms (see Fig. 1.1). During the last decades, intensive research has been carried out on spatial brightness scaling of laser diode emitter arrays in order to build high-power diode laser for direct applications \[42\]. Generally, these techniques can be divided into two groups which are coherent and incoherent beam combining. Coherent beam combining requires a precise and stable control of the relative phase of the individual com-
combined gain elements on a sub-wavelength scale which is the reason why, presently, various demonstrated approaches in the context of laser diode arrays [2, 43–46] can not provide robust, cost-effective and simple coupling schemes and laser designs which are suited for noisy industrial environments [14]. Less challenging and more commonly used are incoherent beam-combining techniques which comprise spatial beam combining (SBC), polarization beam combining (PBC) and wavelength beam combining (WBC). SBC enables a scaling of the output power by placing laser sources simply side-by-side in a one- or two-dimensional array. But the spatial brightness of the resulting beam can not be increased by this technique, since, in the ideal case without aperture underfilling, the output power as well as the BPP are simultaneously increased by the same factor which is given by the number of spatially multiplexed laser beams according to Eq. (1.1). Incoherent beam-combining techniques which enable an increase of the output power while simultaneously maintaining the BPP of the involved laser beams are PBC and WBC. In systems utilizing PBC, two input laser beams of orthogonal polarization are coupled into a combined colinear beam via polarizing coupling optics. Thus, the spatial brightness of the resulting beam can be increased by a factor of 2 at maximum. Higher brightness scaling factors, at the expense of an increased spectral bandwidth, are achievable in terms of WBC. Here, multiple beams exhibiting different wavelengths are combined via a wavelength-selective beam coupler which consist of dispersive optical elements such as bandpass interference filters [47], volume Bragg gratings (VBGs) [48] or a diffraction grating. In this case, the theoretical brightness scaling factor is given by the number of coupled wavelength channels $N_\lambda$. In conventional architectures, the wavelength channels of the diode laser sources have a spectral spacing of 20nm to 40nm. Predominantly spectrally unstabilized laser diode modules operating at different emission wavelengths are used for this technique and beam combining is performed by sequentially employing dichroic edge filters which are tailored to match the spectrum of the laser diode source in the corresponding wavelength channel. The spectral denseness, and therefore the spectrally induced brightness enhancement factor, is technically limited by the spectral slope steepness of the filters and furthermore by the spectral linewidth in conjunction with the current-dependent wavelength shift of the emitted laser diode spectrum [14]. As consequence, a brightness scaling factor of $N_\lambda < 10$ is attainable employing CWBC of GaAs based BAL diodes in the 9xx-nm wavelength band. The direct diode lasers whose beam parameters in Fig. 1.1 lie within the typical range for welding applications make use of the discussed incoherent beam combining techniques. Depending on the design and beam characteristics of the applied laser diode platform in the different wavelength channels for CWBC, multi Kilowatts of output power and a BPP in the range of $40 \text{mm} \times \text{mrad}$ have been demonstrated with excellent
1. Introduction

e-o conversion efficiencies [49–52]. Compared to reported direct diode laser systems without a WBC implementation [53–55] employing certain beam shaping, transforming and stacking techniques, the achievable spatial brightness could be significantly improved and reaches the presented theoretical limit for pure beam stacking with maximal spatial filling factor (FF). However, the mentioned technical constrains for the brightness scaling factor prevent direct diode laser systems which are based on CWBC from entering a higher spatial brightness level.

This thesis deals with the possibility of applying direct diode lasers to even brighter laser metal processing applications, such as flat sheet metal cutting or remote welding, by using dense wavelength beam combining (DWBC) of hundreds of individual BAL diode emitters. In contrast to CWBC, spectrally stabilized diode laser sources are used in DWBC architectures which enable a significantly smaller spectral channel spacing of the combined laser beams and consequently a larger brightness scaling factor. Due to the spectral stabilization of the laser diode source, the current-dependent wavelength shift of the emitted laser diode spectrum is overcome and therefore allows for a denser spectral stacking. Different implementations of DWBC have been demonstrated over the years predominantly in terms of fiber-optic communications for the telecom industry [56, 57] but only recently successfully applied to realize kW-class high-brightness direct diode lasers systems with comparable beam quality to diode-pumped solid-state lasers [58, 59]. The approaches generally differ by the optical components which are used for beam combining and the form of how spectral stabilization of the laser diode emitters is performed. DWBC architectures where the spectral stabilization of the laser diode source is decoupled from the beam combining element are referred to as open-loop [60]. In this case, laser diode emitter arrays are wavelength stabilized and spectrally narrowed via VBGs [61, 62] and beam combining is realized either by a sequential series of several bandpass interference filters [63–65] or VBGs [66], or alternatively by use of a single diffraction grating [67] which allows for simultaneous coupling of multiple beams. By using open-loop DWBC techniques, several companies and research institutes have demonstrated direct diode lasers with output powers at the kW level and a BPP in the range of 10 mm × mrad (see Fig. 1.1). The only well-known architecture for closed-loop DWBC are external resonators employing a single intra-cavity diffraction grating for simultaneous wavelength stabilization and beam combination. This approach has been proposed by White in the early nineties in the context of WDM of low-power semiconductor laser transmitters for optical communication [68]. Figure 1.2 shows the reported schematic setup of the external grating cavity from the original publication. It is important to note that the external cavity structure was intended not to scale the power of the optical output but to increase the
optical transmission bandwidth by coupling multiple wavelength channels into a single fiber. Effectively, this is the same as scaling the spatial brightness. Later, this architecture has been adapted to high-power laser diode arrays and successfully used for spatial brightness scaling [69]. Here, very similar to the setup shown in Fig. 1.2, the combination of a Fourier lens, a diffraction grating and output coupling mirror in the external laser cavity forces the emission spectrum of each individual emitter of a laser diode array on a unique wavelength. Consequently, \( N \lambda \) is given by the number of individual gain elements which is provided by the diode laser source in the beam-combining dimension. At the same time, the individual spectrally stabilized emitter sub-beams are diffracted into a single combined beam at the grating. Commercially available high-power laser turn-key systems which make use of this technology in conjunction with conventional SBC and PBC techniques provide an output power of 4 kW with an e-o conversion efficiency of 44\% and a BPP of 4 \text{mm} \times \text{mrad} [70]. Consequently, DWBC based high-brightness direct diode lasers are potentially suited to serve all kinds of high-brightness continuous-wave kW-class metal processing applications. However, competitive costs and equivalent reliability, compared to well established high-power solid-state thin-disk or fiber lasers, and a sufficient lifetime of the laser diodes under external optical feedback [71–73] will be basic prerequisites for a successful market penetration of those lasers in the future.

This thesis is a contribution to DWBC of laser diode emitter arrays in external laser cavities. Two different external cavity architectures for either open- or
closed-loop DWBC are investigated and compared with regard to an efficient spatial brightness scaling of high-power BAL diode bars towards the kW power level with minimal beam quality deterioration. First, the mentioned closed-loop approach for DWBC employing an intra-cavity transmission grating in the external laser cavity (hereafter referred to as “Transmission grating approach”). Second, a novel external multi-laser cavity for open-loop DWBC which is based on a single thin-film filter (TFF) as dispersive optical element inside the external resonator (hereafter referred to as “Thin-film filter approach”). TFFs have already been used for WDM applications in fiber-optic telecommunication networks [74, 75] or spectral narrowing and wavelength tuning of single laser diodes [76, 77] but not yet for spatial brightness scaling of high-power BAL diode bars in external laser cavities. Using a TFF as wavelength selective element inside the external resonator has major advantages. First of all, TFFs exhibit an increased spectral angular dispersion compared to conventional diffraction gratings which allows for a high spectral denseness of the stabilized wavelength channels even at moderate focal lengths of the Fourier lens. Furthermore, the TFF multi-laser cavity provides an intrinsic suppression of spectral emitter cross-talk in the optical feedback between adjacent laser diode emitters which in intra-cavity transmission grating based DWBC approaches is typically accomplished by introducing space-frequency filters. Compared to commercial VBGs, which are recorded into photo-thermo-refractive glass, TFFs exhibit much lower thermo-optically induced wavelength shift which ensures a stable wavelength stabilization with respect to the beam-combining element. Finally, spectral stabilization of hundreds of individual gain elements can be achieved by only one individual optical component inside the resonator. This is the reason why this approach is suited to realize robust and low-cost optical designs of the external laser cavity. The overall aim of this work is the realization of a 1-kW high-brightness direct diode laser module with largest possible e-o conversion efficiency by using the investigated approaches for DWBC (see Fig. 1.3). The consequential research issue is the question if the spatial brightness provided by BAL diode emitters of state-of-the-art high-power laser diode bars is sufficient for the realization of highly efficient kW-class direct diode laser systems by use of DWBC in external laser cavities whose beam parameters are suited for high-brightness laser applications and furthermore, what are the limiting brightness degrading mechanisms using this technique in either open-loop or closed-loop cavity architectures in general. The thesis is structured as follows: Chapter 2 gives a brief introduction to the physical properties of BAL diode bars. The focus is mainly on the physical properties and beam characteristics of the laser diode bars which have been used for the experiments in this thesis. In Chapter 3, the theoretical background and the functional principle of both investigated DWBC approaches are explained. Based on theoretical
considerations and results of individual-bar experiments, the capability of both external cavity designs for an efficient spatial brightness scaling of BAL diode bars is discussed and the dominant mechanisms of beam quality deterioration, which limit the minimal achievable BPP of the combined output beam, are identified and investigated. Chapter 4 deals with the high-brightness direct diode lasers which have been realized in this thesis. Experimental results of the 1-kW high-brightness direct diode laser modules are presented. Here, the focus is mainly on the impacts of both an increased intra-cavity power and an order of magnitude larger stabilized spectral interval on the beam parameters of the combined output beam of the laser compared to the individual-bar experiments presented in Chapter 3. Based on the experimental results which have been achieved using both DWBC approaches, the advantages and disadvantages of both systems are discussed regarding spatial brightness scaling to multi-kW power levels.
2

High-Power Broad-Area Laser Diode Bars

The topic of this chapter are the physical properties of high-power BAL diode bars. In this context the architecture, micro-optical components for beam shaping and the radiation characteristics are explained with regard to the usage of BAL diode bars for dense wavelength beam-combined high-brightness direct diode lasers. A more comprehensive description of the discussed aspects and a detailed treatment of the underlying semiconductor physics can be found in [2, 14, 78–81].

2.1. Architecture and setup

A laser diode bar (see Fig. 2.1a) consists of a horizontal array of several BAL diodes which are fabricated onto a single monolithic chip, which exhibits the vertical layer structure, by dividing the p-contact area into several contact stripes through photo-lithographic patterning, etching and the deposition of insulating dielectric layers. The resulting individual beam sources of a diode bar are called emitters and are electrically connected in parallel. The emitter pitch \( p_{em} \) describes the lateral spacing of adjacent emitters on a diode bar and defines, in conjunction with the width \( W \) of the contact opening, the FF \( W/p_{em} \) of the diode bar. Typically, the lateral chip dimension is 10 mm comprising between 8 to 50 BAL diode emitters depending on the specific application and the desired optical output power. Figure 2.1b shows the schematic setup of a state-of-the-art edge-emitting laser diode emitter. In all modern semiconductor laser diodes double-hetero p-i-n junctions are utilized to achieve population inversion. In this structure a thin layer of intrinsic direct semiconductor material is embedded between p- and n-doped regions of semiconductor material with a larger band gap. The intrinsic layer serves as laser-active region and is typically realized in form of a quantum well (QW) with a thickness \( d_{QW} \) of 5 nm to 10 nm (see Fig. 2.2). Laser diodes with an emission wavelength in the spectral region from 700 nm to 1000 nm are typi-
Fig. 2.1: Schematic setup of a BAL diode bar with beam axis and emitter pitch definition (a) and an edge-emitting semiconductor laser diode emitter with epitaxial layer growth, refractive index profiles and beam axis definition (b).

cally realized on gallium arsenid (GaAs) substrates with epitaxially grown layers of III-V compound semiconductor alloys which are lattice-matched to GaAs. The wavelength of the laser transition is mainly determined by the band gap energy \( E_g \) and can thus be tuned by the material composition of the intrinsic semiconductor crystal or by introducing mechanical biaxial strain into the QW using material compositions whose lattice constants are not completely matched. For example, in an indium gallium arsenide (InGaAs) QW, as shown in Fig 2.2, the incorporation of In atoms into a GaAs QW results in a compressively strained QW. Depending on the In concentration, which is typically below a few ten percents, the emission wavelength ranges from 870 nm (bulk GaAs) of up to about 1100 nm [2, 14].
Fig. 2.2: Band gap distribution and relevant energy levels of an InGaAs QW which is embedded between larger-band-gap waveguide layers consisting of AlGaAs. The QW results in a quantization of the electronic wave function in discrete energy levels for the electrons in the conduction band (subband energies $e_1$, $e_2$) and holes in the valence band (subband energies $hh_1$, $lh_1$). In the transition region of the junction, where both carrier types coexist and population inversion takes place, an electron in the conduction band and a hole in the valence band will radiatively recombine. A photon with energy $\hbar \omega > E_g$ is generated ($\hbar$: reduced Planck constant; $\omega = 2\pi c/\lambda$ photon angular frequency; $c$: speed of light) [14].

In case of edge-emitting laser diodes, the resonator for optical feedback at the laser transition is realized by the laser diode structure itself by using the cleaved front and back facets of the semiconductor crystal as resonator mirrors (reflectivities $R_{ff}$ and $R_{bf}$) to realize a Fabry-Pérot resonator with cavity length $L$ for the generated radiation. Dielectric mirror coatings are used to change the reflectivity of the back and front facet and furthermore to passivate the cleaved crystal surfaces. In order to achieve an emission of the major portion of the generated optical power through the front facet, the back facet mirror exhibits a high reflectivity of $R_{bf} > 95\%$. Due to the high modal gain, large light extraction can be achieved in semiconductor laser diodes resulting in a high e-o conversion efficiency. Laser threshold can be reached with low values of the front facet reflectivity. Thus,
the front facet mirror typically exhibits a single layer anti-reflection (AR) coating with a reflectivity of $R_{ff} < 5\%$ for high-power devices with cavity lengths between 2 mm to 4 mm [2, 14]. The vertical layer structure serves as a dielectric optical waveguide, since the refractive index of the low-band-gap active layer is higher than the refractive index of the surrounding larger-band-gap layers, which consist of aluminum gallium arsenide (AlGaAs), enabling low-loss wave-guiding by internal total reflection. The resulting refractive index profile $n(y)$ of the vertical layer structure is shown in the inset of Fig. 2.1b. Since the thickness of a single QW is too small to realize sufficient wave-guiding and confinement of an optical mode, the double heterostructure in QW lasers is embedded between an additional layer of larger-band-gap material which are called cladding layers. The actual waveguide is formed by the core region, which consists of the laser-active QW and the waveguide layers, in conjunction with the cladding layers. The small dimension of the waveguide in conjunction with the diffraction-limited beam quality of the propagating optical mode result in a large far-field divergence of the output beam in the vertical beam dimension ($y$-axis) which is the reason why the vertical beam axis is called fast-axis (FA). Depending on the waveguide thickness, the full-angle beam divergence is typically between $40^\circ$ to $60^\circ$ [2, 14]. In the lateral dimension ($x$-axis) of the laser diode, the width $W$ of the active layer is defined by the opening of the top Ohmic p-contact (see Fig. 2.1b). In order to achieve lateral current and photon confinement, different mechanisms are used [2, 82, 83]. A very common mechanism is current confinement by use of a current aperture beside the contact opening which is realized by either an insulating dielectric layer or ion implantation resulting in a gain-guided lateral waveguide. In these so-called gain-guided lasers only those lateral optical modes are amplified, whose electric field distributions have a sufficient overlap with electrically pumped active area below the top contact. In case of BAL diodes, the width of the contact opening is typically around 100 $\mu$m allowing for high output powers of several Watts at moderate optical power densities on the front facet. The large extent of the lateral waveguide results in multi-transverse-mode operation of the device in the lateral beam dimension. The lateral beam axis is called slow-axis (SA), since the far-field divergence is approximately an order of magnitude smaller compared to the beam divergence in vertical beam dimension. Depending on the lateral waveguide structure and the operation conditions, the full-angle beam divergence is typically between $5^\circ$ to $10^\circ$ resulting in a BPP in the range of $3 \text{ mm} \times \text{ mrad}$. Due to the multi-mode beam characteristics, the far-field intensity distribution shows a top-hat-like profile.

The basic parameters of the BAL diode bars which are used for the experiments in this thesis are listed in Table 2.1. Both commercial (bar A and bar B) [84]
### Tab. 2.1: Basic parameters of the deployed BAL diode bars within this thesis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bar A</th>
<th>Bar B</th>
<th>Bar C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of emitters</td>
<td>19</td>
<td>45</td>
<td>23</td>
</tr>
<tr>
<td>Pitch (µm)</td>
<td>500</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>FF (%)</td>
<td>20</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Cooler</td>
<td>passive (CN)</td>
<td>passive (CN)</td>
<td>active (ILASCO)</td>
</tr>
<tr>
<td>Typical operation current (A)</td>
<td>120</td>
<td>200</td>
<td>180</td>
</tr>
<tr>
<td>Optical power (W)</td>
<td>100</td>
<td>140</td>
<td>150</td>
</tr>
<tr>
<td>Central wavelength (nm)</td>
<td>960</td>
<td>1010</td>
<td>940 - 1000</td>
</tr>
<tr>
<td>FA divergence (°) (95% p.c.)</td>
<td>47</td>
<td>47</td>
<td>40</td>
</tr>
<tr>
<td>FAC focal length (µm)</td>
<td>410</td>
<td>160</td>
<td>300</td>
</tr>
<tr>
<td>Typical SA divergence (°) (95% p.c.)</td>
<td>8</td>
<td>9</td>
<td>8</td>
</tr>
</tbody>
</table>

![Schematic setup of the used passively and actively cooled BAL diode bar packages.](image)

and non-commercial (bar C) BAL diode bars with 100-µm contact opening of different FFs are used. All diode bar chips have a cavity length of 4 mm and a front facet reflectivity $R_{ff} < 0.5\%$ which is necessary for the spectral stabilization of the diode bar emitters in an external laser cavity (see section 2.2.2). The vertical layer structure of the chip exhibits a single InGaAs QW which is embedded in an AlGaAs waveguide structure. The laser diode bar emitters have an uncollimated full-angle beam divergence $2\theta_{FA,em}$ in FA of 40° or 47°, corresponding to a power content (p.c.) of 95%. The different beam divergence parameters result from a
varying thickness of the vertical optical waveguide. For lateral emitter confinement, exclusively ion implantation is used in case of bar A and bar B. In case of bar C, an emitter design with either ion implantation or an insulating dielectric layer beside the contact opening is used. Different operation wavelengths of the diode bars in the spectral region from 940 nm to 1000 nm are obtained by using epitaxial chip designs with varying photoluminescence wavelength. In a laser diode bar package, the chip is mounted on a copper heat sink for the removal of Ohmic heat from the laser-active region. For this purpose, different cooling techniques and mounting technologies are used [14]. Two of the most common techniques and types of diode bar packages are deployed for the diode bars which are used in this thesis (see Fig. 2.3). The first type of package or cooling technique is passive conduction cooling as in case of bar A and B. Here, soft soldering with ductile In solder is used for mounting the diode bar on the p-side to a massive copper (Cu) heat sink. The diode bar package itself is mounted on a water-cooled Cu plate. In the second type of package, as in case of bar C, a Cu microchannel cooler is used for active convection cooling [86]. The diode bars are hard-soldered on the p-side, using gold-tin (AuSn) solder, on a copper-tungsten (CuW) submount which provides an adaption of the coefficient of thermal expansion (CTE) between the chip and the used active isolated laser cooler (ILASCO) [85]. The second interface between the submount and the cooler is also hard-soldered. For both discussed diode bar package types, the typical cooling water temperature is 25°C. The diode bars are operated at a flow rate of 60 L/h.

For the collimation of the emitter sub-beams of the diode bar in the fundamental-mode FA, an aspherical cylindrical micro-lens is used which is referred to as fast-axis collimator (FAC). The principle of beam collimation in FA is schematically shown in Fig. 2.4. The resulting emitter beam divergence \( \theta_{FAC,em} \) in FA behind the FAC mainly depends on the focal length \( f_{FAC} \) of the FAC, the quality of the aspherical lens surface and the alignment accuracy and stability during the lens mounting process [14]. The used diode bars exhibit a commercial FAC [87–89] with a focal length of either 160 \( \mu \)m, 300 \( \mu \)m or 410 \( \mu \)m depending on the FF of the respective diode bar (see Table 2.1). Besides the FAC, an additional micro-optical component is used for shaping the output beams of the diode bar after beam collimation in FA. The micro-optical component, which is referred to as beam transformation system (BTS), consists of an monolithic array of cylindrical micro-lens telescopes which are tilted by 45° with respect to the beam axis of the propagating emitter sub-beams of the diode bar (see left part of Fig. 2.5) [52, 90]. As a result of the imaging, each individual emitter sub-beam is rotated by 90° in the direction of propagation, so that FA and SA beam direction are interchanged with respect to the fixed coordinate system of the laser diode bar (see right part
of Fig. 2.5). The beam transformation yields a horizontal array of emitter sub-beam which are stacked in FA and thus a significantly improved symmetry of the BPP of the diode bar output [91]. As later explained in section 3.1, the emitter beam transformation by use of the BTS plays a key role in terms of feedback re-imaging and beam quality preservation in the investigated external laser cavities for DWBC. The FF of the diode bar in conjunction with the beam divergence 

Fig. 2.4: Schematic principle of beam collimation in FA by use of an aspherical cylindrical micro-lens which is referred to as fast-axis collimator (FAC).

Fig. 2.5: Beam shaping by use of a micro-optical beam transformation system (BTS). Left, principle of beam imaging using a tilted cylindrical micro-lens telescope and schematic setup of the micro-optical component. Right, schematic emitter beam cross-sections before and after beam shaping by the BTS. Each emitter sub-beam is rotated by 90° in the direction of propagation.
of the emitter sub-beams in SA limit the aperture of the array elements of the BTS and furthermore the maximal distance of the micro-optical component from the front facet of the diode bar chip. In order to achieve individual beam transformation for each individual emitter, it has to be ensured that adjacent emitter sub-beams are sufficiently spaced in the lateral SA direction in front of the BTS which consequently limits the distance from the front facet. In turn, the focal length of the FAC is determined by this distance. Due to the mentioned reasons, the maximum focal length of the FAC is a function of the FF. The higher the FF of the diode bar for a fixed emitter beam divergence in SA, the smaller the possible FAC focal length. Relating thereto are the differing FAC focal lengths of the used diode bars in Table 2.1. For the experiments in this thesis, commercially available BTSs are used [92–94] which match the geometrical design of the respective laser diode bar in terms of emitter pitch and number of emitters.

2.2. Radiation characteristics

2.2.1. Optical output power and polarization

The optical output power $P$ of a laser diode emitter has a linear dependency on pumping current $I$ above threshold which can be described by [14]:

$$ P = \eta_d \frac{\hbar \omega}{q} \cdot (I - I_{\text{thr}}). $$

Here, the elementary charge is denoted by $q$, $\eta_d$ represents the differential efficiency of the laser and $I_{\text{thr}}$ corresponds to the diode current at laser threshold. The first two factors in Eq. (2.1) comply with the slope efficiency $\eta_s = \frac{dP}{dI}$ of the power characteristics curve above threshold. The corresponding e-o conversion efficiency $\eta_{eo}$ is given by the quotient of the optical output power to the electrical input power

$$ \eta_{eo} = \frac{P}{U \cdot I}, $$

where $U = U_0 + I \cdot R_s$ being the device voltage which comprises the voltage $U_0$ applied to the p-n junction and the voltage resulting from the series resistance $R_s$ of the device. The output power characteristics curves of the diode bars which are listed in Table 2.1 are presented in Fig. 2.6. For each diode bar type, the curve of one selected device is exemplary shown. The measurement of the optical output power is performed after lensing of the FAC. Bar A, emitting at a central wavelength of 962nm, provides an output power of about 120W at a
2.2. Radiation characteristics

Fig. 2.6: Output power characteristics curves for different 962-nm diode bars (bar A and bar C) and a 1010-nm diode bar (bar B). Measured output power (a) and corresponding e-o conversion efficiency (b) vs. diode current.

...diode operation current of 140 A. The corresponding e-o conversion efficiency is about 58% at 140 A. The maximal e-o conversion efficiency ($\eta_{eo} = 59\%$) is achieved at 120 A (106 W). The output power of the actively cooled 962-nm bar C is 170 W at a diode operation current of 200 A. At this operation current, the e-o conversion efficiency is approximately 53%. The diode bar provides an e-o conversion efficiency maximum of 59% at a diode current of 120 A (105 W). The used diode bar exhibits an ion implantation for lateral emitter confinement. Devices exhibiting an insulating dielectric layer as current aperture of the identical type (bar C) and with similar spectral emission show no significant differences in the output power characteristics curve. Both bar A and bar C show a similar linear output power characteristics curve with comparable slope efficiencies ($\eta_s \approx 0.94$ W/A) and threshold currents ($I_{thr} \approx 15$ A). In the investigated current range, no thermal rollover of the output power is observable. Bar B provides an output power of about 140 W at a diode operation current of 200 A. The corresponding e-o conversion efficiency is about 50% at 200 A which is 2% lower than the maximum value which is attained at 160 A (114 W). The lower slope efficiency ($\eta_s \approx 0.81$ W/A) and e-o conversion efficiency compared to bar A and bar C is related to the long-wave emission at a wavelength of 1010 nm. Due to the increased number of emitters of bar B, a larger threshold current of $I_{thr} \approx 30$ A is needed to achieve laser operation. The measured optical output power after lensing of the FAC serves as benchmark for the spectrally stabilized and wavelength beam-combined output power. Hereafter, the measured optical output power of
the diode bar or an individual emitter after lensing of the FAC is referred to as “free-running”, since no implementation of wavelength stabilization is present at this stage.

Besides the achievable optical output power, the degree of polarization (DOP) of the emitted radiation of the diode bar is an important property which, as later discussed in Chapter 3, has a major impact on the diode bar performance in both investigated external laser cavities for DWBC. The DOP depends on both the mounting technology of the laser diode bar package and the type of lateral emitter confinement. In case of compressively strained InGaAs QWs, the main optical transition yields transverse electric polarized laser emission with an electric field vector oscillating in plane with respect to the epitaxial layers of the chip [81]. Packaging-induced external and internal strain in the diode bar chip result in a depolarization of the laser output due to stress-induced birefringence in the waveguide [14, 83]. The source for the mechanical strain is related to the thermal expansion mismatch between the diode bar chip and the heat sink materials during the mounting process as well as during operation. Figure 2.7a shows the output power characteristics curve for transverse electric (TE) and transverse magnetic (TM) polarization of an 962-nm diode bar (bar C) with ion implantation. For the measurement a polarizing beamsplitter (PBS) is used to split the respective power fraction of the diode bar output. From the presented data it

![Fig. 2.7: (a) Measured output power vs. diode current for TE and TM polarization of a 962-nm diode bar (bar C) exhibiting an ion implantation for lateral emitter confinement. (b) DOP for TE polarization vs. diode current for 962-nm diode bars (bar C) exhibiting an emitter design with an insulating dielectric layer as current aperture or ion implantation.](image-url)
becomes evident that the optical output power is mainly emitted in TE polarization. The DOP, given by the ratio of the emitted power in TE polarization to the overall optical output power of the diode bar, is 98% and shows no dependency on diode current as shown in Fig. 2.7b. Furthermore, Fig. 2.7b shows a comparison of the DOP as a function of diode current for different diode bar package types and diode chip designs for bar C. Compared to the data presented for the diode bar with ion implantation, the same bar type (bar C; CuW submount; AuSn hard solder; 962-nm emission wavelength) exhibiting an lateral emitter design with an insulating dielectric layer as current aperture has a significantly lower DOP which furthermore shows a dependency on diode current. At the typical operation current of 180A, the DOP is about 94%. Similar results are obtained for diode bars of the same type independent of the operation wavelengths in the spectral region from 940 nm to 1000 nm. A possible explanation for the differing performance of both bar types is a lower packaging-induced strain in case of the chip design with ion implantation due to the flat and homogeneous chip surface at the p-contact. In case of the emitter design with an insulating dielectric layer as current aperture, the lateral patterning of the p-contact of the diode bar chip results in a more complex surface topography which inherently yields higher strain of the diode chip after packaging using hard solder. An even lower value for the DOP (≈87% at 100A) is obtained for the diode bar package without submount, where no thermal expansion matching between the hard-soldered chip and the cooler is present. The DOP of the soft-soldered diode bars (bar A and bar B), which exhibit an ion implantation for lateral emitter confinement, has not been discussed so far. The DOP of the optical output of these bars is larger than 98% due to the ductile solder which significantly reduces mechanical stress which is induced in the diode bar chip. In this case, stress is balanced out by plastic deformation of the solder [14].

2.2.2. Spectrum and wavelength tunability

At laser threshold, the longitudinal mode of the Fabry-Pérot resonator of the laser diode bar emitter which is in closest spectral vicinity to the peak wavelength of the modal gain spectrum is amplified. The cavity length determines the spectral spacing of the longitudinal Fabry-Pérot modes which is typically below 100 pm for devices with a cavity length larger than 2 mm [2]. Due to the high spectral density of the longitudinal modes in conjunction with the multi-mode lateral beam characteristics, the spectral bandwidth of the emitted spectrum is typically between 1 nm to 2 nm (FWHM) for BAL diodes [14]. The emission wavelength furthermore depends on temperature. With increasing device temperature, the emitted spectrum shifts to longer wavelengths. The main reason for the thermally
induced wavelength increase is the shift of the peak wavelength of the modal gain spectrum by about 0.3 nm/K for GaAs based laser devices due to the decreasing band gap energy with temperature [95]. Figure 2.8 exemplary shows the measured spectrum of the optical output of a 954-nm diode bar (bar C) at different diode operation currents and the corresponding current-dependent shift of the extracted central wavelength of the spectrum. From the presented spectra in Fig. 2.8a one can see that both the spectral bandwidth and the peak wavelength of the emitted spectrum increase with increasing diode operation current. Slightly above laser threshold at a diode current of 20 A, the spectral width is about 760 pm (FWHM) and grows to a value of 4.4 nm (FWHM) at 200 A. With increasing diode cur-

![Normalized intensity vs. Wavelength (nm)](image1)

![Central wavelength vs. Current (A)](image2)

Fig. 2.8: (a) Spectrum of the output beam of a 954-nm diode bar (bar C) at different diode operation currents. (b) Current-dependent wavelength shift. Measured central wavelength vs. diode current extracted from the spectra shown in (a) and linear curve fit.

rent, the shape of the spectrum becomes asymmetrical with a short-wave blue tail which arises from varying operation temperatures of the diode bar emitters along the lateral chip dimension. Outer emitters experience lower thermal cross-talk of neighboring emitters, thus resulting in a lower operation temperature compared to the inner emitters of the diode bar. Besides this non-uniform lateral heat spreading, the lateral stress distribution in the mounted diode bar chip also affects the emitted spectrum due to a varying strain in the QW of the diode bar emitters [14]. The current-dependent shift of the central wavelength of the measured spectra shown in Fig. 2.8a is extracted from the data and presented in Fig. 2.8b. The central wavelength is evaluated by calculating the centroid of the corresponding spectrum. The data show that the central wavelength linearly
increases with increasing diode current due to the thermally induced decrease of the band gap energy in the InGaAs QW. The total wavelength shift amounts to 12.5 nm from 20 A up to an operation current of 200 A, which corresponds to a relative shift of 70 pm/A or 76 pm/W with reference to the optical output power. The current-dependent wavelength shift depends on the heat transfer of the dissipated thermal power from the p-n junction to the heat sink of the diode bar package. In this context, the thermal resistance of the laser diode bar package is a characteristic value for the cooling performance and mainly determines the thermal operation conditions of the diode bar. The thermal resistance \( R_{\text{therm}} \), given by

\[
R_{\text{therm}} = \frac{\Delta T}{P_{\text{therm}}},
\]

(2.3)
describes the increase in temperature \( \Delta T \) at the p-n junction which is induced by the dissipated thermal power \( P_{\text{therm}} \) during operation [14]. Both quantities can either directly or indirectly be obtained from electro-optical diode bar characterization data, as presented in the Figs. 2.6 and 2.8, by use of the following two relations. The dissipated thermal power \( P_{\text{therm}} \) is directly given by

\[
P_{\text{therm}} = U(I) \cdot I - P
\]

(2.4)
and consequently follows from the measured output power characteristics curve. The rise in junction temperature \( \Delta T \) can indirectly be obtained by measuring the shift of the central wavelength \( \lambda_c \) of the emitted diode bar spectrum as a function of the dissipated thermal power:

\[
\Delta T = \frac{\lambda_c(P_{\text{therm}}) - \lambda_c(P_{\text{therm}} = 0)}{\Delta \lambda_{\text{therm}}}, \quad \text{with} \quad \Delta \lambda_{\text{therm}} = \frac{d\lambda}{dT}
\]

(2.5)
being the thermal wavelength drift factor which describes the spectral shift of the modal gain spectrum of the laser structure. Using the described method, a thermal resistance of about 0.71 K/W is obtained for the passively cooled diode bar package of bar A and bar B, as can be seen from the data which are presented in Fig. 2.9a. The actively cooled diode bar package of bar C provides a significantly lower thermal resistance of approximately 0.33 K/W and 0.23 K/W with and without submount, respectively. For the calculation of the thermal resistance according to Eq. (2.3), the slope of the corresponding linear curve fit in Fig. 2.9a is divided by the measured wavelength drift factor of \( \Delta \lambda_{\text{therm}} = 0.31 \text{ nm/K} \) (see Fig. 2.9b). For the measurement of the wavelength drift factor, presented in Fig. 2.9b, the device is operated in pulsed mode (100-A diode current; 4-\( \mu \)s pulse width) with low duty cycle (d.c.) (0.02%) in the absence of cooling water flow.
The diode bar package is mounted on a heat plate for temperature control and the device temperature is measured on top of the cooler beside the diode bar chip by use of a platinum resistance temperature detector.

In contrast to standard high-power devices, the front facet of the chip of the deployed diode bars exhibit a broadband multi-layer AR coating with a reflectivity below 0.5%. As a result, important laser parameters like threshold current, slope efficiency and optical output power are affected by a reduced front facet reflectivity, whereby an increased threshold current is the most clear indication for the higher mirror losses at the front facet of the laser diode emitter. At laser threshold, the modal gain of the guided optical mode within the vertical waveguide compensates the internal losses $\alpha_{in}$ and the mirror losses $\alpha_{oc}$ of the Fabry-Pérot resonator for a roundtrip. Scattering of the optical mode at defects and free carrier absorption are the main contributions to the internal losses [96]. The mirror losses of the Fabry-Pérot resonator depend on the mirror reflectivities $R_{ff}$ and $R_{bf}$ of the front and back facet, respectively, and the cavity length $L$. The threshold gain $g_{thr}$ for laser operation can be described by the relation [2]:

$$g_{thr} = \alpha_{in} + \alpha_{oc} = \alpha_{in} + \frac{1}{2L} \ln \left( \frac{1}{R_{ff} R_{bf}} \right).$$  

(2.6)

![Fig. 2.9: (a) Thermal resistance $R_{therm}$ for the passively (bar A and bar B) and actively (bar C) cooled laser diode bar package. Measured central wavelength of the diode bar spectrum vs. dissipated power of 962-nm diode bars and linear curve fit used for the calculation of the thermal resistance. (b) Measured central wavelength of the diode bar spectrum vs. junction temperature of a 962-nm diode bar (bar C) in pulsed operation and linear curve fit used for the determination of thermal wavelength drift factor $\Delta\lambda_{therm}$.](image-url)
A low reflectivity of the front facet is an important requirement for wavelength stabilization of the diode bar emitters in an external laser cavity. Due to the low front facet reflectivity, the spectral emission of the diode bar emitters can be controlled by an external resonator which provides optical feedback for spectral locking by use of a frequency-selective component such as a diffraction grating [97], an interference filter [76, 77] or a VBG [98]. In a simplified model, the operating principle of the external resonator can be described by a wavelength-selective reflector which effectively replaces the front facet of the laser diode. For a sufficiently small front facet reflectivity, the influence of the emitter facet can be neglected and the wavelength-dependent reflectivity of the external resonator dominates the spectral emission of the laser diode due to a significantly lower threshold gain value [see Eq. (2.6)] compared to free-running operation [99]. Hence, laser emission occurs at the wavelength which is determined by the external resonator. The spectral bandwidth of the optical feedback provided by the external resonator in turn determines the spectral narrowing of the laser diode spectrum and depends on the specific external cavity design and implementation. Wavelength tunability and the spectral locking range of the wavelength-stabilized diode bar emitters are affected by both the value and spectral course of the front facet reflectivity and furthermore by the amount of optical feedback which is coupled back into the laser diode. The spectral bandwidth of the modal gain in an InGaAs QW can reach values of several ten nanometers [14] which basically makes wavelength tuning possible. Figure 2.10 schematically shows the principle of spectral stabilization and wavelength tuning of a laser diode emitter by use of an external resonator. The wavelength range over which spectral stabilization is possible, is limited by the difference in threshold gain between the internal laser diode and the external resonator, as simplified shown in Fig 2.10a. The external threshold gain is reached with the smallest excess carrier density \( N_1 \) if the stabilized wavelength \( \lambda_c \) corresponds to the peak wavelength of the modal gain spectrum. Due to the lower excitation level of the excess carrier density, the voltage at p-n junction of the laser diode emitter declines [100, 101] which is, besides a reduced threshold current, a clear indication for wavelength stabilization. If the stabilized wavelength is detuned from this spectral position, the external threshold gain can only be reached for a higher pumping level \( (N_2 > N_1) \) which correspondingly leads to an increased threshold current (see Fig. 2.10b). Spectral stabilization can be achieved within the wavelength interval where the modal gain equals or surpasses the threshold gain of the external resonator. At the border of the spectral locking range, the peak value of the corresponding modal gain spectrum (carrier density \( N_3 \)) equals the internal threshold gain of the laser diode. Beyond this region, spectral locking is not possible, since the modal gain for the internal laser diode is higher. As a consequence, the laser diode emits at its free-running radiation spectrum.
The larger the difference of the threshold gain values, which is achieved for a large ratio of the reflectivity of the external reflector to the front facet reflectivity, the larger the resulting locking range. In reality, both the internal and external threshold gain depend on wavelength due to the wavelength dependency of the internal losses and the spectral course of the front facet reflectivity. Thus, besides a low value of the front facet reflectivity, also a spectrally flat course is needed to provide a sufficiently large locking range. In order to investigate spectral stabilization of the diode bar emitters, an external laser cavity is employed where a $-1^{\text{st}}$ order reflection grating in Littrow configuration is used as frequency-selective component. The schematic setup of the external resonator is depicted in Fig. 2.11. Similar external cavity setups have been reported in [102–104] and used for wavelength stabilization and spectral narrowing of BAL diode bars. In the vertical FA direction ($y$-axis), the emitter sub-beams emerging from the BAL diode bar are collimated by use of a FAC. Subsequent, the far fields of the collimated and coaxially propagating emitter sub-beams are imaged onto a $-1^{\text{st}}$ order reflection grating by a cylindrical lens with a focal length of $f_{FA} = 150 \text{ mm}$. Each sub-beam, which is incident on the grating, has the same angle of incidence (AOI) $\alpha$ with respect to the surface normal of the grating. The cylindrical lens is placed in a telecentrical configuration with respect to the front facet of the diode bar and the grating. Consequently, the near field of the diode bar output of each emitter sub-beam is imaged upon the grating. In the lateral SA direction ($x$-axis), a $4f$-telescope, consisting of two cylindrical lenses (focal lengths $f_{SA1} = 50 \text{ mm}$ and $f_{SA2} = 100 \text{ mm}$), is used to image the beam waist of the emitter sub-beams in
Fig. 2.11: Schematic setup and states of polarization of the external laser cavity with adjustable optical feedback strength for wavelength stabilization of individual diode bar emitters by use of a -1\textsuperscript{st} order reflection grating in Littrow configuration.

SA onto the grating. The reflection grating, exhibiting $\Lambda^{-1} = 1250\text{ lines/mm}$, is placed in Littrow configuration with respect to the emitter rays which propagate along the optical axis of the external resonator. In Littrow configuration, the AOI $\alpha$ equals the diffraction angle into the -1\textsuperscript{st} order which is the reason why each incident emitter sub-beam is reflected back into itself at the grating. The angular dispersion of the grating determines the diffracted wavelength. From the grating equation it follows that the corresponding wavelength-to-AOI dependency in Littrow configuration is given by

$$\lambda_c = 2\Lambda \sin (\alpha) ,$$

(2.7)

where $\lambda_c$ is the central wavelength of the diffracted emitter beam and $\Lambda$ denotes the groove spacing of the grating. In order to adjust the optical feedback strength, a polarization-dependent output coupling unit is used which consists of a PBS and an achromatic quarter-wave plate (QWP). Each emitter sub-beam passes the unit twice during one cavity roundtrip. In the first pass, most of the incident laser power $P_{in}$ is transmitted by the PBS because of the TE-polarized diode bar emission which corresponds to TM polarization with respect to the plane of incidence at the PBS (see bottom part of Fig. 2.11). Depolarized power fractions are reflected out of the external cavity by the PBS. Behind the PBS,
the emitter sub-beams pass the QWP a first time. After the back reflection by the grating, the sub-beams again are incident upon the QWP. In this way, the QWP effectively acts as half-wave plate (HWP) and leads to a rotation of the initial TM polarization of the emitter sub-beams. The respective power fraction in TM or TE polarization after the second pass depends on the rotation angle of the QWP between its optic crystal axis and the oscillation direction of the electric field vector of the incident linearly polarized laser beams. Since exclusively TM-polarized power fractions are transmitted by the PBS at the second pass, the optical feedback power $P_{FB}$ which is coupled back into the diode bar emitters can be adjusted by rotating the QWP. The adjusted optical feedback strength is controlled using two power meters (PMs) by which a defined power fraction of the input laser power ($P_1$) respectively optical feedback power ($P_2$) is measured which is reflected out of the external cavity by a partially reflective mirror (PRM) of known spectral transmission. In this way, the adjusted optical feedback strength corresponds to the averaged optical feedback over all diode bar emitters. In the described measurement configuration, the feedback ratio with reference to the input laser power is given by (see appendix A):

$$\frac{P_{FB}}{P_{in}} = \frac{P_2}{P_1} \cdot T_{TM,PRM}(\lambda).$$

In the upper equation, $T_{TM,PRM}(\lambda)$ corresponds to the wavelength-dependent intensity transmission coefficient of the PRM for TM polarization. The deduced optical feedback ratio in Eq. (2.8) constitutes an upper limit for the optical feedback strength, since the effective optical feedback power, which is coupled back into the waveguide of the laser diode emitter, furthermore depends on the coupling efficiency of the feedback light into the waveguide of the laser diode emitter which is mainly determined by the imaging quality of the external resonator [105]. The emitter sub-beams which are transmitted at the grating are spatially separated by a short focal length lens and then sent to an integrating sphere in order to measure the spectrum of an individual stabilized diode bar emitter by a spectrometer (Ocean Optics HR4000; 100-pm spectral resolution at 960 nm). Figure 2.12a exemplary shows the locking range measurement of an individual emitter of a 954-nm diode bar (bar C) at a diode current of 120 A. The adjusted optical feedback ratio is 10%. As a reference, the free-running diode bar spectrum at 20 A and 200 A are shown. In the center of the locking range, where the stabilized central wavelength corresponds to the central wavelength of the free-running emitter spectrum, the external cavity is adjusted for maximal peak intensity of the stabilized emitter spectrum in order to ensure optimal feedback re-imaging. The sideband suppression amounts to about 20 dB (see Fig. 2.12b). By changing the
2.2. Radiation characteristics

Fig. 2.12: (a) Locking range measurement of an individual emitter of a 954-nm diode bar (bar C). (b) Stabilized spectrum of an individual emitter in the center of the locking range at a diode current of 120 A extracted from the measurement shown in (a). (c) Locking range vs. optical feedback ratio of an individual emitter of a 962-nm diode bar (bar C) at a diode current of 90 A for different locking range definitions. (d) Locking range for a complete wavelength stabilization at 90 A and an optical feedback ratio of 10 % vs. central wavelength of the free-running diode bar spectrum at a diode current of 200 A.

Grating AOI, the central wavelength of the stabilized emitter spectrum is detuned from the center to shorter respectively longer wavelengths. As can be seen from the stabilized emitter spectra presented in Fig. 2.12a, no free-running power fractions appear in the spectrum within a wavelength range of 35 nm. Beyond this spectral region, self-lasing of the diode bar emitter at its free-running spectrum sets in and the peak intensity of the stabilized emitter spectrum declines. The
wavelength range without any appearance of free-running power fractions in the spectrum is defined as the spectral locking range for a complete wavelength stabilization of the diode bar emitter. The locking range sub-linearly increases with increasing feedback ratio. Figure 2.12c shows the locking range of an individual emitter of a 962-nm diode bar (bar C) as a function of the optical feedback ratio at a diode current of 90 A for different locking range definitions. Besides the discussed locking range definition, an alternative way to specify the spectral locking range is to use a certain drop of the peak intensity of the stabilized emitter spectrum with reference to the intensity maximum of the stabilized emitter peak in the center of the locking range. Assuming a constant spectral linewidth, the peak intensity decline is directly proportional to a power drop. As can be seen from Fig. 2.12c, the power drop within the locking range for a completely stabilized emitter is $\leq 10\%$ for all investigated feedback strengths. Outside the locking range for a completely stabilized emitter, the stabilized power rapidly decreases to half the maximum value within less than 3 nm. Thus, the initial locking range definition for a complete wavelength stabilization of the diode bar emitter provides a reasonable value for the spectral interval over which spectral locking can be achieved without significant power losses. The dependency of the spectral locking range on the operation wavelength of the diode bar is presented in Fig. 2.12d. The graph shows the average value of the measured locking range at 90 A and a feedback ratio of 10% of at least ten diode bars with identical epitaxial chip design as a function of the central wavelength of the free-running diode bar spectrum at a diode current of 200 A. The indicated error bars result from the statistical analysis of the presented data. As can be seen from the data, the spectral locking range only slightly varies for diode bars with different operation wavelengths. A trend to an increased locking range for long-wave diode bars is visible. For all investigated operation wavelengths, the AR coating of the front facet provides a spectral locking range of larger than 30 nm at a feedback ratio of 10%. Consequently, the achieved locking range is large enough to compensate for the current-dependent wavelength shift of the free-running spectrum (see Fig. 2.12a) which amounts to about 15 nm (bar A and bar C) resp. 30 nm (bar B) for the employed BAL diode bars over the whole diode operation current range. In this way, a stable and current-independent wavelength locking is ensured which is a basic requirement for DWBC in external laser cavities.

### 2.2.3. Beam quality

As already mentioned in section 2.1, the diode bar emitters exhibit diffraction-limited ($M^2 = 1$) beam quality in the vertical FA direction which, at an emission wavelength of $\lambda = 960$ nm, corresponds to a BPP of $BPP_{FA,em} = \lambda/\pi \approx$
0.31 mm × mrad. The intensity distribution in the far field exhibits a Gaussian shape (see Fig. 2.13). The far-field width for a power content of 95% corresponds to the full-angle emitter beam divergence $2\theta_{FA,em}$ in FA which amounts to 47° resp. 40° for the BAL diode bars which are deployed in this thesis (see Table 2.1).

![Graph showing far-field intensity distribution](image)

**Fig. 2.13:** Measured FA far-field intensity distribution of a 938-nm diode bar (bar C) at 180-A diode current and Gaussian curve fit.

By use of the FAC, the output beam of the individual diode bars emitters are collimated resulting in a significantly smaller beam divergence $\theta_{FAC,em}$ (see Fig. 2.4). In the ideal case, the diffraction-limited emitter beam quality is preserved and not affected by the FAC. For a completely flat arrangement of the individual emitters on the diode bar, the beam divergence behind the FAC of the total emitter ensemble ($\theta_{FAC}$) equals the beam divergence of the individual gain element ($\theta_{FAC,em}$). In reality, diode bar smile results in a deviation of both quantities. One speaks of diode bar smile if the emitters of a diode bar have vertical offsets of the centroid positions in the optical near field compared to each other. The reasons for diode bar smile are related to mounting- and packaging-induced strain of the diode bar chip [106]. The corresponding smile parameter is defined as the total difference in height between the highest and lowest emitter [107]. The relative vertical position offsets of the emitters result in beam pointing deviations of the emitter sub-beams in FA after the collimation by a FAC which consequently increase the far-field divergence $\theta_{FAC}$ of the beam ensemble along this direction. Figure 2.14a shows a measurement of the far-field intensity distribution in FA behind the FAC of diode bars with different smile values at diode current of 25 A. The investigated bars (bar C) have an uncollimated emitter beam divergence in FA of $2\theta_{FA,em} = 40^\circ$ and each exhibit a 300-µm FAC (see Table 2.1) which gives a far-field divergence of an individual collimated emitter of $2\theta_{FAC,em} = 5.6$ mrad behind the FAC. This
Fig. 2.14: Far-field broadening in FA due to diode bar smile. (a) Measured FA far-field intensity distribution behind the FAC for diode bars (bar C) with different smile at 25-A diode current. (b) Measured far-field divergence $2\theta_{FAC}$ vs. smile of the BAL diode bar at 25-A diode current and linear curve fit. The presented data correspond to a power content of 95%.

value represents the ideal theoretical minimum which can only be reached in case of a diode bar with zero smile. The far-field divergence of the beam ensemble linearly depends on the smile value as can be seen from Fig. 2.14b. The deviations of the measured data compared to the linear curve fit result from the particular shape of smile which is not incorporated by using the unweighted total difference in height for the definition of the smile value. Typical values for the beam divergence behind the FAC of the total emitter array for the deployed low-FF diode bars are $2\theta_{FAC} = 5$ mrad (bar A) resp. $2\theta_{FAC} = 6$ mrad (bar A) for low smile values ($\approx 1 \mu m$). Due to the significantly smaller FAC focal length in case of the high-FF bar B, the beam divergence is typically in the range of $2\theta_{FAC} = 12$ mrad. An influence of the emitter beam transformation by the micro-optical BTS on the collimated far-field divergence in FA is not present.

In the lateral SA dimension, the diode bar emitters exhibit multi-transverse-mode operation which is the reason why the resulting BPP is typically about an order of magnitude larger ($M^2 \approx 10$) compared to the fundamental-mode FA direction. The BPP in the SA dimension depends on operation current for all implementations of lateral emitter confinement (insulating dielectric layer or ion implantation). The SA-BPP increases with increasing diode current due to a effect referred to as far-field blooming, meaning an increase of the far-field divergence in SA which consequently leads to a poorer beam quality [14, 108]. Far-field
2.2. Radiation characteristics

Blooming is related to both thermal and non-thermal contributions. Self-heating of the device due to the series resistance and non-radiative carrier recombination rise the temperature in the active region which leads to an increase of the refractive index. The lateral heat flow away from the active region results in a non-uniform temperature distribution which leads to a lateral refractive index gradient similar to a thermal lens. The thermal lensing effect enhances index-guiding of higher order lateral modes with increasing diode current which exhibit a larger far-field divergence [109]. Besides the described thermally induced lateral index-guiding, a substantial non-thermal contribution to the far-field blooming is caused by an increasing carrier and gain non-uniformity in the QW with rising operation current which results in an excitation of higher order lateral modes [110].

Figure 2.15a exemplary shows the effect of far-field blooming with increasing operation current by use the measured far-field intensity distribution in the lateral SA dimension of a 946-nm BAL diode single-emitter with 100-µm contact opening at different emitter currents. The corresponding measured near-field intensity distributions are shown in Fig. 2.15b. The deployed single-emitter is mounted on Peltier cooler which is operated at a temperature of 25 °C. The laser structure for lateral confinement and the vertical layer structure of the device are comparable to the emitter design of bar C with an insulating dielectric layer as current aperture. The presented far-field intensity profiles in Fig. 2.15a clearly show an increasing width with rising emitter current. The far-field width for a power content of 95% corresponds to the full-angle emitter beam divergence $2\theta_{SA,em}$ in SA. As can be seen from Fig. 2.15c, the emitter beam divergence $2\theta_{SA,em}$ linearly depends on current within the investigated emitter current range. The measured near-field width $2\omega_{SA,em}$ (95% p.c.) shows an increase (10% to 20%) beyond the lateral dimension of the contact stripe which is the result of lateral current spreading [111]. By use of both deduced quantities, the SA-BPP for a power content of 95% is given by $BBP_{SA,em} = \omega_{SA,em}\theta_{SA,em}$ for the respective operation current. The resulting data of the SA-BPP as a function of emitter current are depicted in Fig. 2.15d. The presented data show an almost linear increase of the SA-BPP with increasing diode current. At typical emitter operation currents in the range of 6 A to 8 A, the SA-BPP is $BBP_{SA,em} \leq 3.5 \text{ mm} \times \text{ mrad}$. As a comparison, the measured SA-BPP data of a 954-nm BAL diode single-emitter with ion implantation are shown in Fig. 2.15d. The ion-implanted single-emitter shows an only slightly improved SA-BPP, since lateral current spreading is typically less pronounced in case of ion implantation for lateral emitter confinement. Due to the varying operation conditions in terms of cooling, packaging-induced strain and current injection, the beam quality in SA of an individual diode bar emitter is significantly worse compared to a single-emitter BAL diode device. Figure 2.16a shows the measured far-field divergence $2\theta_{SA,em}$ and near-field width $2\omega_{SA,em}$ in
Fig. 2.15: Measured far-field (a) and near-field (b) intensity distribution in the lateral SA dimension of a 946-nm BAL diode single-emitter with an insulating dielectric layer as current aperture at different emitter currents. (c) Left axis, far-field width \(2\theta_{SA,em}\) in SA vs. emitter current. Right axis, corresponding near-field width \(2\omega_{SA,em}\) in SA vs. emitter current. The presented data correspond to a power content of 95\% and are extracted from the corresponding measured intensity profile which is partially shown in (a) and (b). (d) SA-BPP vs. emitter current of a 946-nm BAL diode single-emitter with an insulating dielectric layer as current aperture and a 954-nm BAL diode single-emitter with ion implantation.

SA as a function of the emitter current of an individual emitter of a 954-nm diode bar (bar C) with an insulating dielectric layer as current aperture. At the typical diode bar operation current of 180\,A, which corresponds to an emitter current of 7.8\,A, the emitter beam divergence amounts to \(2\theta_{SA,em} \approx 8^\circ\) corresponding to the value given in Table 2.1, where also typical values for the SA
emitter beam divergence of the other deployed diode bar types are listed. The deduced SA-BPP as a function of emitter current resulting from the measured near- and far-field widths (see Fig 2.16a) is depicted in Fig. 2.16b. The data show a linear increase of the SA-BPP from 2.8 mm × mrad at 2.2-A emitter current to about 4.6 mm × mrad at the maximal investigated current of 8.7 A. In the typical diode bar operation current range around 180 A (7.8-A emitter current), the SA-BPP is $BBP_{SA,em} > 4 \text{ mm} \times \text{ mrad}$. For the passively cooled diode bars (bar A and B) with ion implantation, the SA beam quality of an individual diode bar emitter is the range of 3.5 mm × mrad for the respective typical operation current listed in Table 2.1. The measured values later serve as a rough reference for the achieved SA-BPP of the combined output beam using the approaches for DWBC which are presented in Chapter 3. As shown by the presented measurements in this section, the beam quality of a individual diode bar emitter in both the fundamental-mode FA and the multi-transverse-mode SA beam dimension are in the range which is sufficiently for high-brightness laser applications (see Fig. 1.1). In the following chapter, the technique of spatial brightness scaling by use of DWBC in external laser cavities is introduced which enables coupling of individual low-power emitter sub-beams of a diode bar into a single high-power beam, whereby the high beam quality of the individual diode bar emitter is mostly preserved.

![Fig. 2.16: (a) Left axis, measured far-field divergence $2\theta_{SA,em}$ in SA vs. emitter current of an individual emitter of a 954-nm diode bar (bar C) with an insulating dielectric layer as current aperture. Right axis, corresponding near-field width $2\omega_{SA,em}$ in SA vs. emitter current. The presented data correspond to a power content of 95%. (b) SA-BPP vs. emitter current calculated by use of the data shown in (a).](image-url)
In this chapter, the theoretical background and the functional principle of the DWBC approaches, which have been investigated in this thesis, are explained. First of all, the general functional principle of DWBC of BAL diode bars in external resonators is discussed in section 3.1. On this basis, the wavelength stabilization, beam combination and beam quality preservation in the two different external resonators of the investigated DWBC approaches are explained. In section 3.2, the transmission grating based external cavity is discussed which represents a well-known closed-loop architecture for simultaneous wavelength stabilization and beam combination. In the following section 3.3, a novel open-loop external cavity architecture for DWBC is presented which is based on a TFF as dispersive optical element.

3.1. Introduction and functional principle

Diffraction grating based DWBC architectures work like an inverse spectrometer, as depicted in Fig. 3.1. Instead of splitting and spatially separating the spectral components of a polychromatic input beam by a dispersive optical element like in a spectrometer, sub-beams of different wavelengths are diffracted at the grating into a combined output beam. Due the grating diffraction, the incident sub-beams spatially overlap in the near and far field. For a fixed spectral resolution of the grating, the overall spectral bandwidth of the combined output beam increases with increasing number of resolved wavelength channels, which corresponds to the number of wavelength-combined beams. Thus, the spatial brightness is increased at the cost of an increased spectral bandwidth. DWBC requires a precise control of the wavelength and the AOI of the sub-beams which are incident upon the
grating. In this context, mainly two basic configurations for DWBC are utilized which are closed-loop and open-loop WBC [60]. Closed-loop external cavity architectures enable simultaneous wavelength stabilization and beam combination. The principal setup is similar to the scheme presented in Fig. 3.1. It consists of a horizontal array of laser diode emitters, a Fourier transform lens, a transmission grating and an additional PRM in the optical path of the diffracted beam which serves an output coupling mirror (OC) (not shown in Fig. 3.1). The OC in conjunction with the back facet of each emitter of the horizontal laser diode array forms an optical cavity. In order to get optical feedback from the OC, the emitter sub-beams must be normally incident upon the OC. The transform optic converts the lateral position $x_i$ of each emitter of the array into a unique AOI $\alpha_i$ at the location of the grating. Due to this position-into-angle mapping by the transform lens, the stabilized central wavelength $\lambda_i$ of each individual emitter is self-determined by its lateral position along the array. Transmission grating based external laser cavities for closed-loop DWBC are discussed in detail in section 3.2. In open-loop cavity architectures, spectral stabilization of the laser diode emitters is decoupled from the beam-combining element, as indicated in Fig. 3.1. DWBC takes place in two steps. The laser diode emitters are first spectrally stabilized each at an appropriate and unique wavelength. Subsequent, the individual wavelength-stabilized emitter sub-beams pass the transform optics and are superimposed upon the grating for beam combination. In this case, it has to be ensured that the wavelength-AOI pairing of each emitter sub-beam perfectly fits the spectral angular dispersion of the combiner grating to achieve a combined beam, where all sub-beams completely overlap in the far field. A novel approach for open-loop DWBC is presented in section 3.3.
3.1. Introduction and functional principle

Both discussed DWBC approaches are subjected to a generic constraint concerning the spectral denseness of the coupled wavelength channels resp. number of combinable gain elements [60]. By analogy to the inverse grating spectrometer shown in Fig. 3.1, the number of sub-beams that can be combined within a given spectral bandwidth is limited by the spectral resolution $R_G$ of the grating

$$R_G = \frac{\lambda}{\Delta \lambda_G} = N_G = \frac{2 \omega_G}{\cos(\beta)} \cdot \frac{1}{\Lambda}, \quad (3.1)$$

where $\Delta \lambda_G$ denotes the minimal spectral resolution of the grating at wavelength $\lambda$. $N_G$ corresponds to the number of illuminated grating grooves which is given by the ratio of the projected beam diameter $2 \omega^*_G = 2 \omega_G / \cos(\beta)$ upon the grating, with $\beta$ being the grating AOI, to the groove spacing $\Lambda$ of the grating. Imaging a collimated beam with $N_\lambda$ wavelength channels, which are equally spread over a certain spectral bandwidth, passing the scheme shown in Fig. 3.1 in reverse order. In this case, the wavelength channels can only be completely spatially resolved in the focal plane of the transform lens if the spectral channel spacing is larger than the minimal spectral resolution of the grating. Consequently, $\Delta \lambda_G$ constitutes a lower limit for the spectral channel spacing $\Delta \lambda_{em}$ of adjacent emitter sub-beams of a horizontal laser diode array, given by:

$$\Delta \lambda_{em} \geq \Delta \lambda_G = \frac{\lambda \cdot \Lambda}{2 \omega_G / \cos(\beta)} \cdot \bar{\rho}, \quad (3.2)$$

The number of emitter sub-beams, which can be combined within a given spectral bandwidth $\Delta \lambda$, therefore follows from the relation

$$N_\lambda \leq \frac{\Delta \lambda}{\Delta \lambda_G} \cdot \bar{\rho} = \frac{\lambda}{2 \omega_G} \cdot \rho \cdot \frac{\Delta \lambda}{\lambda} \cdot \frac{1}{\Lambda \cdot \cos(\beta)} \cdot \bar{\rho} =: D_\alpha, \quad (3.3)$$

where the fraction of the last factor of the product corresponds to the angular dispersion $D_\alpha$ of the grating and $\rho < 1$ being the FF which accounts for the spectral gap between adjacent beams [60]. Following Eq. (3.3), the beam diameter upon the grating must be

$$2 \omega_G \geq \frac{N_\lambda}{\rho \cdot D_\alpha} \cdot \frac{\lambda}{\Delta \lambda} \cdot \bar{\rho} \cdot \frac{1}{\Lambda \cdot \cos(\beta)} \cdot \bar{\rho}, \quad (3.4)$$

in order to combine $N_\lambda$ sub-beams. Figure 3.2a shows lines of constant $N_\lambda$ in a plot of the minimal beam diameter $2 \omega_G$ at the location of the grating as a function of the bandwidth ratio $\Delta \lambda / \lambda$ resulting from Eq. (3.4). The graph shows that 100
Fig. 3.2: (a) Beam diameter $2\omega_G$ at the location of the grating vs. bandwidth ratio $\Delta \lambda / \lambda$ for different values of a constant number $N_\lambda$ of sub-beams that can be combined. For the grating dispersion a value of $D_\alpha = 2.5 \text{ mrad/nm}$. A typical FF of $q = 0.25$ for BAL diode bars is used. For a operation wavelength at $\lambda = 960 \text{ nm}$, the gray shaded area indicates the typical bandwidth ratio (5%) for GaAs based BAL diodes of different wavelength-shifted epitaxial layer designs. (b) Left axis, spectral channel spacing $\Delta \lambda_{em}$ vs. transform focal length $f_{TL}$ for typical diode bar and grating parameters ($p_{em} = 400 \mu\text{m}; 2\theta_{FAC,em} = 6 \text{ mrad}; 2\theta_{SA,em} = 8^\circ; D_\alpha = 2.5 \text{ mrad/nm}$). Right axis, calculated projected beam diameter $2\omega_G^*$ upon the grating for DWBC along the FA and SA beam dimension. The red and green curve indicate the minimal spectral resolution $\Delta \lambda_G$ of the grating which follows from the corresponding beam diameter in FA ($2\omega_{G,FA}$) and SA ($2\omega_{G,SA}$) at the location of the grating.

to 1000 sub-beams and even more can be combined by allowing for sufficiently large values of both the beam diameter $2\omega_G$ and the spectral bandwidth $\Delta \lambda$. Since the beam diameter upon the grating is a linear function of the transform focal length $f_{TL}$, scaling of $N_\lambda$ within a certain spectral bandwidth can only be achieved by an increase of the transform focal length by the same factor. Due to the telecentrical optical imaging by the transform lens, raising the spectral dense-ness simultaneously results in an increased length of the external laser cavity. Applying the general considerations to the case of high-power BAL diode bars as beam source for DWBC, which have been discussed in Chapter 2, the stabilized spectral interval is limited to about 50 nm for GaAs based laser diodes due to the availability of different wavelength-shifted epitaxial layer designs. Furthermore, concerning potential high-power laser applications, the bandwidth has to be kept in the same range in order to allow for good imaging quality without chromatic aberrations in laser processing heads with few optical elements. The beam di-
ameter at the location of the grating is determined by the far-field divergence of the emitter sub-beams in the beam-combining axis and the focal length of the transform lens. On the other hand, for a fixed dispersion of the grating, the focal length of the transform lens also determines the spectral channel spacing of adjacent emitters $\Delta \lambda_{em} = \frac{p_{em}}{f_{TL} D_{a}}$ which are spatially separated by the emitter pitch $p_{em}$ along the lateral dimension of the array. For successful beam combination, the spectral channel spacing must exceed the minimal value which is imposed by the spectral resolution of the grating [see Eq. (3.2)]. Figure 3.2b shows the calculated spectral channel spacing as a function of the transform focal length for typical diode bar and grating parameters ($p_{em} = 400 \mu m; 2 \theta_{FAC,em} = 6 \text{ mrad}; 2 \theta_{SA,em} = 8^\circ; D_{a} = 2.5 \text{ mrad/nm}$). As one can see from the graph, beam combining in both beam dimensions is possible, since the spectral channel spacing is larger than the minimal spectral resolution of the grating for all presented focal lengths. For practical reasons, the beam size should be kept within acceptable levels in order to prevent from spherical aberrations in the transform optics and to keep the size of the grating small. The transform focal length and thus the spectral denseness of the coupled emitter sub-beams are restricted by those technical constraints.

The spatial brightness of the resulting combined output beam emerging from the DWBC architecture shown in Fig. 3.1 depends on the power of the spectrally stabilized laser diode emitters and the beam quality of the combined output beam, which is in the ideal given by the beam quality of an individual emitter sub-beam. Introducing some kind of cavity losses (factor $\eta_{WBC}$) and beam quality deterioration induced by the external cavity (factor $\Delta$), the resulting spatial brightness $B_{CB}$ of the combined beam can be described as

$$B_{CB} = \frac{N_{\lambda} \cdot P_{em} \cdot \eta_{WBC}}{\pi^2 \cdot BPP_{FA,em} \cdot BPP_{SA,em} \cdot \Delta} \quad (3.5)$$

according to Eq. (1.1). In the upper equation $P_{em}$ is the power of an individual wavelength-stabilized BAL diode emitter. $BPP_{FA,em}$ and $BPP_{SA,em}$ represent the BPP in the FA and SA beam direction of an individual emitter, respectively. Examples for typical cavity loss mechanisms, incorporated by the factor $\eta_{WBC}$, are losses at the diffraction grating due the limited diffraction efficiency and losses due to absorption of optical components inside the resonator. For practical reasons, the WBC efficiency $\eta_{WBC}$ is in the following defined by the ratio of the power of the combined output beam to the free-running power of the diode bar after lensing of the micro-optics. Several beam quality degrading mechanisms, which are captured by the factor $\Delta$, result in a BPP in the beam-combining axis of the combined output beam which is larger than the beam quality of an individual emitter.
sub-beam. For example, both closed-and open-loop transmission grating based DWBC architectures suffer from beam quality deterioration due to the residual spectral emitter linewidth of the stabilized diode bar emitters and diode bar smile. In general, diffraction grating based DWBC architectures can be applied either to the FA or SA beam direction of the BAL diode bar, as suggested by the calculations presented in Fig. 3.2b. However, FA-DWBC by use of a micro-optical BTS [112, 113], which has been discussed in section 2.1, has major advantages compared to beam combining in the multi-transverse-mode SA direction. First of all, due to the diffraction-limited beam quality of the diode emitters in FA, the collimated beam divergence is comparatively small with values between 5 mrad to 12 mrad depending on the FAC focal length. Consequently, Fourier transform lenses with large focal lengths can be used to achieve a high spectral denseness of the stabilized emitters without the leakage of spherical aberrations which deteriorate beam quality. At the same time, the resulting beam diameter of the overlapping emitter sub-beams at the location of the grating is small (see Fig. 3.2b), even at large transform focal lengths, which keeps the resulting size of the grating small. For identical transform focal lengths, the beam diameter at the location of the grating in SA is approximately an order of magnitude larger compared to the FA beam dimension which results from the intrinsic lower beam quality. Furthermore, the usage of a BTS reduces diode bar smile-induced imaging errors and losses in the optical feedback in closed-loop DWBC architectures, since the external laser cavity is self-compensating with regard to beam pointing errors in the beam-combining axis [114]. However, as it will be presented in section 3.2.3, the associated beam quality degradation due to diode bar smile can not be impeded or improved using a BTS. In case of SA-DWBC, there is no space left for external cavity induced beam quality deterioration, since the BPP of an individual BAL diode emitter in SA is typically above $3 \, \text{mm} \times \text{mrad}$, as discussed in section 2.2.3. Beam quality deterioration in the SA beam dimension would result in an increased astigmatism of the output beam which will prevent from efficient fiber coupling into beam delivery fibers for high-brightness laser applications typically requiring a BPP of less than $5 \, \text{mm} \times \text{mrad}$. This is the reason why SA-DWBC is generically unfavorable for realizing high-brightness direct diode lasers. Not yet experimentally verified is the potentially detrimental impact of SA beam combining on the lifetime of the diode bar under external optical feedback [71, 72]. In the lateral multi-transverse-mode SA direction, the diode emitters tend to filamentation in the optical near field which can be enforced by the position-into-wavelength transformation inside the external resonator [115]. Near-field filamentation results in large spatio-temporal peak intensities on the front facet [116, 117] which can cause catastrophic optical mirror damage (COMD) and instabilities in power and beam quality of the combined output beam.
Due to the mentioned reason, the focus in this thesis is exclusively on FA-DWBC. In order to realize a 1-kW high-brightness direct diode laser module with key beam parameters presented in Fig. 1.3, \(N_\lambda \geq 200\) sub-beams have to be combined within the available spectral interval of \(\Delta \lambda \leq 50\) nm assuming a typical emitter power of \(P_{em} = 5\) W. The resulting maximal limit for the spectral channel spacing of \(\Delta \lambda_{em} \leq 250\) pm is achieved for transform focal lengths of \(f_{TL} \geq 900\) mm for the low-FF bars A and C (see Fig. 3.2b). In order to realize a comparable spectral denseness in case of individual-bar experiments, this value serves as design criterion for the transform optics in both investigated DWBC approaches which are discussed in the following two sections.

3.2. Transmission grating based cavity

3.2.1. Wavelength stabilization and beam combination

The schematic setup of the investigated external laser cavity is shown in Fig. 3.3. The emitter sub-beams emerging from the BAL diode bar are collimated in the vertical FA direction (y-axis) by use of a FAC. In order to perform beam combining in the fundamental-mode FA direction, commercial micro-optical beam rotators are used, as discussed in section 2.1. Consequently, beam combining in FA can be done along the horizontal dimension (x-axis) of the cavity architecture. In the beam-combining direction, the far fields of the collimated and coaxially propagating emitter sub-beams are imaged onto a -1st order transmission grating by a cylindrical Fourier transform lens with a focal length of \(f_{TL} = 900\) mm. Consequently, each sub-beam, which is incident on the grating, has an individual AOI with respect to the surface normal of the grating. The transform lens is placed in a telecentrical configuration with respect to the front facet of the diode bar and the grating. A zero-order HWP is used to rotate the TE-polarized laser output of the diode bar emitters into TE polarization with respect to the plane of incidence at the grating. The grating is placed in Littrow configuration with respect to the central ray propagating along the optical axis of the external resonator, which means that the AOI of the central emitter upon the grating equals the diffraction angle into the -1st order. The grating in conjunction with an OC with a reflectivity of about 5% complete the external resonator and force the individual emitters to adjust their emission wavelengths in such a way that they get optical feedback from the OC. The respective emitter sub-beam is diffracted at the grating in the direction of the newly defined optical axis which emerges along the diffraction angle of the central emitter. The wavelength stabilization can be
explained by use of the grating equation for a -1st order transmission grating with groove spacing $\Lambda$

$$\Lambda \cdot [\sin (\alpha) + \sin (\beta)] = \lambda , \quad (3.6)$$

where $\alpha$ is the AOI upon the grating and $\beta$ denotes the diffraction angle into the -1st order. Applying Eq. (3.6) to the cavity architecture of Fig. 3.3, each emitter of the diode bar is stabilized at an unique central wavelength $\lambda_i$ which is given by:

$$\lambda_i = \Lambda \cdot \left\{ \sin (\alpha_i) + \sin [\beta_L(\lambda_c)] \right\} . \quad (3.7)$$

In the upper equation, $\alpha_i$ is the AOI of the $i^{th}$ emitter ($i = 1, \ldots, n_{em}$) upon the grating and

$$\beta_L(\lambda_c) = \arcsin \left( \frac{\lambda_c}{2\Lambda} \right) . \quad (3.8)$$
3.2. Transmission grating based cavity

describes the Littrow angle of the central emitter of the diode bar which is stabilized at wavelength $\lambda_c$. The Littrow angle follows from Eq. (3.6) by applying the Littrow condition ($\alpha = \beta$). Using a small-angle approximation, the AOI of the emitter sub-beam can be expressed as

$$\alpha_i = \beta_L(\lambda_c) - \frac{x_i}{f_{TL}},$$

(3.9)

where $x_i$ is the lateral emitter position along the beam-combining axis ($x$-axis). Simultaneously, as a consequence of the wavelength stabilization, a combined output beam is realized behind the OC with all emitter sub-beams overlaying in the near and far field. The corresponding stabilized spectral interval $\Delta \lambda$ of the diode bar is given by

$$\Delta \lambda = (n_{em} - 1) \cdot D^{-1}_\alpha [\alpha_i = \beta_L(\lambda_c)] \cdot \frac{p_{em}}{f_{TL}},$$

(3.10)

where $\Delta \lambda_{em}$ is the spectral channel spacing of the $n_{em}$ stabilized diode bar emitters with lateral pitch $p_{em}$ and

$$D_\alpha := \frac{d\alpha}{d\lambda}|_{\lambda_i} = \frac{1}{\Lambda \cdot \cos (\alpha_i)}$$

(3.11)

being the angular dispersion of the grating. Alternative to the definition in Eq. (3.10), the stabilized spectral interval can more generally be expressed in terms of the lateral spatial separation $\Delta x$ between the outer emitters of an arbitrary horizontally arranged diode emitter array:

$$\Delta \lambda = D^{-1}_\alpha [\alpha_i = \beta_L(\lambda_c)] \cdot \frac{\Delta x}{f_{TL}} \cdot \frac{x_i}{f_{TL}} =: \Delta \lambda_{em}$$

(3.12)

In the upper equation, $\Delta \alpha$ defines span of the angular spectrum which is incident on the grating. The telescope in the optical feedback path behind the grating consists of two cylindrical lenses with focal lengths $f_{X1} = 300$ mm and $f_{X2} = 50$ mm. The telescope complies two tasks. First, it is used for imaging the optical feedback back into the originating emitters. Second, in conjunction with the OC, it acts as a space-frequency filter to suppress spectral emitter cross-talk in the optical feedback between adjacent emitters. Due to the lateral beam compression, cross-talk beams, exhibiting larger diffraction angles, are deflected by the telescope in such a way that they can not hit the OC under normal incidence and are consequently not fed back by the external resonator. The specific configuration of
the telescope lenses and the OC for cross-talk suppression is explained in detail in section 3.2.3.3. In order to collimate the rotated emitter sub-beams in SA, a cylindrical slow-axis collimator (SAC) with a focal length of $f_{SAC} = 40\, \text{mm}$ is used. Subsequent to the SAC, two additional cylindrical lenses (focal lengths $f_{SA1}$ and $f_{SA2}$) are used to image the beam waist of the emitter sub-beams in SA onto the OC for feedback re-imaging.

The $-1^{\text{st}}$ order transmission grating is the key component inside the external resonator. Specifically, the grating is a dielectric rectangular surface relief transmission grating [118, 119] with $\Lambda^{-1} = 1600\, \text{lines/mm}$. The grating structure is fabricated into a fused silica substrate. The structure parameters are optimized for a maximal diffraction efficiency into the $-1^{\text{st}}$ order for TE polarization and a design wavelength of 955 nm. The operation of the grating in Littrow configuration ensures a maximal diffraction efficiency for the incident laser beam at the corresponding wavelength. The theoretical diffraction efficiency of the grating in Littrow configuration is $\eta_G = 98.5\%$ for TE-polarized light at the design wavelength of 955 nm, which corresponds to a Littrow angle of about 50° according to Eq. (3.8). The diffraction efficiency $\eta_G$ is defined as the ratio of the optical power $P_{-1}$ which is diffracted into the $-1^{\text{st}}$ order to the incident laser power $P_{\text{in}}$.

Figure 3.4 shows the calculated diffraction efficiency of the grating as a function of the AOI $\alpha$ upon the grating and wavelength of the incident laser beam. The presented data are based on numerical calculations by rigorous Fourier modal method.

![Figure 3.4](image)

**Fig. 3.4:** Numerically calculated diffraction efficiency $\eta_G$ of the used $-1^{\text{st}}$ order transmission grating vs. grating AOI $\alpha$ and wavelength of the incident laser beam based on rigorous Fourier modal method (data provided by [120]).
method which have been performed by [120]. The diffraction efficiency of the
transmission grating mainly affects the resulting WBC efficiency of the external
resonator. Generally, there exist three loss channels which are shown in Fig. 3.5.
These are the portions of the optical power of the incident beam $P_{in}$ which are
reflected ($P_R$) and transmitted ($P_T$) at the grating and furthermore the optical
power $P_{-1,R}$ which is diffracted into the -1st reflected order. The loss channel of
the beam which is reflected at the grating is related to the Fresnel reflection at the
interface between air and the grating substrate. The transmission losses are due
to the restricted diffraction efficiency of the grating into the -1st order and fur-
thermore, in external cavity operation, remaining TM-polarized power fractions
of the incident emitter sub-beams after the rotation of the initial polarization by
the HWP. One can see from the left part of Fig. 3.5 that for a grating which is

\[
\begin{align*}
\text{Littrow: } \alpha &= \beta = \beta_L(\lambda_c) \\
\text{off-Littrow: } \alpha &\neq \beta
\end{align*}
\]

![Fig. 3.5: Loss channels of a -1st order transmission grating. Left, grating alignment in Littrow configuration $[\alpha = \beta = \beta_L(\lambda_c)]$. Right, grating is rotated off the initial Littrow condition ($\alpha \neq \beta$).](image)

placed in Littrow configuration $[\alpha = \beta = \beta_L(\lambda_c)]$, the beam of the -1st reflected
order propagates along the direction of the input beam. Consequently, depending
on the actual value of $P_{-1,R}$, the beam causes a unintended locking of the diode
bar emitters in the external cavity, which negatively affects the wavelength sta-
bilization resulting from the optical feedback which is provided by the OC. In
order to prevent this effect, the grating in the external cavity is operated slightly
off the Littrow condition ($\alpha - \beta \approx 0.3^\circ$) with respect to the optical axis of the
resonator, as shown in the right part of Fig. 3.5. In this case, the beam which is
reflected into the -1st diffraction order can not be imaged back into the locations
of the originating emitters. Experimentally, the Littrow configuration of the grat-
ing is indicated by a turning point of the beam pointing angle $\gamma$ of the diffracted beam with reference to incident beam, when the grating AOI is changed during the alignment of the external cavity. Assuming that an arbitrary laser beam with wavelength $\lambda_c$ is incident on the grating, the diffraction angle $\beta$ into the -1\textsuperscript{st} order as a function of the grating AOI can be expressed as

\[ \beta(\alpha) = \arcsin \left( \frac{\lambda_c}{\Lambda} - \sin (\alpha) \right) \]  

(3.13)

using the general grating equation of Eq. (3.6). Consequently, the beam pointing angle $\gamma(\alpha)$ in Fig. 3.5 is given by:

\[ \gamma(\alpha) = 180^\circ - \alpha - \beta(\alpha) \]  

(3.14)

The resulting curve of the beam pointing angle $\gamma(\alpha)$ for a wavelength of $\lambda_c = 955$ nm is shown in Fig. 3.6a. The plot shows that the maximal pointing angle is achieved in Littrow configuration [$\alpha = \beta_L(\lambda_c)$] for the corresponding wavelength of the incident beam. For a grating AOI smaller or larger than the Littrow angle, the beam pointing angle decreases which explains the experimentally observable turning point. During wavelength stabilization in the external cavity, the beam pointing angle stays constant when the grating AOI is varied, since exclusively the alignment and position of the OC determines the diffraction angle into the -1\textsuperscript{st} order. A change of the AOI of the emitter sub-beams upon the grating results in a variation of the stabilized wavelength governed by Eq. (3.7). This fact shows the self-compensating character of the wavelength stabilization inside the external cavity, since any change of the AOI of the emitter sub-beams is compensated by a change of the stabilized wavelength and hence does not affect the pointing angle of the combined output beam. Furthermore, the self-compensating character of the external cavity in terms of a variation of the AOI of the emitter sub-beams in the beam-combining axis upon the grating is the reason why imaging errors and losses in the optical feedback due to diode bar smile or optomechanical misalignments are significantly reduced in case of FA-DWBC by use of a BTS. However, wavelength tuning by a variation of the grating AOI can only be done within the locking range around the free-running central wavelength of the diode bar emitters without significant power losses, as discussed in section 2.2.2. The accompanied spectral shift again shows a turning point in the stabilized wavelength, if the grating AOI $\alpha$ approaches the Littrow angle $\beta_L(\lambda_c)$, as can be seen in Fig. 3.6b. The plot shows the stabilized wavelength of the central emitter (solid line) as a function of the relative angle (off-Littrow angle) of the grating AOI with reference to the Littrow angle $\beta_L(\lambda_c = 955$ nm). In Littrow configura-
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Fig. 3.6: (a) Beam pointing angle $\gamma$ vs. grating AOI $\alpha$ for a wavelength of $\lambda_c = 955\,\text{nm}$. (b) Left axis, stabilized wavelength of the central emitter (solid line) and the outer emitters (dotted and dashed line) of a horizontal diode emitter array ($\Delta\alpha = 111.5\,\text{mrad}$) vs. relative angle (off-Littrow angle) of the grating AOI with reference to the Littrow angle $\beta_L(\lambda_c = 955\,\text{nm})$. Right axis, corresponding stabilized spectral interval $\Delta\lambda$ vs. off-Littrow angle. The turning point of the beam pointing angle and the stabilized central wavelength are achieved for the Littrow angle $[\alpha = \beta_L(\lambda_c)]$, respectively.

...tion, the stabilized wavelength reaches a maximum and decreases if the grating AOI is detuned. Furthermore, the plot shows the stabilized wavelengths of the outer emitters (dotted and dashed line) of a horizontal diode emitter array with an angular span of $\Delta\alpha = 111.5\,\text{mrad}$, which corresponds to the span of the angular spectrum of the emitter sub-beams of the multiple-bar laser diode modules which will be presented in section 4.1. Besides the spectral turning point, the plot shows another effect which concerns the stabilized spectral interval of the horizontal diode emitter array. As one can see from Fig. 3.6b, the spectral interval $\Delta\lambda$, which is defined in Eq. (3.12), significantly changes when the grating AOI is detuned. With increasing grating AOI, the spectral interval is compressed which is, according to Eq. (3.11), a direct consequence of the increasing angular dispersion of the grating. However, a lower diffraction efficiency is expected if the grating is operated off the Littrow configuration. In order to investigate the diffraction efficiency of the transmission grating, Fig. 3.7a shows the experimentally deduced diffraction efficiency of the transmission grating in Littrow configuration for a wavelength of $\lambda_c = 955\,\text{nm}$. Furthermore, as a comparison, the theoretically expected values from the simulation, which has been presented in Fig. 3.4, are shown.
Fig. 3.7: Experimentally deduced diffraction efficiency $\eta_G$ of the used transmission grating in Littrow configuration for a wavelength of $\lambda_c = 955$ nm vs. (a) wavelength of the incident laser beam and (b) off-Littrow angle compared to the theoretically calculated values, which are extracted from the simulation shown in Fig. 3.4.

For the measurement, the collimated output beam of a wavelength-tunable fiber-coupled single-mode diode laser (Sacher Lasertechnik LION) is used. The laser provides a wavelength tunability from 920 nm to 1000 nm. The output power at a wavelength of 960 nm is about 30 mW. Initially, the laser is operated at a wavelength of 955 nm. The AOI of the laser beam upon the grating corresponds to the Littrow angle of the grating \[ \alpha = \beta_L(\lambda_c = 955 \text{ nm}) \]. The beam hits the grating in a central region and has a diameter of about 5 mm. From the measured incident laser power and the measured optical power which is diffracted into the -1st order, the diffraction efficiency is deduced. Subsequent to the initial configuration, the laser wavelength is detuned. Simultaneously, the AOI of the incident laser beam is changed in such a way that the diffracted beam exhibits the identical -1st order diffraction angle compared to the initial wavelength. The rotation angle of the grating remains unchanged. In this way, the measurement configuration exactly corresponds to the operation of the transmission grating during wavelength stabilization inside the external cavity. The measured data are in good agreement with the theoretical predictions in the spectral range from 940 nm to 990 nm. The diffraction efficiency is larger than 95% in the spectral interval of 930 nm to 980 nm. A maximal diffraction of 98.5% is achieved in Littrow configuration, as expected from theory. The impact of the grating detuning from the initial Littrow configuration \[ \alpha = \beta_L(\lambda_c = 955 \text{ nm}) \] is shown in Fig. 3.7b. The data of both the theoretical simulation and the experiment show that the diffraction
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Efficiency symmetrically decreases with increasing off-Littrow angle. The decline is at maximum about 2.5% within the investigated angle interval between $-3^\circ$ to $2^\circ$. As a consequence, the discussed detuning of the grating of only $0.3^\circ$, in order to suppress the unintended locking of the diode bar emitters by the $-1^{st}$ reflected diffraction order, is uncritical in terms of the power losses at the grating inside the external cavity.

Besides the output coupling via the OC, a second output coupling method has been used in this thesis, which is the polarization-dependent output coupling scheme. The schematic setup of the polarization-dependent output coupling scheme in the feedback branch of the external cavity and the corresponding states of polarization are shown in Fig. 3.8. The functional principle is similar to the method of output coupling in the external cavity which was used for the measurement of the spectral locking range of individual diode bar emitters (see Fig. 2.11) presented in section 2.2.2. As depicted in Fig. 3.8, the OC in the cavity architecture of Fig. 3.3 is replaced by an arrangement which consists of a thin-film polarizer (TFP), an achromatic QWP and a highly reflective mirror (HR). The emitter sub-beam which is diffracted by the grating is mainly TE-polarized with reference to the input plane at the TFP. The TFP is operated at an AOI of $70^\circ$ for which a reflectivity of larger than 99% is achieved for TE-polarized light in the wavelength range from 900 nm to 1000 nm. Consequently, the main part of the optical power $P_{in}$ of the input beam is reflected at the TFP towards the achromatic QWP. After the reflection by the HR, the beam passes the QWP a second time. Depending on the rotation angle of the QWP, the initially TE-polarized beam is rotated into a polarization state with TE- and TM-polarized power fractions. The TE-polarized power fraction again is reflected at the TFP providing the optical feedback power $P_{FB}$ which is imaged back into the originating emitter. The

\[ P_{FB} \]

Fig. 3.8: Schematic setup and states of polarization of the polarization-dependent output coupling scheme.
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TM-polarized power fraction of the polarization-rotated beam is coupled out of the cavity at the location of the TFP, which has a transmission coefficient for TM polarization of larger than 98% in the spectral region from 930 nm to 1000 nm. Hence, the polarization-dependent output coupling unit provides variable optical feedback which can be adjusted by the rotation angle of the QWP. For the wavelength stabilization in the external cavity it is important in terms of output power, e-o conversion efficiency and lifetime of the diode bar emitters that the output coupling unit provides wavelength-independent optical feedback within the range of the stabilized spectral bandwidth. Assuming, that the layer design of the TFP exhibits a wavelength-independent course of the reflectivity for both polarization states within the relevant spectral bandwidth of the stabilized diode bar emitters, the spectral response of the polarization-dependent output coupling scheme is mainly determined by spectral retardance of the QWP. An achromatic performance of the QWP is crucial to achieve a wavelength-independent feedback ratio using the polarization-dependent output coupling scheme. Specifically, the achromatic design of the used QWP pairs an air-spaced positive uniaxial birefringent quartz and magnesium fluoride (MgF$_2$) plate. The design represents a common way to realize achromatic waveplates for input beams with normal incidence [121, 122]. Besides the correct thickness of both plates, the orientation of the birefringent optic crystal axis compared to each other is a critical parameter which influences the spectral retardance of the optical component. A spectrally flat course of the wavelength dependent retardance is only achieved, if the orientation of the ordinary optic axis of the quartz plate corresponds to the extra ordinary optic axis of the MgF$_2$ plate and vice versa.

3.2.2. Characteristics of the combined output beam

In the following, the stabilized spectrum, the output power characteristics and the measured BPP of the combined output beam for the BAL diode bars of Table 2.1 are investigated. The presented results are achieved using the cavity architecture of Fig. 3.3. The output coupling is performed by use of an OC with a reflectivity of about 5%. After the external cavity, the combined output beam is sent to a variety of diagnostics including a PM, an integrating sphere whose output is fiber-coupled to a high-resolution spectrometer (HighFinesse HDSA; 40-pm spectral resolution at $\lambda = 960$ nm) and a camera based automatic laser beam profiler (Ophir Photonics; $M^2$-200s) for beam quality measurements.

By way of example, the spectrum of the combined cavity output of bar A at a diode current of 100 A is shown in Fig. 3.9. The 19 emitters of the diode bar are stabilized within a spectral bandwidth of $\Delta \lambda = 3.8$ nm at a central wavelength
3.2. Transmission grating based cavity

of $\lambda_c = 958$ nm. This value is in good agreement with the theoretical prediction of Eq. (3.10). For $n_{em} = 19$, $p_{em} = 500 \mu m$, $f_{TL} = 900$ nm and the corresponding angular dispersion of the transmission grating ($D_\alpha = 2.49$ mrad/nm at $\lambda_c = 958$ nm) the theoretical value is 4.0 nm. A possible reason for the small discrepancy of 7% is a higher angular dispersion of the grating if the AOI of the central emitter upon the grating differs from the Littrow angle $\beta_L(\lambda_c)$, as discussed in the previous section. The spectral channel spacing of adjacent emitters is $\Delta \lambda_{em} = 209$ pm. The spectrum shows a high modulation depth and the spectral lines of the stabilized emitters are completely resolved which proves that no spectral emitter cross-talk is present inside the external resonator. The residual spectral linewidth of the stabilized emitters is $\delta \lambda = 105$ pm ($4\sigma$). The stabilized spectra of the other investigated bars show a similar course and comparable parameters, with the exception of the spectral channel spacing and the central wavelength of the spectrum of the high-FF bar which is stabilized around 1000 nm.

The measured output power and the related e-o conversion efficiencies as a function of diode current are depicted in Fig. 3.10a. An output power of 110 W at a diode current of 140 A is achieved using the passively cooled low-FF bar (bar A). The corresponding e-o conversion efficiency is larger than 50%. The same output power is achieved for the high-FF bar (bar B) at 200-A diode current. The significantly lower e-o conversion efficiency of about 40% is due to higher power losses at the transmission grating. For wavelengths around 1000 nm with a corresponding Littrow-angle of about 53°, the theoretical diffraction efficiency into the -1st order for TE-polarized light is reduced to approximately 90%
The actively cooled bar (bar C) provides a higher combined output power of approximately 150 W at 200 A. The e-o conversion efficiency of 48 % is slightly lower compared to the value of the passively cooled bar (bar A) at 120 A, due to a principally lower free-running e-o conversion efficiency of bar C at an operation current of 200 A (see Fig. 2.6b). In order to investigate the power losses inside the external resonator in more detail, Fig. 3.10b shows the WBC efficiency with respect to the free-running optical output power for bar A. Furthermore, the corresponding measured relative power loss of the three loss channels at the transmission grating (see Fig. 3.5) with respect to the free-running optical output power are shown, which represent the main loss channels which are experimentally accessible during ongoing diode bar operation in the external cavity. The WBC efficiency is about 90 % and shows a current-independent course. The current-independent course of the WBC efficiency implies that the emission characteristics of the diode bar is mostly determined by the external resonator. Additionally, this observation shows that the spectral locking range is large enough to realize a sufficient spectral overlap of the wavelength-stabilized diode bar emitters with the modal gain spectrum within the investigated diode current range. In this way, a stable locking performance of the laser diode bar is achieved without a decrease in WBC efficiency with diode current variation. In case of a stabilization of the diode bar emitters outside the locking range at a specific operation current, the diode bar emitters partially begin to emit at their free-running spectrum, as

![Graphs showing WBC efficiency and power losses](image-url)
discussed in section 2.2.2. The free-running power fractions are not diffracted into the combined output beam, governed by Eq. (3.7), and consequently cause a decrease of the combined output power. The measured overall relative power loss at the grating is about 4%. The losses are slightly higher than the losses of 2% predicted by the diffraction efficiency of the grating (see Fig. 3.7), since the incident emitter sub-beams are not completely TE-polarized. Furthermore, the optical feedback, which is imaged back into the originating emitters, influences the powers which are measured in the corresponding loss channels at the grating in ongoing operation. In a good approximation, the grating losses stay constant with diode current variation. The lowest relative power loss of 0.5% is attributed to the power which is reflected at the grating. The relative power loss due to the transmission of depolarized power fractions is about 1%. This loss channel mainly depends on the degree of TE polarization of the incident emitter sub-beams, which is about 98% for bar A (see section 2.2.1), and the wavelength-dependent retardance of the HWP. The largest relative power loss of about 2% is caused by the power fraction which is reflected into the -1st diffraction order. The power fraction is in the same order of magnitude as the feedback provided by the OC. Consequently, an unintended locking of the diode bars is very likely to occur if the grating is operated in Littrow configuration with respect to the optical axis of the external cavity. This results proves the importance of operating the grating slightly off the Littrow condition. The remaining relative power loss of about 6% is caused by output coupling losses at the OC, losses at other the resonator optics and furthermore by the alignment and configuration of the cross-talk filtering telescope. The measured relative power loss of the resonator optics which are located in front of the grating (lenses and HWP) is about 3% in free-running diode bar operation. The impact of the cross-talk suppression optics are, depending on the alignment and configuration, smaller than 5% (see section 3.2.3.3).

Figure 3.11 shows the measured FA- and SA-BPP of the combined output beam of the cavity as a function of diode current. The BPP values correspond to a power content of 95%. The BPP in the beam-combining FA is about $0.45 \text{ mm} \times \text{ mrad}$ ($M^2 \approx 1.5$) at low currents. Depending on the diode current, the BPP increases and reaches a value of $0.85 \text{ to } 1.05 \text{ mm} \times \text{ mrad}$ ($M^2 \approx 3$) at the maximum operation current of the corresponding diode bar. The BPP in SA shows a typical linear dependency on diode current. At low currents, the BPP is approximately $1.5 \text{ mm} \times \text{ mrad}$. At the maximum operation current of the corresponding diode bar, the SA-BPP of the combined beam is in the range of $4 \text{ to } 6 \text{ mm} \times \text{ mrad}$. Due to the higher FF of bar B, the emitter current is a factor of about 2 lower compared to the low-FF bars A and C which is the reason why a significantly
lower SA-BPP is achieved at a given diode operation current. Furthermore, no significant impact of the wavelength stabilization in the external cavity on the SA-BPP of the emitter sub-beam is observed in the experiments. If one compares the SA-BPP of the combined output beam for bar C with the measured free-running SA-BPP of an individual emitter, presented in Fig. 2.16b, both quantities are in the same range of 4.5 to 5 mm × mrad at diode current of 180 A resp. emitter current of about 8 A. In a good approximation, the SA-BPP of the combined output beam corresponds to the SA-BPP of an individual stabilized diode bar emitter.

### 3.2.3. Beam quality deterioration

The presented results in Fig. 3.11a show that the output beam quality in the beam-combining FA is significantly larger compared to the diffraction-limited ($M^2 = 1$) value of an individual unstabilized emitter ($BPP_{FA,em} ≈ 0.31 \text{ mm} \times \text{ mrad}$ at $\lambda = 960 \text{ nm}$) and furthermore shows a dependency on diode operation current. These observations can be related to three main mechanisms which deteriorate beam quality. These are the residual spectral linewidth of the stabilized emitters,
diode bar smile and spectral emitter cross-talk. Consequently, the resulting BPP in the beam-combining FA can be described as:

\[
BPP_{FA} = \omega_{G,FA} \cdot \theta_{G,FA} = \left( \Delta_{\text{linewidth}} \cdot \Delta_{\text{smile}} \cdot \Delta_X \right) \cdot BPP_{FA,em} \cdot \Delta.
\]

(3.15)

The factor \(\Delta\) in Eq. (3.15) captures the contribution of the three mechanisms to the deterioration of the beam quality \(BPP_{FA,em}\) of the free-running emitter. The effects are multiplicative, since each mechanism affects only one factor of \(BPP_{FA}\) - either the beam waist radius \(\omega_{G,FA}\) upon the grating or the far-field divergence \(\theta_{G,FA}\) behind the grating. In the following, these mechanisms are investigated in detail.

### 3.2.3.1. Residual spectral emitter linewidth

The residual spectral linewidth of the stabilized emitters is determined by the interaction and phase relation of the internal mode characteristics of the laser diode emitter and the mode spectrum which is imprinted by the external laser cavity [123, 124]. Depending on the optical feedback strength and the external cavity length, the effects of linewidth narrowing or broadening are reported for single-mode emitters [125, 126]. To the best of knowledge, analogous detailed investigations for BAL diode emitters, which exhibit spectral multi-mode operation in the lateral SA direction, have not been reported so far. However, regardless of the laser diode source, the coupling bandwidth \(\delta\lambda_{cb}\) of the external laser cavity depicts an estimate for the upper limit for the residual spectral linewidth \(\delta\lambda\) of the stabilized emitters. The coupling bandwidth describes the maximal spectral linewidth which enables a complete re-imaging of the optical feedback in the beam-combining axis into the originating emitters after a resonator roundtrip and can be regarded as the passive spectral filter function of the external cavity. In the absence of lens aberrations and beam distortions, the coupling bandwidth is proportional to the far-field divergence \(\theta_{G,FA,em}\) of an emitter sub-beam in the beam-combining FA at the location of the transmission grating, which can be expressed in terms of the focal lengths \(f_{TL}\) and \(f_{FAC}\), and inversely proportional to the angular dispersion \(D_\alpha\) of the grating [127]:

\[
\delta\lambda \leq \delta\lambda_{cb} = 2 \cdot \theta_{FA,em} \cdot \frac{f_{FAC}}{f_{TL}} \cdot D_\alpha^{-1} \approx \frac{2\lambda}{\pi \cdot \theta_{FAC,em} \cdot f_{TL}} \cdot D_\alpha^{-1}.
\]

(3.16)
In the upper equation, $\theta_{FA,em}$ denotes the uncollimated beam divergence of an emitter in FA and $\theta_{FAC,em}$ is the corresponding collimated far-field divergence behind the FAC. Figure 3.12a shows a generic measurement of the stabilized spectrum of an individual emitter. The $4\sigma$-linewidth was measured using a high-resolution spectrometer (HighFinesse HDSA; 40-pm spectral resolution at $\lambda = 960\,\text{nm}$). Starting from a low-current value of 93 pm, the linewidth increases to a value of 131 pm at a maximum emitter current of 8.7 A. Besides, the central wavelength of the stabilized emitter peak shifts by about 10 pm which is related to a small change ($\approx 2\%$) of the beam pointing angle in FA with increasing diode current. According to Eq. (3.16), an increasing emitter linewidth could be the result of an increasing beam divergence at the location of the grating which could not be observed in the experiment. Linewidth broadening is also observable in wavelength stabilization experiments using diode bars without a BTS, as for example in the external cavity of Fig. 2.11 which has been used for the locking range measurements. Hence, the influence of the BTS on this effect can be neglected. Even in pulsed operation (5-ms pulse duration; 5% d.c.), where thermal impacts, e.g. thermal lens effects in the micro-optics or a thermally induced misalignment of the FAC, can be neglected, linewidth broadening was still present. This indicates that this effect has a non-thermal character. A potential explanation for the dependency of the stabilized spectral emitter linewidth on emitter operation current are higher order lateral modes of the radiated electric field in SA with increasing emitter current, which prevent narrowband spectral operation of the diode emitter [97, 108, 128]. The BPP in SA hereby indicates the increas-

![Graph](image_url)

Fig. 3.12: (a) Linewidth broadening with increasing emitter current. (b) Residual spectral emitter linewidth $\delta\lambda$ and SA-BPP vs. emitter current.
3.2. Transmission grating based cavity

ing lateral modality of the radiated electrical field of the emitter. The measured spectral emitter linewidth and the corresponding SA-BPP as a function of emitter current are shown in Fig. 3.12b for an individual emitter of two different diode bars. Furthermore, as a comparison, the corresponding coupling bandwidth of the external cavity is plotted. The coupling bandwidths are calculated on the basis of Eq. (3.16) and the experimentally determined far-field divergence of the emitter sub-beam at the location of grating. The latter quantity can be deduced by a measurement of the emitter beam diameter at that location of the grating. The data show that both the emitter linewidth and the SA-BPP linearly evolve with increasing diode current. For low emitter currents, the linewidth of both bars is approximately 100 pm and thus below the calculated coupling bandwidth limit. With increasing current, the SA-BPP gets larger which leads to a significant increase of the emitter linewidth. The presented measurements show that both quantities correlate. The linewidth at high currents approaches the value of the corresponding coupling bandwidth. In case of bar C, the measured linewidth seems to cross the coupling bandwidth limit which can be explained by the limited spectral resolution of the spectrometer and the fact that aberrations are neglected in the calculation of the coupling bandwidth.

Regarding beam quality preservation of the combined cavity output, the residual spectral linewidth results in an increased far-field divergence of the emitter sub-beam due to the diffraction at the grating. The higher beam divergence behind the grating, compared to a monochromatic emitter \((\delta \lambda = 0)\), will consequently deteriorate the BPP of the combined beam [129]. In order to determine the associated deterioration factor, the far-field intensity distribution of the diffracted emitter sub-beam has to be calculated, which is given by the convolution of the monochromatic Gaussian emitter intensity distribution \(J_\theta\) \((4\sigma\text{-width} \ 2\theta_{G,F,A,em})\) with the Gaussian approximated spectral intensity distribution \(\tilde{J}_\lambda\) transformed into angle space \((4\sigma\text{-width} \ \delta \theta)\):

\[
J_\theta(\theta; 2\theta_{G,FA}) = \int_{-\pi/2}^{\pi/2} \tilde{J}_\lambda(\theta_k; \delta \theta) \cdot J_\theta(\theta - \theta_k; 2\theta_{G,F,A,em}) \ d\theta_k .
\] (3.17)

The corresponding far-field intensity distributions, which enter the calculation in the upper equation, are exemplary depicted in Fig. 3.13 for typical experimental parameters. The analytical result of Eq. (3.17) is a Gaussian intensity distribution with a \(4\sigma\text{-width}\) given by:

\[
2\theta_{G,FA} = \sqrt{\delta \theta^2 + (2\theta_{G,F,A,em})^2} , \quad \text{with} \quad \delta \theta = D_\alpha \cdot \delta \lambda .
\] (3.18)
Fig. 3.13: Increase of the far-field divergence of the emitter sub-beam which is diffracted at the transmission grating due to the residual spectral emitter linewidth. For the calculation of the corresponding far-field intensity distribution, typical experimental parameters have been used (\( \lambda_c = 960 \text{ nm} \); \( \delta \lambda = 127 \text{ pm} \); \( 2\theta_{G,FA,em} = 317 \mu\text{rad} \); \( \Lambda^{-1} = 1600 \text{ lines/mm} \)).

The ratio of the width \( \theta_{G,FA} \) of Eq. (3.18) to the far-field divergence \( \theta_{G,FA,em} \) of an individual monochromatic emitter sub-beam yields the following deterioration factor:

\[
\Delta_{\text{linewidth}} := \frac{\theta_{G,FA}}{\theta_{G,FA,em}} \stackrel{(3.18)}{=} \sqrt{1 + \left( D_{\alpha} \cdot \frac{\delta \lambda}{2\theta_{G,FA,em}} \right)^2}. \tag{3.19}
\]

Equation (3.19) represents a general expression for the beam quality deterioration factor which is valid for an arbitrary laser beam which is incident on a diffraction grating. By use of the theoretical expression for the coupling bandwidth \( \delta \lambda_{cb} \) of Eq. (3.16) as an estimate for the upper limit of the stabilized emitter linewidth \( \delta \lambda \), the deterioration factor simplifies to \( \Delta_{\text{linewidth}} = \sqrt{2} \). Consequently, this value constitutes an upper limit for the minimal achievable BPP in the beam-combining axis. In order to verify the validity of Eq. (3.19), Fig. 3.14a shows the measured FA-BPP as a function of emitter current compared to the theoretical predictions. As input parameters for the theoretical calculations, the measured emitter linewidth of Fig. 3.12b and the experimentally deduced far-field divergence of the emitter sub-beam at the location of the grating are used. Both emitters are stabilized at a central wavelength of 963 nm, where the angular dispersion of the grating is 2.50 mrad/nm. The measured data are in good agreement.
with theory at emitter currents $<2\text{A}$ for both investigated diode bars. The measured FA-BPP is $0.44\text{mm} \times \text{mrad}$ which corresponds to a deterioration factor of about 1.4 compared to the diffraction-limited value. The deviation is in the range of the measurement accuracy of $\pm 0.05\text{mm} \times \text{mrad}$ of the automatic laser beam profiler which was used for the measurement. In a good approximation,

\begin{figure}[h]
\centering
\includegraphics{fig3_14.png}
\caption{(a) Measured and calculated FA-BPP and deterioration factor $\Delta_{\text{linewidth}}$ vs. emitter current. (b) CCD camera image of the beam spot at the location of the grating at an emitter current of 5A imaged by a telescope with 0.4x magnification.}
\end{figure}

the measured BPP for bar A stays constant over the whole emitter current range, as predicted by the theoretical calculations. At emitter currents $>6\text{A}$, the measured data show a slight increase of up to $0.49\text{mm} \times \text{mrad}$. On the contrary, in case of bar C, the experimental data deviate from the theoretical predictions with increasing emitter current. A significantly larger FA-BPP is measured at emitter currents $>2\text{A}$. Furthermore, the FA-BPP shows a linear dependency on the emitter current. The reason for the deviation is a tilted beam cross section at the location of the grating. Figure 3.14b shows a charged-coupled device (CCD) camera image of the beam spot at the location of the grating. The FA direction of the emitter beam has an angle of about $4.5^\circ$ compared to the horizontal beam-combining axis. Because of that projection effect, a significant part ($\approx 4.8\%$) of the emitter beam in SA is diffracted into the beam-combining axis which further increases the resulting BPP. By including the beam tilt into the theoretical calculations, a good agreement with the measured data for bar C is achieved. For this purpose, based on the measured SA-BPP data of Fig. 3.12b, 4.8% of the SA-BPP value is added to the theoretically calculated FA-BPP at the corresponding emitter current. If the beam tilt of $0.9^\circ$ is also included into the theoretical
calculations for bar A, a better matching with the experimental data at emitter currents >6A is achieved. Reasons for the observed beam tilt are an incomplete beam rotation by the micro-optical beam rotators due to deviations of the center thickness of the tilted telescopes and the uncollimated SA beam divergence at the location of the BTS [130]. From the measurements it is obvious that for sufficient beam quality preservation a good BTS performance is crucial to achieve minimal beam quality degradation. Furthermore, the presented results show that the BPP deterioration factor, exclusively due to the residual spectral emitter linewidth, is well described by Eq. (3.19). Consequently, depending on the spectral linewidth of the stabilized emitter, the minimal achievable FA-BPP is deteriorated by a factor of $\Delta_{\text{linewidth}} \leq \sqrt{2}$ compared to the diffraction-limited value of an individual unstabilized emitter.

### 3.2.3.2. Diode bar smile

The influence of diode bar smile on the beam quality in the beam-combining axis has been excluded so far. In case of FA-DWBC using a micro-optical BTS, the smile-induced beam pointing errors of the emitters, which have been discussed in section 2.2.3, are transformed into the beam-combining axis. The beam pointing errors are the reason for an increased beam diameter $2\omega_{G,FA}$ upon the diffraction grating, since the individual emitter sub-beams (beam diameter $2\omega_{G,FA,em}$) can not completely overlap in the focal plane of the Fourier transform lens. This effect leads to a degradation in beam quality which can be approximated by:

$$\Delta_{\text{smile}} := \frac{\omega_{G,FA}}{\omega_{G,FA,em}} = \frac{\theta_{FAC}}{\theta_{FAC,em}} \approx \theta_{FAC} \cdot \frac{\tan (\theta_{FA,em}) \cdot f_{FAC}}{\lambda/\pi}.$$  \hspace{1cm} (3.20)

Since the far-field divergence $\theta_{FAC}$ of the beam ensemble linearly increases with increasing smile, as shown in Fig. 2.14b, the deterioration factor $\Delta_{\text{smile}}$ is also expected to show a linear dependency on this parameter. Figure 3.15a shows a measurement of the resulting BPP in the beam-combining FA as a function of smile of the diode bar at a diode operation current of 40A. Furthermore, the FA-BPP of an individual emitter of the corresponding bar is plotted which experimentally realizes the case of a bar without smile. The deterioration factor $\Delta_{\text{smile}}$ can be extracted from the experimental data and is given by the ratio of the FA-BPP of the complete bar to the FA-BPP of an individual emitter. In accordance with the theoretical prediction of Eq. (3.20), the smile-induced beam quality deterioration factor linearly increases with the value of diode bar smile. For low-smile ($\approx 1 \mu m$) bars, the factor is $\Delta_{\text{smile}} \approx 1.2$. For bars with large smile of $>2 \mu m$, the deterioration factor exceeds a value of 1.4. As input parameter for the theoretical calculations, the linear curve fit of Fig. 2.14b is used for the
3.2. Transmission grating based cavity

dependency of far-field divergence $2\theta_{FAC}$ on the smile value. In a further measurement, the FA-BPP of a bar (bar A; 0.7-µm smile) as a function of the number of emitters, which are present inside the external cavity, is investigated for low- and high-power operation of the diode bar. For this purpose, an adjustable aperture is used to block the corresponding emitter sub-beams directly in front of the diode bar, where the emitters are still far enough separated to be individually blocked. Additionally, the beam diameter $2\omega_{G,FA}$ at the location of the grating is measured for the corresponding configuration by imaging the zero-order transmitted beam upon a CCD camera by use of a cylindrical telescope with 0.4x magnification. As expected, the measured data in Fig. 3.15b show that the BPP and the beam diameter are lowest for only one individual emitter of the diode bar resonating inside the cavity which corresponds to the case of a bar with zero smile. The larger FA-BPP of the individual emitter at 140 A is related to the current-dependent effects of beam quality deterioration which have been discussed in the previous section. If, starting from the central emitter, adjacent emitters are successively faded in, the FA-BPP increases, since the more emitters present the higher the smile-induced beam pointing errors which lead to an increased beam diameter $2\omega_{G,FA}$ and, according to Eq. (3.20), a higher BPP deterioration factor.

![Fig. 3.15: Beam quality deterioration in FA due to diode bar smile for FA-DWBC using a micro-optical BTS. (a) Measured FA-BPP and beam quality deterioration factor $\Delta_{smile}$ vs. smile of the BAL diode bar at a diode current of 40 A. As a comparison, the theoretically expected curve for $\Delta_{smile}$ as a function of smile is plotted. (b) Measured FA-BPP and beam diameter $2\omega_{G,FA}$ at the location of the grating vs. numbers of emitters resonating inside the external cavity at a diode current of 20 A and 140 A (bar A; 0.7-µm smile).](image-url)
The effect is plainest to see at the maximal operation current of 140 A, where the deterioration factor is \( \Delta_{\text{smile}} \approx 1.8 \). For lower operation currents, the smile-induced deterioration factor is significantly smaller (\( \Delta_{\text{smile}} \approx 1.4 \) at 20 A). This deviation can be explained by an increasing far-field divergence \( \theta_{\text{FAC}} \) of the bar with increasing diode current indicated by an increased beam diameter at the location of the grating. From Fig. 3.15b it is evident that the beam diameter \( 2\omega_{G,FA} \) increases by about 15% from 20 A to 140 A, in case of the configuration with the total emitter number \( n_{em} = 19 \). According to Eq. (3.20), this effect leads to a higher deterioration factor. A potential reason for this observation are additional thermally induced beam pointing errors of the emitter sub-beams due to a heating of the FAC micro-lens. The theoretically predicted BPP deterioration factor \( (\Delta_{\text{smile}} \approx 3.5 \text{ at 140 A}; \ n_{em} = 19) \) based on Eq. (3.20) and the measured beam diameters presented in Fig. 3.15b significantly deviates from the experimentally deduced value. The reason for this discrepancy is most likely an error in the measurement of the beam diameter upon the grating. Potentially, the CCD camera was not exactly positioned in the focal plane behind the telescope resulting in a measured value which is larger than the actual beam diameter, especially at large emitter numbers. In summary, the presented results show that diode bar smile can drastically affect the beam quality of the combined cavity output which is the reason why low-smile BAL diode bars are needed for sufficient beam quality preservation.

### 3.2.3.3. Spectral emitter cross-talk

Besides the residual spectral linewidth of the stabilized emitter and diode bar smile, spectral emitter cross-talk deteriorates the beam quality in the beam-combining axis of the resulting cavity output. Emitter cross-talk is present, if parts of the optical feedback of an individual emitter of the diode bar is partially coupled back into a neighboring emitter, since the feedback sub-beam has a small angle deviation \( \Delta\beta \) compared to the combined output beam (see Fig. 3.16a). The stabilized wavelength \( \lambda_{X} \) of the spectral cross-talk channel, which enables a resonator roundtrip, is given by

\[
\lambda_{X} = \frac{\lambda_{i} + \lambda_{i+1}}{2} + \sin \left[ \beta_{L}(\lambda_{c}) \right] \cdot \left[ \cos (\Delta\beta) - 1 \right] \approx \frac{\lambda_{i} + \lambda_{i+1}}{2} \quad (3.21)
\]

for low-order cross-talk with small angle deviations \( (\Delta\beta \rightarrow 0) \) compared to the diffraction angle \( \beta_{L}(\lambda_{c}) \) of the combined output beam. The derivation of Eq. (3.21) can be found in the appendix B. Emitters, exhibiting spectral cross-talk, are partially stabilized at the cross-talk wavelength \( \lambda_{X} \), which means that these power fractions are not diffracted into the combined output beam, governed
by Eq. (3.7), and consequently deteriorate beam quality of the cavity output. In order to suppress spectral emitter cross-talk even of the lowest order, a cylindrical telescope is used acting as a space-frequency filter in conjunction with the OC. As shown in the left scheme of Fig. 3.16a, the distance $z_3$ of the OC from the telescope is crucial for cross-talk suppression. For small distances, a spectral cross-talk channel can resonate inside the cavity. In this case, cross-talk can generally be suppressed by introducing an aperture in the region of the focal plane between the two telescope lenses to block the channel. But this approach is very critical because the cross-talk beam and the combined beam are only slightly separated which potentially leads to a cutting of the combined beam by the aperture and significant power losses, as reported in [113]. By increasing the distance $z_3$ of the OC from the telescope, the cross-talk channel is no longer fed back by the external cavity and cross-talk is suppressed without the use of an aperture. Figure 3.17a shows a measurement of the FA-BPP of the combined cavity output beam as a function of the distance $z_3$ of the OC from the position of the telescope at a diode current of 100 A. For the measurements, two different telescopes are used with magnifications $f_{X1}/f_{X2}$ equal to 6 and 9. The telescope is placed in a non-telecentrical configuration ($z_1 = 80$ mm; $z_2 = f_{X1} + f_{X2}$). Using the telescope with lower magnification, cross-talk is present inside the cavity for small

Fig. 3.16: (a) Spectral emitter cross-talk. (b) Corresponding output spectra at 100-A diode current. The blue spectra indicate spectral emitter cross-talk. The labels 1A, 1B, 2A and 2B are explained in the text.
Fig. 3.17: (a) Measured FA-BPP and normalized power of the combined cavity output vs. distance of the OC from the telescope $z_3$ for two telescopes with different magnifications at 100-A diode current. (b) Measured FA-BPP and normalized power of the combined cavity output vs. deviation of the distance $z_2$ between the telescope lenses at 100-A diode current ($f_{X1}/f_{X2} = 9$). The labels 1A, 1B, 2A and 2B are explained in the text.

distances which can clearly be seen in the corresponding spectrum 1A shown in Fig. 3.16b, where the blue spectra indicate spectral emitter cross-talk. The spectral peaks of the individual emitter show a low contrast and are not clearly distinguishable due to the resonating cross-talk. Furthermore, the beam quality in the beam-combining FA is significantly deteriorated to about $2.3 \text{ mm} \times \text{mrad}$. If the distance is further increased, the FA-BPP is lowered and reaches a minimum value of approximately $0.8 \text{ mm} \times \text{mrad}$ at $z_3 = 450 \text{ mm}$ accompanied by a power drop of 10%. The corresponding spectrum 1B shows distinct emitter peaks and a high modulation depth. No cross-talk is present for this configuration and the beam quality deterioration is purely dominated by the residual spectral emitter linewidth and smile of the diode bar [$\Delta_X \rightarrow 1$ in Eq. (3.15)]. The power drop-off can be explained by a reduced imaging quality of the optical feedback, since the effective feedback ratio stays constant when the mirror is moved. If the magnification of the telescope is changed to 9, cross-talk is suppressed independently of the distance of the OC from the telescope indicated by a constant FA-BPP and the spectrum 2A without any distortion due to upcoming resonating cross-talk wavelengths. Furthermore, the influence of a deviation of the distance $z_2$ between the telescope lenses on the combined cavity output beam quality and power for a fixed position of the OC is investigated ($f_{X1}/f_{X2} = 9$). From Fig. 3.17b one can
see that there exist two configurations with a trade-off between the minimal beam quality and maximal output power. In case of an individual emitter being present inside the external cavity, a maximum of the output power and a minimum of the BPP is reached if the telescope is aligned for best optical feedback imaging into the originating emitters. In contrast to that, one can see that the complete bar exhibiting the same telescope configuration has not the minimal BPP. Due to the optimal alignment, a small amount of cross-talk is still present which deteriorates beam quality. By changing the lens position, the BPP can be minimized at the cost of a lower output power which shows that a slightly detuned cavity is needed to achieve a complete suppression of cross-talk for the entire emitter ensemble. In summary, the presented results show that a telescope with appropriate magnification can be used for cross-talk suppression without major power losses. In the telescope configuration for minimal BPP deterioration the losses are $<5\%$. The magnification depends on the spectral channel spacing of the emitters which is proportional to the ratio of the emitter pitch to the transform focal length [see Eq. (3.10)]. With decreasing channel spacing, the angles of the cross-talk channels become smaller which is the reason why telescopes with higher magnifications are needed. This effect makes cross-talk filtering more sophisticated. For example, in case of using a high-FF bar (bar B) with an emitter pitch of $200\,\mu m$, a telescope with a magnification of 20 has to be used to completely eliminate cross-talk inside the external cavity.

3.2.3.4. Conclusion

The presented results in this section demonstrate that beam quality deterioration in dense wavelength beam-combined BAL diode bars, employing an external resonator with an intra-cavity transmission grating, can be related to the discussed three main mechanisms in case of beam combining in the fundamental-mode FA beam dimension by use of a micro-optical BTS. The residual spectral linewidth of the stabilized emitters constitutes a lower limit to the beam quality in the beam-combining axis with a deterioration factor $\Delta_{\text{linewidth}} \leq \sqrt{2}$ compared to the diffraction-limited value ($M^2 = 1$) of an individual free-running emitter ($BPP_{FA,em} \approx 0.31\,\text{mm} \times \text{mrad}$ at $\lambda = 960\,\text{nm}$). The factor depends on the emitter linewidth and reaches its maximum if the linewidth is equal to the coupling bandwidth of the external cavity. The deterioration factor due to diode bar smile is $\Delta_{\text{smile}} \approx 1.2$ for low-smile ($\approx 1\,\mu m$) diode bars. Beam quality deterioration due to cross-talk inside the external cavity is negligible ($\Delta_X \rightarrow 1$) if an appropriate cross-talk filtering telescope is used in the optical feedback path of the cavity. Consequently, the overall deterioration factor amounts to $\Delta \approx 1.7$ which sets up a minimal value of $\Delta \cdot BPP_{FA,em} \approx 0.53\,\text{mm} \times \text{mrad}$ ($M^2 \approx 1.7$) for the resulting
BPP in the beam-combining axis. Here, a residual spectral emitter linewidth in the range of the coupling bandwidth of the external cavity is assumed, as it has been observed in the experiment. Deviations from the minimal value with increasing diode current are due to an incomplete beam rotation of the micro-optical BTS and thermally induced beam pointing errors of the emitter sub-beams in the beam-combining axis.

### 3.3. Thin-film filter multi-laser cavity

#### 3.3.1. Wavelength stabilization

The thin-film filter (TFF) approach for DWBC represents an open-loop external cavity architecture, where the wavelength stabilization is decoupled from the beam-combining element, in contrast to the transmission grating based cavity which has been discussed in the previous section. The stabilization of the diode bar emitters is realized by the angle-dependent spectral transmission of an ultranarrowband TFF, whereas beam combining is performed by use of a -1st order transmission grating. The TFF represents the key component of the external resonator whose functionality is based on multiple beam interference similar to a Fabry-Pérot etalon. As depicted in Fig. 3.18a, a Fabry-Pérot etalon consists of a plane-parallel plate (thickness \(d_{FP}\); refractive index \(n_{FP}\)) whose partially reflective surface layers exhibit identical reflection and transmission properties. A plane wave with amplitude \(E_0\) of the electric field vector which is incident upon the etalon undergoes multiple reflections inside the etalon. The reflected and transmitted sub-beams, which are coupled out after propagation through the optical component, interfere. Depending on the optical path difference resp. phase relation of the sub-beams compared to each other, the multiple-beam interference is constructive or destructive. The geometrical phase difference \(\delta_{FP}\) is given by

\[
\delta_{FP} (\lambda, \Theta') = \frac{4\pi n_{FP} d_{FP}}{\lambda} \cos (\Theta'),
\]

where \(\lambda\) is the wavelength of the incident plane wave [131]. The angle \(\Theta'\) is related to the AOI \(\Theta\) upon the etalon by Snell’s law \(n_{FP} \sin (\Theta') = n_a \sin (\Theta)\), where in the following \(n_a = 1\) is assumed for the refractive index of air as the surrounding medium. Assuming an ideal etalon, without optical power losses due to absorption, the intensity of the transmitted light can be deduced by the taking the sum of the electric field amplitudes of the transmitted sub-beams under
consideration of the correct phase relation. The resulting transmitted intensity \( J_T \) is given by the Airy function [131]:

\[
J_T = J_0 \cdot \frac{1}{1 + F \sin^2(\delta_{FP}/2)}, \quad \text{with} \quad F = \left( \frac{2r}{1-r^2} \right)^2 = \frac{4R}{(1-R)^2}. \quad (3.23)
\]

In the upper equation \( J_0 \) denotes the overall intensity of the incident plane wave and \( R = r^2 \) represents the intensity reflection coefficient. Figure 3.18b shows the course of the transmitted intensity for different values of the reflectivity \( R \) of the surface layers of a Fabry-Pérot etalon as a function of the phase \( \delta_{FP} \). The modulation depth strongly depends on the reflectivity, since this value determines the number of sub-beams which participate in multiple-beam interference. For small values \( (R = 4\%) \), the modulation is weak and shows a cosine-like course. With increasing reflectivity, sharp interference peaks build up. At high values \( (R = 90\%) \), the course of the transmitted intensity in the vicinity of an interference maximum can be described as a Lorentzian line with full width at half maximum [131]:

\[
\Delta \delta_{FP,FWHM} = \frac{4}{\sqrt{F}}. \quad (3.24)
\]
The finesse $\tilde{F}$, with

$$\tilde{F} = \frac{2\pi \sqrt{F}}{4} = \frac{\pi \sqrt{R}}{(1 - R)} \tag{3.25}$$

is defined as the ratio of the distance of adjacent transmission maxima to the width of a maximum and determines the effective number of interfering sub-beams. Furthermore, the finesse constitutes an important value in terms of the spectral resolution, if the etalon is employed as a spectrometer. The spectral resolution $R_{FP}$ of a Fabry-Pérot etalon, in case of vertical incidence, is given by

$$R_{FP} = \frac{\lambda}{\Delta\lambda_{FP}} = m \cdot \tilde{F} \tag{3.26}$$

where $m = 2d_{FP}/\lambda$ being the transmission order and $\Delta\lambda_{FP}$ being the minimal spectral resolution of the etalon [132]. Besides the spectral resolution, the spectral position and the spectral bandwidth of the transmitted interference maximum is important for the understanding of the wavelength stabilization in the external TFF multi-laser cavity. The transmitted wavelength of the first-order interference maximum ($m = 1$) can be calculated from Eq. (3.22) by using the condition

$$\delta_{FP}(\lambda, \Theta') = \frac{4\pi n_{FP} d_{FP}}{\lambda} \cos (\Theta') \overset{1}{=} 2\pi \tag{3.27}$$

for which the denominator of Eq. (3.23) equals to one. Solving Eq. (3.27) for the wavelength $\lambda$ and using Snell’s law for the angle $\Theta'$ yields

$$\lambda_{FP}(\Theta) = \frac{2n_{FP} d_{FP}}{\sqrt{1 - [\sin (\Theta)/n_{FP}]^2}} \overset{!}{=} \lambda_0 \tag{3.28}$$

for the dependency of transmitted wavelength $\lambda_{FP}$ on the AOI $\Theta$ of the plane wave upon the etalon. Here, $\lambda_0$ denotes the resonant transmitted wavelength for vertical incidence. The corresponding spectral transmission bandwidth follows from Eq. 3.26 and is given by:

$$\Delta\lambda_{FP,FWHM} = \lambda \cdot \tilde{F}^{-1} \tag{3.29}$$

Furthermore, Eq. (3.28) enables the calculation of the spectral angular dispersion of an etalon which determines the stabilized spectral interval of the wavelength.
3.3. Thin-film filter multi-laser cavity

stabilized diode bar emitters in the external cavity. The angular dispersion $D_\Theta$ is given by:

$$D_\Theta := \frac{d\Theta}{d\lambda} = -\frac{n_{FP}}{\lambda_0} \cdot \frac{\sqrt{n_{FP}^2 - \sin^2(\Theta)}}{\sin(\Theta) \cos(\Theta)}.$$  \hspace{1cm} (3.30)

Contrary to the angular dispersion of a transmission grating [see Eq. (3.11)], the angular dispersion $D_\Theta$ of a Fabry-Pérot etalon is negative, which means that a decrease of the AOI results in a larger wavelength of the resonance. The principal difference of a TFF compared to a standard Fabry-Pérot etalon is the differing distance between the partially reflecting surface layers. Typically, the plane-parallel plate of an etalon is a glass substrate with a thickness of several centimeters on which a coating is applied. In case of a TFF, the plane-parallel plate is realized as a thin spacer layer with a thickness in the range of the wavelength of the incident light which is located in between a highly reflective layered stack. Due to the small spacer layer thickness, a TFF provides a high spectral angular dispersion. Figure 3.19a shows the schematic layer design of the ultra-narrowband TFF which has been used for the wavelength stabilization experiments in this thesis. The filter is made up of a tantalum pentoxide ($\text{Ta}_2\text{O}_5$)/quartz ($\text{SiO}_2$) quarter-wave stack, $0.57L(HL)_{10}HLLH(HL)_{10}$, exhibiting a low-index $\text{SiO}_2$ spacer in the middle. The filter is designed for 100\% transmission at a wavelength of $\lambda_0 = 1037$ nm for an AOI of 0°. The stack of alternating high- and low-index quarter-wave layers (refractive index $n_H$ and $n_L$) on top and below the spacer layer provides a high reflectivity (>99.99\%) which results in a transmission bandwidth of $\Delta\lambda_{FP,FWHM} = 50$ pm for TE-polarized light. The complete layer structure is sputtered on a fused silica substrate with a thickness of 3 mm and a diameter of 25.4 mm. The substrate material ensures low absorption in the wavelength range from 900 nm to 1000 nm and consequently a stable performance of the filter even at kW power levels. Figure 3.19b shows the calculated transmitted intensity as a function of wavelength of an ultra-narrowband TFF exhibiting the layer design shown in Fig. 3.19a for TE and TM polarization of an incident plane wave at an AOI of $\Theta = 40^\circ$. The presented curves are the result of a simulation of the spectral transmission characteristic of the dielectric layer design of the filter by use of a ray-transfer matrix solver. As already discussed, the TFF design provides a transmission bandwidth of 50 pm (FWHM) for TE-polarized light. At an AOI of 40°, the wavelength for maximal transmission is $\lambda_{FP}(\Theta = 40^\circ) = 953$ nm. This configuration corresponds to the operation condition of the TFF for the wavelength stabilization in the external cavity. For TM polarization, the transmission bandwidth is >500 pm and consequently more than a factor of 10 larger than for TE-polarized light. The reason for the differing transmission bandwidths is
the significantly lower reflectivity of the quarter-wave stack for TM polarization. According to the Eqs. (3.25) and (3.29), a lower reflectivity results in a larger transmission bandwidth. Furthermore, the presented data in Fig. 3.19b show that the wavelength for maximal transmission is slightly shifted by about 30 pm for TM polarization compared to TE-polarized light. This deviation is the result of both the differing refractive index of the SiO₂ spacer layer for TM and TE polarization due to birefringence and furthermore differing distributions of the electric field amplitude inside the filter, as explained in the following. Due to the half-wave spacer thickness of the TFF, the electric field amplitude of the resonant mode inside the spacer layer is strongly enhanced. As shown in the simulation of Fig. 3.20, the evanescent mode of the electric field significantly penetrates into the layers of the quarter-wave stack which surround the spacer layer. Both the intensity enhancement and the overlap with the surrounding layers is strongest for TE polarization. For TM polarization the effects is significantly weaker due to the smaller reflectivity of the quarter-wave stack. Consequently, an incident resonant plane wave not only experiences the refractive index of the spacer layer but also, depending on the polarization, a significant part of the refractive index of the surrounding layer materials. The result of the discussed effects is a changed refractive index of the filter which has to be used for the calculation of the resonant wavelengths according to Eq. (3.28). The changed index of refraction due
to the evanescent mode can be deduced by an effective index model [133]. The resulting effective refractive index $n_{TFF,eff}$ of the filter is given by

$$n_{TFF,eff} = \begin{cases} 
 n_H \cdot \sqrt{\frac{m-(m-1)(n_L/n_H)}{(m-1)-(m-1)(n_L/n_H)+(n_H/n_L)}} & \text{for high-index spacers} \\
 n_L \cdot \sqrt{\frac{m-(m-1)(n_L/n_H)}{(m-m-(n_L/n_H)+(n_L/n_H)^2}} & \text{for low-index spacers}
\end{cases}$$

(3.31)

depending on the design of the spacer layer which exhibits either a high- or low-index material. Using the refractive indices $n_L = 1.4509$ [134] and $n_H = 2.0822$ [135] for Ta$_2$O$_5$ and SiO$_2$ at a wavelength of 960 nm, respectively, yields $n_{TFF,eff} \approx 1.63$ for the presented TFF layer design with a low-index spacer. Consequently, the refractive index $n_{FP}$ in the equations presented for a Fabry-Pérot etalon has to be substituted by the effective index $n_{TFF,eff}$ to ensure a correct description of the transmission properties of the TFF. In order to proof the validity of the effective index model, Fig. 3.21 shows the calculated transmitted wavelength as a function of the AOI upon the TFF based on Eq. (3.28) and the deduced effective refractive index. Furthermore, as a comparison, the experimental deduced resonant wavelength for the corresponding AOI is shown. As laser source for the measurement, the collimated output beam of a wavelength-tunable fiber-coupled single-mode diode laser (Sacher Lasertechnik LION) is used. The...
TFF is mounted on a rotation stage which allows for a precise angular alignment of the filter with respect to the incident laser beam. For the measurement, the rotation angle of the filter is aligned and optimized for maximal transmitted power at various wavelengths of the incident laser beam. The experimentally deduced data are in good agreement with the theoretical calculations based on the presented effective index model. The results proof and justify the usage of the discussed effective index model for the theoretical description of the spectral transmission characteristic of the TFF. Furthermore, Fig. 3.21 shows the calculated angular dispersion of the used TFF as a function of AOI based on Eq. (3.30) and the deduced effective refractive index of the filter. At an AOI of 40°, which corresponds to a resonant wavelength of 953 nm, the angular dispersion is $D_\Theta = -4.77$ mrad/nm. This value is a factor of about 2 larger in amount compared to the angular dispersion of a transmission grating with 1600 lines/mm at the identical AOI.

The schematic setup of the external wavelength-stabilizing multi-laser cavity is shown in the upper part of Fig. 3.22. As in case of the transmission grating based cavity, the emitter sub-beams emerging from the BAL diode bar are collimated in the vertical FA direction ($y$-axis) by use of a FAC. The diode bar exhibits a commercial micro-optical BTS (see section 2.1) in order to perform beam combining in FA along the horizontal dimension ($x$-axis) of the cavity architecture. The cylindrical Fourier transform lens with a focal length of $f_{TL} = 500$ mm images the
far fields of the collimated and coaxially propagating emitter sub-beams of the diode bar in the beam-combining direction upon the ultra-narrowband TFF. The transform lens is placed in a telecentrical configuration with respect to the front facet of the diode bar and the TFF. A zero-order HWP in front of the transform lens is used to rotate the TE-polarized laser output of the diode bar emitters into TE polarization with respect to the plane of incidence at the TFF. The transform lens creates a fan of angled rays which overlap at the location of the TFF. Each sub-beam strikes the TFF under an unique AOI. Mathematically, the Fourier lens transforms the lateral position \( x_i \) of the \( i \)th emitter \((i = 1, \ldots, n_{em})\) of the diode bar with respect to the optical axis into an unique angle \( \Theta_i \) with respect to the surface normal of the TFF, given by:

\[
\Theta_i = \Theta_0 + \varphi_i = \Theta_0 + \frac{x_i}{f_{TL}}. \tag{3.32}
\]

Here, \( \Theta_0 \) denotes the angle between the optical axis and the surface normal of the TFF. Furthermore, a small-angle approximation has been used for the derivation

**Fig. 3.22**: Schematic setup of the TFF multi-laser cavity and the grating combiner.
of the angle \( \varphi_i \) which describes the relative angle of the corresponding emitter sub-beam with reference to the optical axis of the external resonator. According to the derived spectral angular dispersion characteristic in Eq. 3.28 and the effective index model of the TFF, the transmission of the incoming emitter sub-beams is fixed to a specific wavelength \( \lambda_i \) which is given by:

\[
\lambda_i = \lambda_0 \sqrt{1 - \left[ \sin(\Theta_i)/n_{TFF,eff} \right]^2}.
\] (3.33)

Behind the TFF, a cylindrical lens with a focal length of \( f_{FB} = 250 \text{ mm} \) in conjunction with a HR complete the external resonator and image the transmitted frequency-filtered sub-beams back into the originating emitters providing wavelength-selective optical feedback. Consequently, the external laser cavity stabilizes each emitter on an individual wavelength \( \lambda_i \), given by Eq. (3.33), realizing a stable position-to-wavelength mapping for each emitter of the laser diode array which is required for subsequent spectral beam combining by means of a diffraction grating. The corresponding stabilized spectral interval \( \Delta \lambda \) of the diode bar is given by

\[
\Delta \lambda = \left| D_\Theta^{-1}(\Theta_i = \Theta_0) \right| \cdot \frac{\Delta x}{f_{TL}} =: \Delta \Theta
\] (3.34)

where \( \Delta x \) is the lateral spatial separation of the outer emitters of a diode bar or an arbitrary horizontal diode emitter array and

\[
D_\Theta = \frac{n_{TFF,eff}}{\lambda_0} \cdot \sqrt{n_{TFF,eff}^2 - \sin^2(\Theta_i)} \sin(\Theta_i) \cos(\Theta_i)
\] (3.35)

being the angular dispersion of the TFF at the corresponding angle \( \Theta_i \) which results from Eq. (3.30). The span of the angular spectrum, which is incident on the TFF, is denoted by \( \Delta \Theta \). As in case of the transmission grating based cavity, an equivalent definition of the stabilized spectral interval can be given in terms of the channel spacing and the number of stabilized diode bar emitters by replacing the angular dispersion of the grating by the angular dispersion of the TFF in Eq. (3.10). The residual spectral linewidth of the stabilized emitters is larger than the spectral transmission bandwidth of the TFF due to the residual far-field divergence of the emitters in FA in the focal plane of the Fourier transform lens. Furthermore, the spectral multi-mode character of the BAL diode emitter in SA prevents a narrowband spectral operation of the stabilized diode bar emitters. As in case of the transmission based cavity for DWBC, the resulting coupling bandwidth \( \delta \lambda_{cb} \) of the TFF multi-laser cavity depicts an estimate for the stabilized
spectral linewidth $\delta \lambda$ and can be calculated in the absence of lens aberrations and beam distortions based on Eq. (3.16) by simply replacing the angular dispersion of the grating $D_\alpha$ by the absolute value of the angular dispersion $D_\Theta$ of the TFF. Besides, as later explained in section 3.3.4, the filter exhibits a laterally inhomogeneous spacer thickness which results in a spatially varying spectral transmission characteristic of the incident emitter sub-beams. The above mentioned effects are the reason for a stabilized spectral emitter linewidth larger than the transmission bandwidth of the filter. The resulting excess spectrum of the stabilized emitters cannot be transmitted through the TFF and is reflected out of the cavity. As a result, only a small amount of the intra-cavity power is used for optical feedback, whereas the major portion is coupled out of the resonator at the location of the TFF. In the vertical SA direction ($y$-axis), perpendicular to the beam-combining axis, the rotated emitter sub-beams are collimated in SA by a cylindrical SAC with a focal length of $f_{SA} = 50\,\text{mm}$. Subsequent to the SAC, two additional cylindrical lenses (focal lengths $f_{SA1}$ and $f_{SA2}$) are used to image the beam waist of the emitter sub-beams in SA onto the HR for feedback re-imaging. In contrast to the transmission grating based cavity for DWBC, spectral emitter cross-talk is inherently suppressed inside the external TFF multi-laser cavity due to the small transmission bandwidth of the TFF compared to the channel spacing of adjacent emitters in conjunction with the specific angle-to-wavelength mapping described by Eq. (3.33). A potential cross-talk channel of a stabilized emitter ray in the optical feedback branch, which exhibits a small angle deviation in the beam-combining axis, has a non-resonant AOI-wavelength pairing after the re-imaging by the cylindrical lens and the HR. Consequently, cross-talk beams are reflected out of the cavity at the location of the TFF after passing the optics in feedback branch of the resonator. A beam block behind the TFF is used to block the corresponding portions of the optical feedback power which are reflected out of the cavity.

3.3.2. Beam combination and dispersion-matching

In order to perform beam combining of the wavelength-locked emitter sub-beams emerging from the TFF multi-laser cavity, a grating combiner setup is used. A schematic of the setup is shown in the lower part of Fig. 3.22. The setup consists of a cylindrical lens telescope (focal lengths $f_{C1} = 100\,\text{mm}$ and $f_{C2} = 194\,\text{mm}$) and a -1st order transmission grating which is placed in Littrow configuration with respect to the central ray of the diode emitter array exhibiting the central wavelength $\lambda_c$ of the stabilized spectrum. Specifically, the grating is a dielectric transmission grating with $\Lambda^{-1} = 1600\,\text{lines/mm}$ and an optimized diffraction efficiency for TE-polarized light at a Littrow angle of $\beta_L(\lambda_c = 955\,\text{nm}) = 50^\circ$. The
optical component is of the same type as the grating which has been discussed in section 3.2.1 for DWBC using the transmission grating approach. As in case of the transmission grating based cavity, the grating is operated slightly off the Littrow condition (≈0.3°) with respect to the optical axis of the resonator in order to suppress an unintended locking of the diode bar emitters by the beam of the -1st reflected order. Since the wavelength-to-AOI dependency and the spectral angular dispersion characteristic of the TFF, governed by the Eqs. (3.33) and (3.34), and the transmission grating [see Eqs. (3.7) and (3.11)], are different and additionally nonlinear across the relevant wavelength band of the TFF cavity, an exact dispersion-matching upon the combiner grating is required to preserve beam quality after beam combining [136]. The cylindrical telescope is used for linear dispersion-matching between the TFF and the combiner grating across the stabilized bandwidth Δλ of the laser diode array, as shown in Fig. 3.23a. The telescope images the individual emitter sub-beams of the wavelength-stabilized cavity output upon the combiner grating. According to the magnification of the telescope, given by $M = f_{C2}/f_{C1}$, the relative angles $\varphi_i$ of Eq. (3.32) are transformed as $\varphi_i^* = -\varphi_i/M$ in order to match the angular dispersion characteristic of the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3_23}
\caption{Spectral beam combining of the TFF wavelength-locked cavity output. (a) Linear dispersion-matching by use of a telescope. Left axis, measured (symbols) and calculated (lines) relative angle with respect to the TFF AOI $\Theta_0$ and Littrow angle $\beta_L(\lambda_c)$ of the combiner grating at the central wavelength $\lambda_c$ of the stabilized spectrum vs. wavelength. Right axis, dispersion ratio of the TFF to the combiner grating vs. wavelength. (b) Calculated beam pointing angles $\Delta \theta_i$ of the diffracted emitter sub-beams with reference to the Littrow angle $\beta_L(\lambda_c)$ vs. wavelength for different magnifications $M$ of the telescope.}
\end{figure}
combiner grating. As a result, the incident emitter sub-beams are diffracted into one single combined output beam. The magnification of the telescope is given by the absolute value of the dispersion ratio of the TFF and the combiner grating at the central wavelength $\lambda_c$ of the stabilized spectrum ($M = 1.94$ for $\lambda_c = 955\,\text{nm}$). The residual nonlinear part of the dispersion, which can not be matched by the telescope, results in beam pointing errors of the emitter sub-beams with respect to each other after beam combining. Consequently, the far-field divergence of the combined output beam is increased which can, besides diode bar smile and the residual spectral linewidth of the stabilized emitters, significantly deteriorate beam quality in the beam-combining axis. By use of the grating equation [see Eq. (3.6)], the beam pointing angles $\Delta \theta_i$ of the diffracted emitter sub-beams, with reference to the Littrow angle $\beta_L(\lambda_c)$, are given by:

$$
\Delta \theta_i = \sin^{-1} \left\{ \frac{\lambda_i}{\Lambda} - \sin \left[ \beta_L(\lambda_c) + \varphi_i(M) \right] \right\} - \beta_L(\lambda_c) .
$$

Figure 3.23b shows the calculated beam pointing angles $\Delta \theta_i$ as a function of wavelength for different magnifications $M$ of the telescope. From the plot one can see that the curve for $M = 1.94$ lies within the region of the emitter beam divergence $2\theta_{G,FA}$ in the beam-combining axis behind the grating for a spectral bandwidth of $\Delta \lambda = 40\,\text{nm}$ around the central wavelength $\lambda_c$ of the stabilized spectrum. That implies that beam quality is sufficiently preserved. For magnifications differing from the optimal value, the beam pointing angles above and below the central wavelength $\lambda_c$ increase in amount and become larger than the beam divergence of a diffracted individual emitter. As a result, the far-field divergence of the combined beam is increased and the beam quality significantly differs from the BPP of an individual emitter sub-beam in the beam-combining axis. Here, the value of the stabilized spectral interval is crucial for the resulting beam quality. In case of small stabilized bandwidths ($\Delta \lambda < 5\,\text{nm}$), a deviation from the optimal value of the magnification is expected to have a minor influence, whereas for large spectral bandwidths, an exact dispersion-matching is needed to prevent from beam pointing errors which significantly deteriorate beam quality of the combined beam.

### 3.3.3. Characteristics of the combined output beam

In this section, the stabilized spectrum of the output beams out of the TFF multi-laser cavity, the output power characteristics and the measured BPP of the combined output beam are investigated based on individual-bar experiments. The presented results are achieved using the cavity architecture and the grating
combiner setup presented in Fig. 3.22. For the experiments, passively cooled low-
FF bars (bar A in Table 2.1) are used. For the analysis of the stabilized cavity output and the combined beam, the identical diagnostic tools are used as in case of the transmission grating based cavity in section 3.2.2.

The spectrum of the stabilized emitter sub-beams out of the TFF multi-laser cavity at a diode current of 100 A is shown in Fig. 3.24. The 19 emitters of the diode bar are stabilized within a spectral bandwidth of $\Delta \lambda = 3.4 \text{ nm}$ at a central wavelength of $\lambda_c \approx 963 \text{ nm}$. This value is in good agreement with the theoretical prediction of Eq. (3.34). For $n_{em} = 19$, $p_{em} = 500 \mu m$, $f_{TL} = 500 \text{ mm}$ and the corresponding angular dispersion of the TFF ($D_\theta = -4.93 \text{ mrad/nm at } \lambda_c = 963 \text{ nm}$) the theoretical value is $3.7 \text{ nm}$. A possible reason for the small discrepancy of 8% is a slightly differing angular dispersion of the TFF due to the manufacturing tolerance of $\pm 1\%$ of the design wavelength $\lambda_0$ of the filter and furthermore the laterally inhomogeneous spacer thickness (see section 3.3.4). The spectral channel spacing of adjacent emitters is $\Delta \lambda_{em} = 178 \text{ pm}$. The spectrum shows a high modulation depth and the spectral lines of the individually stabilized emitters are completely resolved which proves that no spectral emitter cross-talk is present inside the TFF multi-laser cavity, as expected from the theoretical considerations. The residual spectral linewidth of the stabilized emitters is $\delta \lambda = 124 \text{ pm (4}\sigma)\) .

The measured output power characteristics and the related e-o conversion efficiencies of the free-running laser diode bar, the wavelength-stabilized cavity output and the combined output beam as a function of diode current are depicted
in Fig. 3.25a. At a diode current of 140 A, the combined output power is 84 W with a corresponding e-o conversion efficiency of 39.8%. The WBC efficiency with respect to the free-running optical output power of the laser diode bar is depicted in Fig. 3.25b. Furthermore, the corresponding measured relative power losses at the location of TFF and the combiner grating, with reference to the free-running optical output power, are shown in order to investigate the main loss channels inside the external cavity. The resulting WBC efficiency is about 80% and shows, with the exception of the value at 20 A, a current-independent course. The deviation of the deduced value at 20-A diode current is most likely related to the measurement error of the power meter at low optical powers. The current-independent course of the WBC efficiency indicates a stable locking performance of the diode bar in the investigated diode current range and an emission characteristics which is mostly determined by the external resonator. The relative power loss of 18% of the stabilized cavity output compared to free-running laser diode bar output can mostly be related to the measured power ratio of about 14% which is reflected out of the cavity towards the beam block at the location of the TFF in the feedback branch. The remaining relative power loss of 4% is potentially caused by the resonator optics which are placed in front of the TFF. The measured overall relative power loss in the three discussed loss channels at the
combiner grating is about 4% in the investigated current range and consequently consistent with the losses which have been deduced using the transmission grating approach for DWBC.

Figure 3.26 shows the measured FA- and SA-BPP of the combined output beam behind the combiner grating as a function of diode current. The BPP values correspond to a power content of 95%. The BPP in the beam-combining FA is $1.35 \text{ mm} \times \text{mrad} \ (M^2 \approx 4.5)$ at a diode current of 20 A. The FA-BPP shows a strong dependence on diode current and reaches a value of about $3.1 \text{ mm} \times \text{mrad} \ (M^2 \approx 10.3)$ at the maximum operation current of 140 A. The BPP in SA shows a typical linear dependency on diode current. At low currents, the BPP is approximately $2.1 \text{ mm} \times \text{mrad}$. At the maximum operation current, the SA-BPP of the combined beam is $5 \text{ mm} \times \text{mrad}$. Here again, no significant impact of the wavelength stabilization in the external cavity on the SA-BPP of the emitter sub-beam can be observed in the experiments. As in case of the transmission grating based external cavity (see section 3.2.2), the SA-BPP of the combined output beam corresponds in a good approximation to the SA-BPP of an individual stabilized diode bar emitter.

3.3.4. Optical feedback and spectral characteristics

Based on the theoretical preliminary considerations of the spectral transmission characteristic of a TFF in section 3.3.1 and the experimental results, presented in the previous section, the optical feedback and spectral characteristics of the
external TFF multi-laser cavity will be investigated in the following in more detail. Figure 3.27a shows a measurement of the stabilized spectrum of the cavity output of an individual emitter of the laser diode bar (bar A) at two different operation currents. The 4\(\sigma\)-linewidth was measured using a high-resolution spectrometer (HighFinesse HDSA; 40-pm spectral resolution at \(\lambda = 960\,\text{nm}\)). As in

![Graph showing wavelength vs. normalized intensity](image1)

![Graph showing emitter current vs. SA-BPP](image2)

**Fig. 3.27:** (a) Stabilized spectrum of the cavity output of an individual emitter and linewidth broadening with increasing emitter current. (b) Residual spectral emitter linewidth \(\delta \lambda\) and SA-BPP vs. emitter current.

case of the transmission grating based cavity, a broadening of the stabilized emitter linewidth is observable with increasing emitter current. At an emitter current of 2.1 A, the linewidth is 121 pm. The linewidth increases to a value of 134 pm at 7.4 A. As already mentioned, a potential explanation for the dependency of the stabilized spectral emitter linewidth on emitter operation current are higher order lateral modes of the radiated electric field in SA with increasing emitter current which prevent narrowband spectral operation of the diode emitter in the external cavity. The measured spectral emitter linewidth and the corresponding SA-BPP, which indicates the increasing lateral modality of the radiated electrical field of the emitter, as a function of emitter current are shown in Fig. 3.27b. Furthermore, as a comparison, the corresponding coupling bandwidth of the external TFF multi-laser cavity is plotted. The coupling bandwidth has been calculated on the basis of Eq. (3.16) by replacing the angular dispersion of the grating by the angular dispersion of the TFF [see Eq. (3.35)]. The data show that again both the emitter linewidth and the SA-BPP linearly evolve with increasing diode current. For low emitter currents the linewidth is approximately 100 pm and thus below the calculated coupling bandwidth limit. With increasing current the SA-
BPP gets larger which leads to a significant increase of the emitter linewidth. A correlation between both quantities is clearly visible. The linewidth at high currents (>4 A) approaches the value of the coupling bandwidth. At two emitter currents, the measured linewidth crosses the coupling bandwidth limit which can be explained by the limited spectral resolution of the spectrometer. Another important point concerns the shape of the spectral emitter line. The spectral emitter line in Fig. 3.27a shows no dip in the spectrum in the region of the stabilized central wavelength at both currents. From theory, one would expect a dip in the stabilized emitter spectrum which is reflected out of the external cavity according to the transmission bandwidth of the TFF [50 pm (FWHM) resp. 85 pm (4σ)] which has been presented in Fig. 3.19b. Furthermore, the residual spectral emitter linewidth in the range of 110 pm to 135 pm (4σ) cannot explain the small relative power loss of wavelength stabilization in the external cavity of <15 % (see Fig. 3.25), since both quantities differ only by a factor of about 1.4. In this case, a significantly larger relative power loss (≈70 %) of the free-running laser output compared to the stabilized cavity output is expected, due to a large amount of optical feedback. Both mentioned discrepancies between experiment and theory are related to the laterally inhomogeneous spacer thickness of the TFF, which results in a spatially varying spectral transmission characteristic of the incident emitter sub-beam.

Before analyzing the impact of the laterally inhomogeneous spacer thickness of the TFF on the optical feedback and spectral characteristics of the external cavity, the experimentally deduced feedback ratio, provided by the external cavity, is investigated. In order to determine the optical feedback ratio inside the external cavity during ongoing laser diode bar operation, a measurement setup is used which is shown in Fig. 3.28. For this purpose, the HR in the feedback branch of the external cavity is replaced by a PRM with known spectral transmission properties for TE polarization. At a wavelength of 963 nm, where the stabilized central

![Fig. 3.28: Schematic setup for the measurement of the optical feedback ratio provided by the TFF multi-laser cavity for the complete bar and an individual emitter.](image-url)
wavelength of the diode bar is located, the transmission of the PRM is 2.2%. A beam block in front of the laser diode bar enables the operation of an individual emitter inside the external cavity. For the simultaneous measurement of the optical power at the three indicated measurement locations, respectively one PM is used. From the measured stabilized output power \( P_1 \) and the powers measured behind the PRM \( (P_2) \) and at the location of the beam block \( (P_3) \), the feedback ratio with reference to the incident laser power at the location of the TFF can be deduced and is given by (see appendix A):

\[
\frac{P_{FB}}{P_{in}} = \frac{P_2 \cdot \tau - P_3}{P_1 \cdot T_{TE,PRM}(\lambda) + P_2} \cdot \tau \quad \text{with} \quad \tau := T_{TE,PRM}(\lambda)^{-1} - 1. \quad (3.37)
\]

In the upper equation, \( T_{TE,PRM}(\lambda) \) is the spectral transmission coefficient of the PRM for TE-polarized power fractions. Figure 3.29a shows the deduced feedback ratio as a function of diode current for the complete diode bar (bar A) and an individual central emitter. At a diode current of 100 A, the deduced feedback ratio amounts to 9% for the complete bar and about 8% for the individual stabilized emitter. In the region from 80 A to 120 A, the feedback values of the complete bar and the individual emitter are, in a good approximation, consistent. Beyond this range, the deduced feedback ratio significantly deviates and shows a current-dependent course. The reason for this deviation is most likely related to the measurement errors of the optical powers using three PMs in conjunction

![Fig. 3.29: (a) Deduced optical feedback ratio vs. diode current for the complete laser diode bar (bar A) and an individual stabilized emitter. (b) Spectra of an individual stabilized emitter at the location of the cavity output, the PRM and the beam block at an emitter current of 5.3 A.](image-url)
with the one order of magnitude differing power levels for both measurements. The deduced feedback ratio of smaller than 10% is an additional indication for a changed spectral transmission characteristic of the TFF compared to the theoretically expected performance. Figure 3.29b shows the measured spectra of an stabilized individual emitter at the locations of the optical power measurements for the deduction of the optical feedback ratio at a diode current of 100 A. The emitter spectra of all measurement channels show a comparable course and similar spectral bandwidths in the range of 72 pm to 83 pm (FWHM). The spectrum behind the PRM, which corresponds to the transmitted spectrum of the TFF, is not significantly different compared to the spectrum of the stabilized cavity output. The spectrum of the loss channel in the feedback branch at the location of the beam block is shifted by 25 pm to a smaller central wavelength. The presented spectra will later be used for a qualitative comparison with the theoretically calculated spectra and transmission characteristics of the external cavity including the laterally inhomogeneous spacer thickness of the TFF.

The spatially resolved spacer thickness and the spectral transmission characteristic of the TFF were investigated using the measurement setup which is depicted in Fig. 3.30. As laser source for the measurements, the collimated output beam of a fiber-coupled laser diode with a wavelength of 1030 nm and a spectral bandwidth of 40 pm (FWHM) is used. The collimated output beam is first incident upon a PBS to realize a well-defined TE polarization state of the input laser beam with reference to the plane of incidence at the TFF. Behind the PBS, the beam is expanded by use of a telescope with 3x magnification. The telescope consists of two spherical lenses. The collimation of the beam behind the telescope is verified by a shearing interferometer plate. The laser beam, which is incident upon the TFF, has a beam diameter which is larger than the optical aperture of the TFF.

![Fig. 3.30: Schematic setup for the measurement of the laterally varying spacer thickness and the spectral transmission characteristic of the TFF.](image-url)
Consequently the complete surface of the optical component is illuminated. The TFF is mounted on a rotation stage which allows for a precise angular alignment of the filter with reference to the optical axis of the incident laser beam. Behind the filter, a black anodized screen is located which is illuminated by the transmitted laser beam of the TFF. The surface of the screen exhibits a laser-engraved rectangular target grid which is used for a length calibration of the CCD camera picture. The transmitted laser beam upon the screen is monitored by a CCD camera which is equipped with an objective lens with manually adjustable focus. Figure 3.31 shows the CCD camera images of the transmitted laser beam on the screen for different AOIs $\Theta$ upon the filter. As a reference, the dashed red circle indicates the dimension of the filter. In case of a lateral homogeneous spacer thickness it is expect that the resonant transmission of the beam occurs exclusively for one individual AOI upon the TFF which is described by Eq. (3.33). Furthermore, the transmission is expected to occur homogeneously distributed over the complete illuminated area of the filter. Contrary to that, the CCD camera pictures show a ring-shaped structure of the transmitted beam, whose radius depends on the specific AOI of the incident laser beam upon the TFF. The observed circular transmission of the input beam is related to a laterally varying spacer thickness of the filter which results from the manufacturing process by magnetron sputtering. The laterally inhomogeneous spacer thickness is the reason why an angle-dependent transmission of the filter is observable at varying lateral locations. In the center of the filter, the thickness $d_{FP}$ is maximal. Consequently, according to Eq. (3.33), the transmission for a fixed wavelength occurs at the largest AOI, as can be seen in Fig. 3.31. If the AOI is decreased, the transmission can only take place at locations where the thickness is smaller in such a way that the condition of Eq. (3.33) is fulfilled. The presented measurements in Fig. 3.31 clearly show a symmetrical lateral decrease of the spacer thickness with decreasing AOI, which results in a ring-shaped structure of the transmitted beam. The width of the transmitted ring-shaped beam depends on the linewidth of the incident laser beam. The presented data enable a determination of the spacer thickness of the TFF as function of the lateral position upon the filter. The spacer thickness $d_{FP}$ for the corresponding AOI $\Theta$ follows from Eq. (3.28) by employing the wavelength $\lambda = 1030\text{ nm}$ of the incident laser beam and the effective refractive index $n_{FP} = n_{TFF,eff} \approx 1.63$ of the filter. The lateral position of the transmitted light can be deduced from the CCD camera pictures by using the laser-engraved rectangular target grid with a edge length of 1 cm for length calibration. Furthermore, the specific AOI has to be taken into account for a correct determination of the lateral position, due the resulting projection effect when the filter is rotated. The resulting data of the deduced spacer thickness as a function of the lateral position upon the TFF are shown in Fig. 3.32. The
Fig. 3.31: CCD camera pictures of the transmitted laser beam on the screen behind the TFF for different AOIs $\Theta$ upon the filter. As a reference, the dashed red circle indicates the dimension of the filter.

Fig. 3.32: Deduced spacer thickness vs. lateral position upon the TFF resulting from the analysis of CCD camera pictures shown in Fig. 3.31.
3.3. Thin-film filter multi-laser cavity

Spacer thickness shows a symmetrical lateral decrease of about 1.1 nm from the center to a lateral position of ±10 mm. The lateral varying spacer thickness is well described by a second order polynomial curve fit of the form

\[ d_{FP}(r_{TFF}) = A_0 + A_1 \cdot r_{TFF} + A_2 \cdot r_{TFF}^2, \]

where \( r_{TFF} = \sqrt{x^2 + y^2} \) being the radial position upon the filter.

Based on the measurement presented in Fig. 3.32, the spectral transmission characteristic of the filter has been simulated. Furthermore, by using the calculated spectral spatial transmission of the filter, the optical feedback ratio and the stabilized emitter spectra are calculated and compared with the measurement results which have been presented in Fig. 3.29. According to Eq. (3.23), the spectral transmission coefficient \( T_{FP} \) of the TFF is given by:

\[ T_{FP} = \frac{1}{1 + F \sin^2(\delta_{FP}/2)}. \]

Due to the laterally inhomogeneous spacer thickness \( d_{FP}(r_{TFF}) \), the geometrical phase difference \( \delta_{FP} \) [see Eq. (3.22)] exhibits an additional dependency on the radial position \( r_{TFF} \) upon the filter and can thus be describes as

\[ \delta_{FP} = \frac{4\pi n_{TFF,eff}}{\lambda} \sqrt{1 - \left[ \frac{\sin(\Theta)}{n_{TFF,eff}} \right]^2}, \]

where again Snell’s law has been applied to express the phase difference as a function of the AOI \( \Theta \) of the incident laser beam. Consequently, the spectral transmission coefficient \( T_{FP}(\lambda, r_{TFF}, \Theta) \) of the TFF is a function of wavelength \( \lambda \), radial position \( r_{TFF} \) and AOI \( \Theta \). Figure 3.33 shows the calculated spectral transmission coefficient \( T_{FP}(\lambda) \) as a function of the lateral position upon the TFF for an AOI of \( \Theta = 40^\circ \). The calculations were carried out using the deduced polynomial curve fit of Fig. 3.32 for the dependency of the spacer thickness on the lateral position upon the filter. Furthermore, an effective index of \( n_{TFF,eff} \approx 1.63 \) has been used, according to the effective index model which has been discussed in section 3.3.1. The factor \( F \) in Eq. (3.39) follows from the Eqs. (3.29) and (3.25) by employing the spectral transmission bandwidth \( \Delta \lambda_{FP,FWHM} = 50 \) pm of the TFF layer design. The simulation results clearly show that the laterally inhomogeneous spacer thickness strongly affects the transmission characteristic of the filter. Two effects are observable from the data presented in Fig. 3.33. First, the transmission bandwidth is strongly increased to about 175 pm (FWHM) compared to the calculated transmission bandwidth of 50 pm (FWHM) of an ideal filter with laterally homogeneous spacer thickness (see Fig. 3.19b) and shows an asymmetrical shape. The transmission wavelength for a fixed lateral position are smeared out to smaller
wavelengths. Second, the resonant wavelength for maximal transmission shows a dependency on the lateral position upon the filter which leads to a bending of the transmission band. Originating from the center of the filter, the resonant wavelength shifts to smaller wavelengths. At a lateral position of ±5 mm, the absolute decrease of the resonant wavelength is approximately 1 nm with reference to the resonant wavelength of 953 nm in the central position. In a next step, the calculated spectral transmission characteristic is used to calculate the transmitted and reflected spectral spatial intensity distribution of an emitter sub-beam which is incident upon the TFF in the external laser cavity of Fig. 3.22. In general, the transmitted \( P_T \) and reflected \( P_R \) power fractions of the input laser power \( P_{in} \) and the power \( P_{FB} \) of the optical feedback can be expressed in the following way:

\[
P_T = \int \int \int J_\lambda(\lambda) \cdot J_{SA}(y) \cdot J_{FA}(x) \cdot T_{FP}(\lambda, x, y) \, dx \, dy \, d\lambda \quad (3.41)
\]

\[
P_R = P_{in} - P_T \quad (3.42)
\]

\[
P_{FB} = \int \int \int J_\lambda(\lambda) \cdot J_{SA}(y) \cdot J_{FA}(x) \cdot T_{FP}^2(\lambda, x, y) \, dx \, dy \, d\lambda \ . \quad (3.43)
\]

In the upper equations, the normalized spectrum of the stabilized emitter sub-beam is denoted by \( J_\lambda \). \( J_{FA} \) and \( J_{SA} \) represent the corresponding normalized spatial intensity distribution of the beam along the horizontal FA and vertical SA direction at the location of the TFF, respectively. The emitter spectrum is assumed to have a Gaussian shape \( J_\lambda(\lambda) = \exp\left\{-2[\lambda/(\delta\lambda/2)]^2\right\} \) with a 4σ-
3.3. Thin-film filter multi-laser cavity

width $\delta \lambda$ given by the residual spectral emitter linewidth. The beam profile in FA and SA are assumed to have a Gaussian intensity distribution $J_{FA}(x) = \exp[-2(x/\omega_{TFF,FA,em})^2]$ and $J_{SA}(y) = \exp[-2(y/\omega_{TFF,SA,em})^2]$ with a $4\sigma$-width which corresponds to the respective beam diameter $2\omega_{TFF,FA,em}$ and $2\omega_{TFF,SA,em}$ upon the filter. The latter assumption truly holds for the nearly diffraction-limited beam in FA, but only constitutes an approximation for the top-hat-like beam profile in the multi-mode SA beam dimension. Furthermore, in the expressions of the Eqs. (3.41) to (3.43) it is implicitly assumed that the angular spectrum of the far-field intensity distribution of the incident emitter sub-beam in both beam axis has a negligible impact on the calculations. This approximation can be justified by the following facts. The far-field divergence of the beam in the beam-combining FA is indirectly incorporated in the calculations by the spectrum of the stabilized emitter and the resulting residual spectral emitter linewidth. Furthermore, the TFF is located in the beam waist of the emitter sub-beam in FA behind the transform lens in the external laser cavity, where the beam divergence is a factor of about $f_{TL}/f_{FAC} = 1200$ smaller compared to the AOI upon the filter ($\Theta \approx 40^\circ$). In the vertical SA beam dimension slightly different conditions take place. At the location of the TFF, the beam in the SA direction does not pass its beam waist. The beam divergence $\theta_{TFF,SA,em}$ is about $17$ mrad ($\approx 1^\circ$) assuming a SA-BPP of $4 \text{ mm} \times \text{mrad}$. Due to the significant beam divergence in SA, an AOI $\Theta_{eff}$ upon the TFF can be defined (see Fig. 3.34) which describes the resulting effective AOI by combining the angles of both beam axis. The calculation of the effective AOI

![Fig. 3.34: Geometry of the incident emitter sub-beam upon the TFF and definition of the effective AOI $\Theta_{eff}$.
](image-url)
by use of standard trigonometric relations (see appendix C) yields the following expression:

\[
\Theta_{\text{eff}} = \arccos \left\{ \frac{\cos(\Theta)}{\sqrt{1 + \tan^2(\theta_{TFF,SA,em})}} \right\}.
\]  

(3.44)

Based on Eq. (3.44) and the mentioned experimental parameters, a value for \(\Theta_{\text{eff}}\) is obtained which deviates by a factor of only \(6 \times 10^{-5}\) compared to the AOI of \(\Theta \approx 40^\circ\). Due to the mentioned facts and estimations, it can be expected that the beam divergence of the emitter sub-beam in both beam axis has a negligible impact on the spectral transmission characteristic of the filter and the optical feedback strength provided by the external laser cavity. In a first step, the expressions of the Eqs. (3.41) to (3.43) are used to calculate the corresponding spectral spatial intensity distributions of an incident wavelength-stabilized emitter sub-beam. As input values for the simulation, the experimental parameters which are listed in Table 3.1 are used. The listed parameters correspond to the experimental configuration and results which have been presented in the Figs. 3.27 and 3.29. In order to obtain the spectral spatial intensity distributions along the horizontal FA dimension, which are depicted in Fig. 3.35, the integration has only been carried out in the vertical SA beam direction (y-axis). Figure 3.35a shows the normalized intensity distribution of the incident emitter sub-beam as a function of the horizontal FA position and wavelength according to the experimental parameters of Table 3.1. Figures 3.35b and 3.35c show the spectral spatial beam profiles of the transmitted and reflected beam, which have been calculated based on the Eqs. (3.41) and (3.42) using the deduced laterally varying spacer thickness of Fig. 3.32. The spectral spatial intensity distribution of the feedback beam after the second transmission at the TFF follows from

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOI (\Theta) (°)</td>
<td>37.2</td>
</tr>
<tr>
<td>Stabilized wavelength (\lambda_c) (nm)</td>
<td>963</td>
</tr>
<tr>
<td>Linewidth (\delta \lambda) (pm)</td>
<td>136 (4(\sigma))</td>
</tr>
<tr>
<td>FA beam diameter (2\omega_{TFF,FA,em}) (mm)</td>
<td>5 (4(\sigma))</td>
</tr>
<tr>
<td>SA beam diameter (2\omega_{TFF,SA,em}) (mm)</td>
<td>6 (4(\sigma))</td>
</tr>
</tbody>
</table>
3.3. Thin-film filter multi-laser cavity

Eq. (3.42) and is depicted in Fig. 3.35d. The simulation results of Fig. 3.35 clearly show that the laterally inhomogeneous spacer thickness of the TFF strongly affects the spectral spatial beam profile of the transmitted and reflected beam. A significant transmission (19.2%) of the incident intensity occurs only in a small spectral spatial interval around the central wavelength and the central horizontal position. The border areas of the spectral spatial intensity distribution of the input beam are off-resonant with respect to the local resonance wavelength of the

![Fig. 3.35: Calculated spectral spatial intensity distributions of an incident wavelength-stabilized emitter sub-beam at the location of the TFF. Normalized intensity vs. horizontal FA position vs. wavelength for (a) the incident beam, (b) the transmitted beam, (c) the reflected beam and (d) the feedback beam. The respective spectral spatial intensity distribution is normalized using the maximum of the input beam intensity.](image-url)
filter. As a consequence, these power fractions are reflected by the TFF. Figure 3.36 shows the corresponding calculated spectra of the transmitted beam, the reflected beam and the feedback beam. The spectra were calculated based on the presented data of Fig. 3.35 by carrying out the integration along the horizontal FA direction (x-axis). Furthermore, the spectrum at the location of the beam block has been calculated, which is given by the complementary spectrum with respect to the spectrum of the transmitted beam and the feedback beam. The presented calculated spectra can be used for a qualitative comparison with the experimentally measured spectra shown in Fig. 3.29b. Here, the measured spectrum of the cavity output corresponds to the calculated spectrum of the reflected beam and the measured spectrum behind the PRM complies with the calculated spectrum of the transmitted beam. In accordance with the measured spectrum of the cavity output, the calculated spectrum of the reflected beam shows no dip in the spectrum. Both the spectral shift of about 50 pm between the calculated spectrum of the reflected and transmitted beam and the resulting slightly asymmetrical shape are not visible in the presented measured spectra. This is most likely due to the limited spectral resolution of the spectrometer. However, the theoretically predicted spectral shift of the spectral line at the location of the beam block compared to the spectrum of the reflected beam is consistent with the experiment. A further comparison between the experimental results and the theoretical calculations is enabled by the calculation of the optical feedback.
ratio. By spectrally integrating the calculated spectrum of the feedback beam in Fig. 3.36, a feedback ratio of 11.2% with reference to the power of the input beam is obtained. The calculated feedback ratio lies in the same range as the experimentally deduced value for an individual emitter at large emitter currents (10%) resp. complete diode bar at low diode currents (12%), which has been presented in Fig. 3.29a. In summary, a qualitative good agreement between the theoretical calculations and the experiment could be obtained. The presented results of the calculation of the spatial spectral transmission and the optical feedback characteristics of the TFF multi-laser cavity clearly show that the laterally inhomogeneous spacer thickness is the reason why small optical feedback ratios below 15% can be achieved even for a residual spectral emitter linewidth which compares to the theoretical transmission bandwidth of 50 pm (FWHM) of an ideal device with a spatially homogeneous spacer thickness. As a direct consequence of the described effect, the optical feedback ratio depends, besides the residual spectral emitter linewidth, both on the position and the beam diameter of the input beam upon the filter. The calculated dependency of the optical feedback ratio on both values is presented in Fig. 3.37. The calculated optical feedback ratio as a function of the lateral position of the input beam with reference to the center of the filter is depicted in Fig. 3.37a. The presented curve shows that even for a small deviation of the position of the input beam from the center of the filter of ±2 mm, the feedback ratio significantly decreases to about half of the value in the center. A qualitatively similar dependency can be observed from the measured experimental data shown in Fig. 3.37b. The deviation of the position of the input beam from the center of the filter is a first explanation for the differing experimentally deduced and theoretically calculated values of the optical feedback ratio. The second explanation approach concerns the beam diameter of the input beam upon the filter. As shown in Fig. 3.37c, an increasing beam diameter leads to a decreasing feedback ratio, since the input beam experiences a larger fraction of the inhomogeneity of the spacer layer. Differing beam diameters in the beam-combining axis of an individual emitter compared to the complete diode bar can be the result of diode bar smile, as discussed in section 3.2.3.2. Consequently, diode bar smile is a potential explanation for the measured different feedback ratio of an individual emitter compared to the feedback ratio of the complete diode bar, as presented in Fig. 3.29. Based on the previous theoretical considerations, the measured current-dependent decrease of the feedback ratio of the complete diode bar can be related to two experimental observations, which are an increasing residual spectral linewidth of the wavelength-stabilized emitters (see Fig. 3.27b) in conjunction with an increasing beam diameter of the emitter sub-beams in SA upon the TFF with increasing diode current. The enlarged beam diameter in SA is a direct consequence of the increasing SA-BPP with increas-
3. Dense Wavelength Beam Combining in External Laser Cavities

Fig. 3.37: (a) Calculated optical feedback ratio vs. lateral position of the input beam upon the TFF with reference to the center of the filter. (b) Experimentally deduced optical feedback ratio vs. lateral position upon the TFF with reference to the center of the filter for a complete diode bar (bar A) at a diode current of 40 A. (c) Calculated feedback ratio vs. FA beam diameter $2\omega_{TFF,FA,em}$ at the location of the TFF. The input beam position corresponds to the center of the filter.

Due to the dependency of the optical feedback ratio on both the residual emitter linewidth and the beam diameter of the emitter sub-beams upon the TFF, the feedback ratio depends on the focal length of the transform lens in the external laser cavity. The focal length of the transform lens determines the beam diameter of the input beam in FA upon the filter and furthermore, according to Eq. (3.16), the coupling bandwidth of the external laser cavity which constitutes an upper limit for the resulting stabilized emitter linewidth. Figure 3.38a shows the calculated feedback ratio as a function
of the focal length $f_{TL}$ of the transform lens for an individual emitter of bar A, which is stabilized at a central wavelength of $\lambda_c = 953\,\text{nm}$ corresponding to an AOI of $\Theta = 40^\circ$ upon the TFF. The calculated coupling bandwidth $\delta \lambda_{cb}$ and the corresponding projected FA beam diameter $2\omega^*_{TFF,FA,em} = 2\omega_{TFF,FA,em}/\cos(\Theta)$ as a function of the transform focal length are depicted in Fig. 3.38b and serve as input values for the theoretical calculation. As before, the SA beam diameter is kept at the value given in Table 3.1. The presented data in Fig. 3.38a show that the feedback ratio increases with increasing transform focal length for focal lengths $f_{TL} < 400\,\text{mm}$, since the decrease in coupling bandwidth overcompensates the increase of the beam diameter. A maximum of about 17\% is reached at a transform focal length of $f_{TL} = 500\,\text{mm}$. For larger focal lengths, the feedback ratio decreases, since the increase of the beam diameter is more pronounced than the decrease of the coupling bandwidth. The presented values of the optical feedback ratio for an individual emitter correspond to the case of an ideal system and thus constitute an upper limit for the feedback ratio. As already discussed, a lower actual feedback ratio can be the result of a deviation of the input beam position from the center of the filter and an increased beam diameter upon the filter due to diode bar smile.
3.3.5. Beam quality deterioration

The presented results of the BPP of the combined output beam in Fig. 3.26 show that, as in case of the transmission grating based cavity, the output beam quality in the beam-combining FA is significantly larger compared to the diffraction-limited ($M^2 = 1$) value of an individual unstabilized emitter ($BPP_{FA,em} \approx 0.31 \text{ mm} \times \text{ mrad at } \lambda = 960 \text{ nm}$). Besides, the presented data also show a dependency of the FA-BPP on diode operation current. The deviation of the beam quality in the beam-combining axis from the ideal diffraction-limited value can be related to four main beam quality deterioration mechanisms, which are the residual spectral linewidth of the stabilized emitters, beam distortion due to the spatial spectral filtering of the TFF, diode bar smile and the dispersion mismatch between the TFF and the combiner grating in case of large stabilized spectral bandwidths. In analogy to the discussion in section 3.2.3, the resulting BPP in beam-combining FA can consequently be expressed as

$$BPP_{FA} = \omega_{G,FA} \cdot \theta_{G,FA}$$

$$= (\Delta_{\text{linewidth}} \cdot \Delta_{bd} \cdot \Delta_{\text{smile}} \cdot \Delta_{\text{dm}}) \cdot BPP_{FA,em} \cdot \Delta$$

where $\omega_{G,FA}$ describes the beam waist radius of the emitter sub-beams upon the combiner grating and $\theta_{G,FA}$ represents the corresponding far-field divergence of the combined beam behind the combiner grating. The factor $\Delta$ in Eq. (3.45) captures the contributions of the four mechanisms to the deterioration of the beam quality $BPP_{FA,em}$ of the free-running emitter. Again, the contribution of the specific mechanism multiplicatively enters Eq. (3.45), since each effect affects only either the beam waist radius or the far-field divergence of the combined beam. As observed in the measured spectrum of the wavelength-stabilized output beams presented in Fig. 3.24, spectral emitter cross-talk is not present in the external TFF multi-laser cavity. Consequently, the beam quality deterioration factor $\Delta_X$ due to spectral emitter cross-talk can be omitted in Eq. (3.45). The impact of the residual spectral emitter linewidth and diode bar smile on the beam quality of the combined beam are identical to the case of the transmission grating based cavity. This is the reason why the corresponding results of the sections 3.2.3.1 and 3.2.3.2 can directly be transferred and adopted in the following considerations. The assumption is valid due to the following two facts and approximations. First, assuming identical transform focal lengths, the coupling bandwidth in the external TFF multi-laser cavity is, according to Eq. (3.16), a factor of about two smaller compared to the transmission grating based cavity due to the higher angular dispersion of the TFF. This results in a smaller residual
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spectral emitter linewidth. But the imaging of the dispersion-matching telescope simultaneously decreases the beam divergence of an individual emitter sub-beam upon the combiner grating by the same factor. Because of that, the ratio of the residual linewidth of the stabilized emitter to the emitter beam divergence at the combiner grating stays in a good approximation unchanged. As a consequence, the beam quality deterioration factor $\Delta_{\text{linewidth}}$, described by Eq. (3.19), remains the same. Second, assuming an ideal imaging of the dispersion-matching telescope without additionally induced beam pointing errors, the considerations concerning beam quality deterioration due to diode bar smile are also valid in case of the TFF multi-laser cavity. An ideal telescope images the near-field intensity distributions of the incident emitter sub-beams in the focal plane of the Fourier transform lens upon the combiner grating which is located in the focal plane of the second lens of the telescope. Thus, the corresponding beam diameters are scaled according to the magnification of the telescope. The beam offsets in the near field of the emitter sub-beams compared to each other, which are induced by diode bar smile, are likewise transformed by the telescope. Consequently, the dispersion-matching telescope will increase both the beam diameter of the individual emitter sub-beam and the beam diameter of the complete emitter beam ensemble in the same way and the beam quality deterioration factor $\Delta_{\text{smile}}$, described by Eq. (3.19), can directly be applied. Deviations from an ideal imaging of the telescope are for example related to spherical lens aberrations in the telescope which can potentially be the reason for a larger smile-induced BPP deterioration factor compared to the results which have been presented for the transmission grating based cavity.

As indicated by Eq. (3.45), two additional factors have to be considered in case of the external TFF multi-laser cavity. The factor $\Delta_{\text{bd}}$ describes the beam quality deterioration due to the beam distortion by the spatial spectral filtering of the TFF in the external cavity, whereas the factor $\Delta_{\text{dm}}$ accounts for the impact of the dispersion mismatch between the TFF and the combiner grating on the BPP of the combined cavity output. In the following, both mechanisms are investigated in detail.

3.3.5.1. Beam distortion

Beam distortion due to the spatial spectral filtering of the TFF is an effect which affects the beam quality of each individual gain element in the beam-combining FA direction. The beam distortion is related to the spatially dependent transmission of the incident emitter sub-beam at the location of the filter, which results from the laterally inhomogeneous spacer thickness which has been discussed in section 3.3.4. The inhomogeneous TFF represents a spatially spectrally apodized diffraction aperture leading to a near and far field modifi-
cation of each stabilized emitter. Both the increased effective near-field beam diameter due to the distorted spatial intensity distribution and the increased far-field divergence due to the diffraction at the TFF will deteriorate the BPP of the wavelength-stabilized resonant emitter sub-beam which is reflected at the TFF. In order to experimentally prove this hypothesis, Fig. 3.39a shows the measured FA-BPP as a function of emitter current of an individual emitter of bar A for two different experimental configurations. In the first configuration, the BPP of the wavelength-stabilized emitter beam is measured behind the combiner grating in the cavity architecture of Fig. 3.22. In the second configuration, the BPP of the identical emitter beam is measured after the reflection at the TFF in front of the dispersion-matching telescope, with and without wavelength-stabilization. In order to prevent wavelength stabilization by the external TFF multi-laser cavity, the transmitted beam in the feedback branch of the resonator is simply blocked. At first, the presented results for the emitter beam behind the combiner grating are discussed. The presented data in Fig. 3.39a show that the FA-BPP is about $0.7 \, \text{mm} \times \text{mrad}$ even at the lowest emitter current of 1A and therefore is significantly larger than the deduced maximum value of $\Delta \text{linewidth} \cdot BPP_{FA,em} \approx 0.44 \, \text{mm} \times \text{mrad}$ resulting from the BPP deterioration due to the residual emitter linewidth. Here, a stabilized emitter linewidth

![Fig. 3.39](image-url)

**Fig. 3.39:** (a) Measured FA-BPP vs. emitter current of an individual emitter of bar A behind the combiner grating. Furthermore, the FA-BPP data of the wavelength-stabilized and unstabilized emitter beam in front of the dispersion-matching telescope are shown. (b) CCD camera image of the beam spot behind the grating combiner at an emitter current of 2.1A in the focal plane of a spherical lens with 300-mm focal length.
in the region of the coupling bandwidth, with \( \Delta_{\text{linewidth}}(\delta \lambda = \delta \lambda_{cb}) = \sqrt{2} \), is assumed. The current-dependent increase is, as already explained for the transmission grating based cavity in section 3.2.3.1, related to a tilt of the emitter beam cross section by an angle of about 10° at the location of the combiner grating, which can be seen from the CCD camera image shown in Fig. 3.39b. However, the beam tilt can not explain the deviation of the measured FA-BPP from the theoretical maximum value. Considering the FA-BPP data in Fig 3.39a for the emitter beam in front of the telescope, it is obvious that the wavelength stabilization negatively affects the beam quality of the cavity output. The FA-BPP of the wavelength-stabilized beam is on average deteriorated by a factor of \( \Delta_{bd} = 1.7 \) compared to the FA-BPP of the emitter beam in case of no wavelength stabilization. The presented results clearly prove the impact of wavelength stabilization in the external cavity on the beam quality of an individual emitter beam in the beam-combining axis. As already mentioned, a theoretical explanation for this observation is a distortion of the emitter beam due to the spatial spectral filtering of the TFF, which is only present in case of wavelength stabilization. In the following, the near- and far-field intensity distributions of a resonant emitter sub-beam in the beam-combining FA are theoretically calculated, in order to qualitatively reproduce the experimentally observed beam distortion. For this purpose, one can refer to the theoretical considerations and simulation results of the previous section 3.3.4. At first, the spatial intensity distribution of a wavelength-stabilized emitter beam, which is reflected at the TFF, is considered. The intensity distribution of the reflected beam in the FA direction follows from Eq. (3.42) by omitting the integration in the spatial FA dimension (x-axis). Since only the FA beam profile is of interest, without loss of generality \( J_{SA}(y) = 1 \) is assumed, which makes the integration in the SA beam dimension (y-axis) redundant. The input beam parameters for the calculations correspond to the values which have already been used for simulation of the optical feedback characteristics of the external TFF multi-laser cavity (see Table 3.1). Figure 3.40a shows the calculated normalized spatial intensity distribution of a reflected wavelength-stabilized emitter sub-beam and the normalized beam profile of the input beam at the location of the TFF. The presented beam profiles show that the beam diameter of the reflected beam is effectively broadened compared to the beam diameter \( 2\omega_{TFF,FA,em} \) of the input beam. The ratio of the input beam diameter to the effective beam diameter of the reflected resonant emitter sub-beam can be considered as the beam quality deterioration factor \( \Delta_{bd} \) due to the beam distortion in the near field. The quantitative analysis of the distorted intensity distribution of the reflected beam yields a value of \( \Delta_{bd} = 1.08 \) by calculating the beam diameter for a power content of 95 %. As a next step, the far-field intensity distribution of a reflected resonant emitter sub-beam in the FA direction is calculated by taking diffraction effects into account.
Fig. 3.40: (a) Calculated normalized spatial intensity distribution along the horizontal FA direction of a reflected wavelength-stabilized emitter sub-beam at the location of the TFF. As a comparison, the normalized spatial beam profile of the input beam is shown. (b) Calculated normalized far-field intensity distribution along the horizontal FA direction of a diffracted wavelength-stabilized emitter sub-beam for different slit widths $b_s$ of the spatial aperture provided by the TFF. As a comparison, the normalized far-field beam profile of the input beam is shown.

Based on the simulation results of the Figs. 3.33 and 3.35 it can be concluded that the spatial interval where a significant transmission of a resonant input beam occurs is small compared to the beam diameter upon the TFF of about 5 mm. The spatial interval is limited by the laterally declining spacer thickness of the filter which results in a shift of the resonance wavelength. The spatial region where the transmission coefficient can be approximated to be constant for a fixed wavelength is smaller than 500 $\mu$m. As a consequence, the TFF constitutes a spatial aperture for the input beam. The spatial width of the aperture is determined by the course of the lateral spacer thickness. Depending on the width of the aperture, a diffraction of the input beam takes places which will increase the far-field beam divergence of the resonant emitter beam. In analogy to the diffraction at a slit, an opening function $\Omega_s(x, b_s)$, which describes the spatial aperture distribution of the filter, can be defined. Here, $b_s$ defines the width of the aperture over which the input beam is completely transmitted ($\Omega_s = 1$ for $-b_s/2 \leq x \leq b_s/2$; $\Omega_s = 0$ for $x > b_s/2$ or $x < -b_s/2$). According to the Fraunhofer diffraction, the resulting diffraction pattern in the far-field region is given by the Fourier transform of the aperture distribution [132]. The far-field intensity distribution of the diffracted beam $J_\theta$ ($4\sigma$-width $2\theta_{TFF, FA}$), which is transmitted by the TFF,
follows from the convolution of the diffraction pattern in the far-field region with the Gaussian emitter intensity distribution $J_\theta(4\sigma$-width $2\theta_{\text{TFF,FA,em}})$:

$$J_\theta(\theta; 2\theta_{\text{TFF,FA}}) = \frac{\pi}{2} \int_{-\pi/2}^{\pi/2} \text{FT}[\Omega_s(x, b_s)](\theta_k) \cdot J_\theta(\theta - \theta_k; 2\theta_{\text{TFF,FA,em}}) \, d\theta_k \text{ . } (3.46)$$

In the upper equation, $\theta_{\text{TFF,FA,em}}$ defines the far-field divergence of an emitter sub-beam in the beam-combining FA at the location of the TFF. A resonant emitter beam, which is reflected by the TFF, experiences the complementary aperture distribution compared to the transmitted beam. Since, according to Babinet’s principle, both aperture distributions yield the identical diffraction pattern, Eq. (3.46) is valid for both the transmitted and reflected resonant emitter beam. Figure 3.40b shows the calculated normalized far-field intensity distribution of a reflected wavelength-stabilized emitter sub-beam for different aperture widths using Eq. (3.46). As a comparison, the normalized far-field beam profile of the input beam is shown, whose far-field divergence $\theta_{\text{TFF,FA,em}} = \text{BPP}_{\text{FA}}/\omega_{\text{TFF,FA,em}} = 122 \text{ mrad}$ follows from the beam parameters of Table 3.1 assuming a diffraction-limited FA-BPP. The presented calculated far-field beam profiles in Fig. 3.40b show that, depending on the slit width, the beam divergence of the diffracted reflected beam is significantly increased compared to the beam divergence $\theta_{\text{TFF,FA,em}}$ of the input beam which results in a deterioration of beam quality. The ratio of the input beam divergence to the far-field divergence of the reflected resonant emitter sub-beam can be considered as the beam quality deterioration factor $\Delta_{bd}$ due to the beam distortion in the far field. The quantitative analysis of the far-field intensity distribution for a slit width of $b_s = 400 \mu\text{m}$ yields a value of $\Delta_{bd} = 1.54$ by calculating the width of the far-field beam profile for a power content of 95%. For even smaller slit widths, which correspond to a larger inhomogeneity of the spacer thickness, the beam quality deterioration factor increases. The calculation yields $\Delta_{bd} = 2.45$ ($b_s = 200 \mu\text{m}$) and $\Delta_{bd} = 4.39$ ($b_s = 100 \mu\text{m}$) for the other presented data in Fig. 3.40b. The total beam quality deterioration factor, which accounts for both the beam distortion in the near and far field, is given by the product of the calculated values in the respective case. In conjunction with the calculated factor for the beam distortion in the near field, a total factor of $\Delta_{bd} = 1.66$ follows for a slit width of $b_s = 400 \mu\text{m}$. This result is in good agreement with the experimentally deduced value of $\Delta_{bd} = 1.7$ resulting from the measurement presented in Fig. 3.39a. In conclusion, the experimentally observed beam quality deterioration of an individual resonant emitter sub-beam could be reproduced by the calculations of the near- and far-field intensity distributions. The simulation results prove that the mentioned effects of
beam distortion are the reason for a FA-BPP of an individual emitter sub-beam behind the combiner grating beyond the limit which is determined by the beam quality deterioration due to the residual spectral emitter linewidth.

3.3.5.2. Dispersion mismatch

As previously explained, an exact dispersion-matching between the TFF and the combiner grating is needed for sufficient beam quality preservation of the combined beam in case of large stabilized spectral bandwidths. In the following, the beam quality deterioration factor due to the dispersion-mismatch is numerically calculated in order to quantify the considerations which have been made in section 3.3.2. For this purpose, two different experimental configurations are investigated and compared, which significantly differ in the stabilized spectral bandwidth. The first configuration corresponds to the case of individual-bar experiments using the external cavity architecture of Fig. 3.22. The second configuration corresponds to the case of spectral beam combining a laser diode module consisting of a horizontal stack of ten laser diode bars which is used to realize a high-brightness direct diode laser (see Chapter 4). In order to quantify the beam quality deterioration in the beam-combining FA due to the dispersion mismatch between the TFF and the combiner grating, the far-field intensity distribution $J_{CB}$ of the combined beam has to be calculated, which is given by the sum of the normalized Gaussian intensity distributions $J_i = \exp\left[\frac{-\left(\frac{\theta}{\theta_{G,FA}}\right)^2}{2}\right]$ of the diffracted emitter sub-beams:

$$J_{CB}(\theta; 2\theta_{CB}) = \sum_i J_i(\theta - \Delta\theta_i; 2\theta_{G,FA}) .$$

(3.47)

Each emitter sub-beam has an angle offset $\Delta\theta_i$ according to Eq. (3.36) and a far-field divergence of:

$$2\theta_{G,FA} = 2\theta_{FA,em} \cdot \frac{f_{FAC}}{f_{TL} \cdot M} \cdot \Delta_{\text{linewidth}} .$$

(3.48)

In Eq. (3.48), the FA beam divergence of the uncollimated diode bar emitter is denoted by $2\theta_{FA,em}$ and $2\theta_{G,FA,em}$ represents the far-field beam divergence of an individual monochromatic ($\delta\lambda = 0$) emitter sub-beam in the beam-combining axis behind the grating. The factor $\Delta_{\text{linewidth}}$ [see Eq. (3.19)] accounts for the broadening of the far-field divergence of an individual emitter sub-beam due to the residual spectral linewidth of the wavelength-stabilized emitters which has been discussed in section 3.2.3.1. The ratio of the $4\sigma$-width $2\theta_{CB}$ of the far-
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Field intensity distribution $J_{CB}$ to the beam divergence $2\theta_{G,FA}$ of an individual emitter sub-beam is a measure for the deterioration factor $\Delta_{dm}$ of the BPP in the beam-combining axis:

$$\Delta_{dm} = \frac{\theta_{CB}}{\theta_{G,FA}}.$$  (3.49)

The width $2\theta_{CB}$ has to be numerically deduced by means of Eq. (3.47), whereas the beam divergence $\theta_{G,FA}$ can directly be calculated from Eq. (3.48). The calculation of the beam quality deterioration factor yields $\Delta_{dm} = 1.02$ in case of beam combining of an individual laser diode bar using the experimental beam parameters which have been presented in section 3.3.3 for bar A ($\Delta\lambda = 3.4\,\text{nm}$; $\delta\lambda = 124\,\text{pm}$ ($4\sigma$); $\lambda_c = 963\,\text{nm}$). The calculation has been carried out using a magnification $M = 1.94$ of the dispersion-matching telescope according to the used experimental setup. The factor only slightly increases to $\Delta_{dm} = 1.07$ ($M = 2$) and $\Delta_{dm} = 1.24$ ($M = 1.9$) if the magnification differs from the theoretical optimal value. A further impact on the beam quality deterioration factor is expected if the AOI of the central emitter sub-beam at the combiner grating differs from the Littrow-angle $\beta_L(\lambda_c)$ at the corresponding stabilized central wavelength. Figure 3.41 shows the measured FA-BPP of the combined beam of bar A behind the combiner grating as a function of the grating AOI at a diode current of 20 A. The measured data are normalized with reference to the minimal

![Graph](image)

**Fig. 3.41:** Left axis, measured FA-BPP of the combined output beam of bar A behind the combiner grating vs. grating AOI. Right axis, experimentally deduced and calculated beam quality deterioration factor $\Delta_{dm}$ vs. grating AOI.
value and used for a comparison with the calculated beam quality deterioration factor $\Delta_{dm}$. One can see, that the experimentally deduced values are in good agreement with theory. The presented data in Fig. 3.41 show a parabolic increase of the beam quality deterioration factor $\Delta_{dm}$ with increasing deviation of the grating AOI from the Littrow condition. Within an angular range of $\pm 1^\circ$ around the grating AOI for which the minimal value $\Delta_{dm} = 1.02$ is achieved, the beam quality deterioration factor is $\Delta_{dm} \leq 1.1$. The grating AOI in the minimum is shifted by about 0.6° compared to the Littrow angle $\beta_L(\lambda_c = 963 \text{ nm})$. This observation is related to the changed stabilized central wavelength of the investigated diode bar, which differs from the design wavelength $\lambda_c = 955 \text{ nm}$ of the grating combiner for which the dispersion ratio of the TFF to the combiner grating exactly matches the magnification $M = 1.94$ of the dispersion-matching telescope. In conclusion, the calculations prove that, as expected, the beam quality deterioration due to the dispersion mismatch is negligible in case of small stabilized spectral bandwidths ($\Delta \lambda < 5 \text{ nm}$). A different situation takes place for large stabilized spectral bandwidths, as they occur in case of beam combining an arrangement of multiple diode bars.

Fig. 3.42: Calculated far-field intensity distribution $J_{CB}$ of the combined beam of laser diode module 1b (key parameters see Table 4.2) for two different magnifications $M$ of the dispersion-matching telescope.
3.3. Thin-film filter multi-laser cavity

The theoretical stabilized spectral bandwidth of the laser diode module (module 1b in section 4.1), which was used for the high-power experiments, amounts to \( \Delta \lambda = 42.9 \text{ nm} \) at a central wavelength of \( \lambda_c = 955 \text{ nm} \) (see Table 4.2). The laser diode module consists of a horizontal stack of ten diode bars (bar C in Table 2.1) of which each bar is equipped with a 300-\( \mu \text{m} \) FAC and a commercial BTS. The transform optics in the external cavity provides an effective transform focal length of \( f_{TL,eff} = 565 \text{ mm} \). In the following, this configuration is exemplary used for the calculation and investigation of the beam quality deterioration factor in case of large stabilized spectral bandwidths. The calculations are later used for a comparison with the experimental results in section 4.3. Figure 3.42 shows the calculated far-field intensity distribution \( J_{CB} \) of the combined beam for two different magnifications \( M \) of the dispersion-matching telescope. As a comparison, the far-field intensity distribution for perfect matching \( (\Delta \theta_i = 0) \) is plotted. Furthermore, the far-field intensity distributions of the ten individual bars of the module are shown. As input parameter for the residual stabilized emitter linewidth, the experimentally observed value of \( \delta \lambda = 129 \text{ pm} \ (4\sigma) \) at a diode current of 40A is used. In case of good matching \( (M = 1.94) \), the widths of both distributions are comparable \( (2\theta_{CB} \approx 2\theta_{G,FA}) \). If the magnification is exemplary changed to \( M = 2 \), the simulation shows a significant far-field broadening \( (2\theta_{CB} \gg \theta_{G,FA}) \). One can see

![Figure 3.43](image.png)

Fig. 3.43: Simulation of the beam quality deterioration factor \( \Delta dm \) as a function of the magnification \( M \) of the dispersion-matching telescope for different groove spacings \( \Lambda \) of the combiner grating. The experimental configuration and simulation parameters correspond to the setup and transform optics of laser diode module 1b (key parameters see Table 4.2).
from Fig. 3.42 that the widths of the far-field intensity distributions of the individual bars are not significantly affected by the changed magnification due to the one order of magnitude smaller stabilized spectral interval. The simulations yield a deterioration factor of $\Delta_{dm} = 1.2$ for the ideal magnification ($M = 1.94$). For $M = 2$ the factor is significantly higher ($\Delta_{dm} = 7.6$). Furthermore, the dependency of the factor $\Delta_{dm}$ on the magnification $M$ of the telescope for different groove spacings $\Lambda$ of the combiner grating has been simulated. The simulation result presented in Fig. 3.43, shows that the system sensibly reacts on both parameters demanding for a precisely adjusted magnification of the telescope and a stable performance of the grating at high power levels for sufficient beam quality preservation.

3.3.5.3. Conclusion

The presented results in this section demonstrate that beam quality deterioration in dense wavelength beam-combined BAL diode bars, using the described novel TFF approach for DWBC, can be related to the discussed four main mechanisms in case of beam combining in the fundamental-mode FA beam dimension by use of a micro-optical BTS. As in case of the transmission grating based external cavity, the residual spectral linewidth of the stabilized emitters constitutes a lower limit to the beam quality in the beam-combining axis with a deterioration factor $\Delta_{\text{linewidth}} \leq \sqrt{2}$ compared to the diffraction-limited value ($M^2 = 1$) of an individual free-running emitter ($BPP_{FA,em} \approx 0.31 \text{ mm} \times \text{ mrad}$ at $\lambda = 960 \text{ nm}$). The corresponding results of section 3.2.3.1 can directly be transferred. The same applies to the beam quality deterioration factor due to diode bar smile (see section 3.2.3.2). Assuming an ideal imaging of the dispersion-matching telescope, the demonstrated result of $\Delta_{\text{smile}} \approx 1.2$ for low-smile ($\approx 1 \mu\text{m}$) diode bars is also valid in case of the TFF approach. The experimentally deduced deterioration factor $\Delta_{bd} = 1.7$ due to the beam distortion, which is induced by the spectral filtering of the TFF, could theoretically be reproduced by the calculation of the near- and far-field intensity distributions of a resonant emitter sub-beam. The discussed effects of beam distortion are the reason for a FA-BPP of an individual emitter sub-beam behind the combiner grating beyond the limit which is determined by the beam quality deterioration due to the residual spectral emitter linewidth. The beam quality deterioration due to the dispersion mismatch is negligible ($\Delta_{dm} \rightarrow 1$) in case of small stabilized spectral bandwidths ($\Delta \lambda < 5 \text{ nm}$) using a telescope with appropriate magnification for linear dispersion matching. For larger bandwidths, the deterioration factor sensibly reacts on a deviation of the magnification from the ideal value. In summary, the overall deterioration factor amounts to $\Delta \approx 2.9$ which sets up a minimal value of $\Delta \cdot BPP_{FA,em} \approx 0.9 \text{ mm} \times \text{ mrad}$ ($M^2 \approx 2.9$) for
the resulting BPP in the beam-combining axis. Here, a residual spectral emitter linewidth in the range of the coupling bandwidth of the external cavity is assumed, as it has been observed in the experiment. Furthermore a sufficiently small stabilized spectral bandwidth has been assumed, where the dispersion mismatch can be neglected. Deviations from the minimal value with increasing diode current can again be related to an incomplete beam rotation of the micro-optical BTS and thermally induced beam pointing errors of the emitter sub-beams in the beam-combining axis. For the discussed experimental parameters of laser diode module Ib with increased stabilized spectral bandwidth (\(\Delta \lambda = 42.9\,\text{nm}\)), the calculated beam quality deterioration due to the dispersion mismatch is \(\Delta_{dm} = 1.2\) assuming an ideal telescope magnification \(M = 1.94\). Consequently, the resulting overall deterioration factor is in theory 20\% larger and amounts to \(\Delta \approx 3.5\), subject to the condition that the deployed diode bars exhibit low smile values (\(\approx 1\,\mu\text{m}\)) for which \(\Delta_{smile} \approx 1.2\) can be assumed.
This chapter deals with applying the concepts introduced before to multiple laser diode bars in one cavity in order to demonstrate their capabilities and restrictions in power scaling. The setup of the deployed laser diode modules, the transform optics designs and the epitaxial diode bar placement are explained in section 4.1. In the sections 4.2 and 4.3, the experimental results of the high-brightness kW-class direct diode lasers using the corresponding DWBC approach are presented.

4.1. Laser diode modules

4.1.1. Setup and transform optics design

Two different laser diode module architectures were used to realize a kW-class direct diode laser based on the DWBC approaches which were presented in Chapter 3. Generally, the architectures differ in the form of the transform optics which are used to image the emitter sub-beams of the diode bars onto the dispersive optical element inside the external resonator. The schematic setup of the two laser diode modules is shown in Fig. 4.1. Both modules consist of a horizontal stack of ten BAL diode bars which are mounted on a shared Cu heat sink. The diode bars are connected in series between the contacts of the current supply via Cu contact bridges. In order to provide a free-running optical output power of around 1.5kW, the actively cooled diode bars (bar C in Table 2.1), which were presented in Chapter 2, are used as laser source. Each diode bar exhibits a 300-µm FAC and a BTS which enables FA-DWBC along the direction of the horizontally stacked diode bars. In case of module I, which is depicted in Fig 4.1a, the equidistant horizontal pitch between two adjacent diode bars on the heat sink is 21 mm. Subsequent to the BTS, a cylindrical SAC with 40-mm focal length collimates the emitter sub-beams of each diode bar in SA. The collimated output beams of the diode bars are directed towards the front of the module by HRs to
create an ensemble of coaxially propagating sub-beams. The architecture ensures a maximized spatial FF at the front of the module for a high spectral denseness and equal propagation distances of the emitter sub-beams of the diode bars with respect to each other. The pitch between the output beams of two adjacent diode bars of the module at the front is 12 mm which results in a horizontal spread of the emitter beam ensemble of 116.8 mm along the FA direction. In order to telecentrically image the far field of the coaxially propagating beam ensemble of the module upon the dispersive element of the external resonator, a transform optics design is used which consists of two cylindrical transform lenses with focal lengths $f_{TL1}$ and $f_{TL2}$. The advantage of using a combination of two cylindrical lenses instead of a single transform lens to create the angular spectrum upon the dispersive element is the reduction and compensation of spherical aberrations, since the refraction of the input beams is distributed over several optical interfaces. Due to the large horizontal spread of the output beams of the laser diode module, a single cylindrical transform lens would induce significant spherical aberrations into the optical imaging system even at large transform focal lengths. Hence, the presented multiple-lens transform optics architecture is a cost-effective alternative to more expensive acylindrical transform lens designs. Based on a ABCD matrix
4.1. Laser diode modules

analysis of the optical system (see appendix D), using a paraxial approximation and assuming ideal lenses, the resulting effective transform focal length $f_{TL,eff}$ of the two-lens transform optics configuration is given by

$$f_{TL,eff} = \frac{f_{TL1} \cdot f_{TL2}}{f_{TL1} + f_{TL2} - d_2} ,$$  \hfill (4.1)

where $d_2$ is the distance between the two transform lenses. In order to provide a telecentrical imaging, the distance $d_1$ of transform lens 1 to the front facet of the diode bar and the distance $d_3$ of transform lens 2 to the dispersive optical element have to fulfill the following expressions:

$$d_1 = f_{TL,eff} \left( 1 - \frac{d_3}{f_{TL2}} \right) \quad \text{and} \quad d_3 = f_{TL,eff} \left( 1 - \frac{d_2}{f_{TL1}} \right) .$$  \hfill (4.2)

The two different transform optics configurations which are used in case of module I are listed in Table 4.1. As one can see from the presented parameters, the total distance of the dispersive optical element from the front facet of the diode bar is significantly smaller compared to a telecentrical imaging using a single transform lens in $2f$-configuration with the same effective focal length. Hence,

**Tab. 4.1:** Transform optics configurations of the laser diode modules.

<table>
<thead>
<tr>
<th>Module</th>
<th>Parameter</th>
<th>Ia (mm)</th>
<th>Ib (mm)</th>
<th>II (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_{TL1}$</td>
<td>1250</td>
<td>1100</td>
<td>1100</td>
</tr>
<tr>
<td></td>
<td>$f_{TL2}$</td>
<td>1350</td>
<td>1100</td>
<td>1100</td>
</tr>
<tr>
<td></td>
<td>$d_1$</td>
<td>280</td>
<td>535</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>$d_2$</td>
<td>989</td>
<td>58</td>
<td>1059</td>
</tr>
<tr>
<td></td>
<td>$d_3$</td>
<td>219</td>
<td>535</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>$f_{TL,eff}$</td>
<td>1048</td>
<td>565</td>
<td>1060</td>
</tr>
</tbody>
</table>

another advantage of the two-lens transform optics architecture is the reduced optical assembly space which allows for shorter external resonator lengths and more compact setups. The setup and the transform optics design of module II, which is shown in Fig. 4.1b, differ from the architecture of module I in two points. First, the beam angle of the diode bars is $47^\circ$ with respect to the direction of the horizontal diode bar stack and exhibits no equidistant horizontal pitch. Second, transform
lens 1 is split into ten individual cylindrical lenses which are placed in front of every diode bar itself to further decrease the impact of spherical aberrations on the optical imaging system. Actually, transform lens 1 is a cross-cylindrical lens which simultaneously acts as transform lens in FA and SAC in SA. The HRs are used to direct the output beams towards the front of the module and, in conjunction with transform lens 2, to overlap the emitter sub-beams of every diode bar upon the dispersive optical element. Due to the non-equidistant horizontal diode bar pitch and the requirement of equal propagation distances of the emitter sub-beams of the diode bars with respect to each other, the angular spectrum of the emitter sub-beams at the location of the dispersive optical element is asymmetric and not equally distributed with reference to the optical axis of the external resonator. The specific transform optics configuration for module II can be found in Table 4.1.

4.1.2. Epitaxial diode bar placement

The architecture of the laser diode modules and the effective transform focal length of the corresponding transform optics configuration are selected such that the resulting stabilized spectral interval at a central wavelength \( \lambda_c = 955 \text{ nm} \) is smaller than \( \Delta \lambda = 50 \text{ nm} \). Table 4.2 shows the calculated stabilized spectral intervals \( \Delta \lambda \) of the wavelength stabilized laser diode modules for the corresponding DWBC approach according to the Eqs. (3.12) and (3.34). Furthermore, the resulting projected beam diameters \( (2 \omega^*_G,FA ; 2 \omega^*_TFF,FA) \) of the overlapping emitters upon the dispersive optical element along the FA beam direction are listed which gives a rough estimate for the horizontal dimension of the optical component. The epitaxial diode bar placement plays an important role for the performance of the wavelength beam-combined laser diode module. The placement affects the combined output power, the e-o conversion efficiency and the current-dependent locking performance. For the epitaxial diode bar placement of the laser diode modules, five different epitaxial chip designs are used. The free-running central operation wavelengths are centered around a design wavelength of 938 nm, 946 nm, 954 nm, 962 nm and 970 nm at a diode current of 160 A, respectively. In order to realize a stable locking performance of the diode bars over the whole diode operation current range, the spectral distance between the central wavelength of free-running diode bar output and the wavelength of the spectral channels of the outer emitters of the stabilized diode bar has to be smaller than the spectral locking range of the diode bar emitters at every diode current value to ensure a sufficient overlap with the modal gain spectrum of the active laser medium. As discussed in section 2.2.2, the AR coating of the front facet allows for a spectral locking range of the diode bar emitters of more than 30 nm at an optical feed-
Tab. 4.2: Calculated stabilized spectral intervals $\Delta \lambda$ and projected beam diameters upon the dispersive optical element ($2\omega_{G,FA}^*, 2\omega_{TFF,FA}^*$) of the wavelength stabilized laser diode modules for the transmission grating and TFF approach for DWBC at a central wavelength $\lambda_c = 955 \text{ nm}$ of the stabilized spectrum.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{TL,\text{eff}}$ (mm)</td>
<td>Ia</td>
</tr>
<tr>
<td>$2\omega_{G,FA}, 2\omega_{TFF,FA}$ (mm)</td>
<td>6.1</td>
</tr>
<tr>
<td>$\Delta x$ (mm)</td>
<td>116.8</td>
</tr>
<tr>
<td>$\Delta \alpha, \Delta \Theta$ (mrad)</td>
<td>111.3</td>
</tr>
<tr>
<td>Grating ($\lambda_c = 955 \text{ nm}$)</td>
<td>$2\omega_{G,FA}^*$ (mm)</td>
</tr>
<tr>
<td></td>
<td>$\Delta \lambda$ (nm)</td>
</tr>
<tr>
<td>TFF ($\lambda_c = 955 \text{ nm}$)</td>
<td>$2\omega_{TFF,FA}^*$ (mm)</td>
</tr>
<tr>
<td></td>
<td>$\Delta \lambda$ (nm)</td>
</tr>
</tbody>
</table>

back ratio of 10%. Within the locking range, the power drop of the stabilized emitter is measured to be smaller than 10% and a stable locking performance is expected. This is the reason why the discussed criterion is reasonable to optimize the locking performance of the diode bar array. The maximal WBC efficiency is expected at the current value, where the sum of the wavelength deviation of all bars is lowest. In the ideal case, this current value is in between the current region of the desired operating point of the laser diode module which ensures a maximal e-o conversion efficiency. As an example, Fig. 4.2 shows the epitaxial diode bar placement of laser diode module Ib using the TFF approach for DWBC and module II employing DWBC based on the transmission grating approach, as they were used in the experiment. In case of module Ib (see Fig. 4.2a), two bar slots of the module, respectively, are assembled with diode bars exhibiting identical epitaxial designs. The identical epitaxial diode bar placement is used in case of module Ia for the experiments based on the transmission grating approach for DWBC, since the stabilized spectral intervals are comparable. In both cases, the maximal WBC efficiency is expected at a diode current of 190 A, where the calculated wavelength deviations are lowest. Due to the asymmetrical spectral distribution of the stabilized diode bars and the larger stabilized spectral interval, the epitaxial diode bar placement of module II differs from the configuration of
module I. The three diode bars exhibiting the largest wavelength are assembled with bars from the 970-nm epitaxial design, whereas only one diode bar of the 946-nm design is used (see Fig. 4.2b). The presented epitaxial diode bar placement provides a calculated maximal WBC efficiency at a diode current of 138 A. In case of the DWBC experiments with module II using the TFF approach, the significant smaller stabilized spectral interval enables to reduce the amount of re-
quired different epitaxial chip designs. In particular, five diode bars of the 954-nm and the 962-nm epitaxial design, respectively, are used.

### 4.2. Transmission grating approach

#### 4.2.1. Module Ia

The first high-power experiments, based on the transmission grating approach for DWBC, were performed using laser diode module Ia. The module is assembled with ten actively cooled BAL diode bars (bar C), which exhibit an emitter design with an insulating dielectric layer as current aperture, according to the epitaxial placement presented in Fig. 4.2. The schematic setup of the external laser cavity is shown in Fig. 4.3. In the beam-combining FA dimension, the transform optics design provides an effective focal length of $f_{TL,eff} = 1048$ mm (see Table 4.1). The telescope for cross-talk suppression consists of two cylindrical lenses with focal lengths $f_{X1} = 300$ mm and $f_{X2} = 30$ mm, thus providing a magnification of 10. The telescope is placed in a non-telecentrical configuration. The distance of the

![Fig. 4.3: Schematic setup of the external laser cavity based on laser diode module Ia.](image-url)
first lens of the telescope from the grating is \( z_1 = 50 \text{ mm} \). The distance between the two lenses is given by \( z_2 = f_{X1} + f_{X2} = 350 \text{ mm} \) and the distance from second lens to the OC is \( z_3 = 400 \text{ mm} \). In order to image the beam waist of the emitter sub-beams in SA onto the OC, subsequent to the SAC lens of the laser diode module, two additional cylindrical lenses with focal lengths \( f_{SA1} = f_{SA2} = 500 \text{ mm} \) are used. All emitter sub-beams share a zero-order HWP which is placed in front of the transmission grating. The OC has a reflectivity in the range of 5.3% to 5.7% within the relevant spectral interval of the external cavity (see Fig. 4.4). As in case of the individual-bar experiments, the combined output beam is sent to a variety of diagnostics including a PM, an integrating sphere whose output is fiber-coupled to a high-resolution spectrometer (HighFinesse HDSA; 40-pm spectral resolution at \( \lambda = 960 \text{ nm} \)) and a camera based automatic laser beam profiler (Ophir Photonics; M\(^2\)-200s) for beam quality measurements.

Figure 4.5 shows the spectrum of the combined output beam of the external cavity at a diode current of 60 A. The 230 emitters of the laser diode module are stabilized within a spectral bandwidth of \( \Delta \lambda = 41.5 \text{ nm} \) around a central wavelength of \( \lambda_c = 953.3 \text{ nm} \). The measured data deviate from the theoretically deduced spectral interval (see Table 4.2) by 3.4 nm, since the grating is operated off the initial Littrow configuration with reference to the optical axis. As explained in section 3.2.1, this results in a shifted central wavelength of the stabilized spectrum and a compressed stabilized spectral interval. Figure 4.6 shows the measured stabilized wavelength of the central emitter of the diode bar as function of the bar number. As a comparison, the calculated stabilized wavelengths for a grating operation in Littrow configuration for a central wavelength of 955 nm is plotted.
4.2. Transmission grating approach

**Fig. 4.5:** Spectrum of the combined output beam of the external grating cavity at a diode current of 60 A. The lower part shows an extract of the spectrum to provide a higher resolution of the spectral lines of the individually wavelength-locked emitters.

**Fig. 4.6:** Stabilized wavelength of the central emitter of the diode bar vs. bar number. Comparison between the experimentally deduced data (symbols) and calculated spectral channels (lines) for a grating operation in and off the Littrow configuration with reference to the optical axis.
The measured data are in good agreement with the theoretical expected curve for a grating AOI which differs by 3.7° from the Littrow angle. As a consequence of the larger grating AOI, the stabilized spectral interval is smaller than for a grating which is operated in Littrow configuration. The spectral channel spacing of adjacent emitters is \( \Delta \lambda_{em} = 145 \text{ pm} \) which can be seen in the extract of the stabilized spectrum in Fig. 4.5. The spectral linewidth of the stabilized emitters is \( \delta \lambda = 60 \text{ pm} \) (FWHM). The spectrum shows a high modulation depth and the spectral lines of the individually wavelength-stabilized emitters are completely resolved, which implies that emitter cross-talk is mostly suppressed. However, partially residual upcoming cross-talk wavelengths are visible in the spectrum, e.g. for diode bar 4 and diode bar 9, which are indicated by a reduced modulation depths of the spectral emitter lines of the corresponding stabilized diode bar. Furthermore, some diode bars show initial emitter failures which are not caused by the wavelength stabilization in the external cavity. The stabilized spectrum further indicates that predominantly the long-wave diode bars have a lower intensity compared with the short-wave diode bars and additionally show an asymmetrical shape in the stabilized spectrum. Both observations are the result of the epitaxial diode bar placement. As can be seen from Fig. 4.2, at low diode currents, the stabilized spectral channels of the long-wave diode bars are significantly further shifted from the central wavelength of the free-running diode bar output which results in a reduced modal gain overlap. At higher diode currents, the overlap with the modal gain spectrum is higher due to the thermal wavelength shift of the free-running central wavelength and the locking performance of the long-wave diode bars is significantly improved. Figure 4.7 shows the spectrum of the combined output beam of the external cavity at a diode current of 180 A. The extract in the lower part of Fig. 4.7 shows the spectrum of three bars of the laser diode module at a diode current of 60 A and 180 A, respectively. Due to the increasing residual spectral emitter linewidth with increasing diode current, the modulation depth of the spectral lines is significantly reduced compared to the spectrum at 60 A. With increasing diode current, a very low thermo-optically induced wavelength shift of 60 pm can be observed in the stabilized spectrum. The wavelength shift is in the range of the resolution of the spectrometer and can be estimated to be in the order of 0.1 pm/W with reference to the combined output power of the laser diode module. Due to material absorption of the incident laser power in the substrate, the transmission grating heats to a peak temperature of the radial temperature distribution of more than 65°C at high power levels. Figure 4.8 shows a thermographic camera image of the temperature distribution upon the transmission grating at a diode current of 140 A, which corresponds to an incident laser power of the free-running laser diode module of 1.17 kW. Due to thermal radiation emitted from the beam blocks which block the reflected and
Fig. 4.7: Spectrum of the combined output beam of the external grating cavity at a diode current of 180 A. The extract in the lower part shows the spectrum of three bars of the laser diode module at a diode current of 60 A and 180 A, respectively.

Fig. 4.8: Thermographic camera image of the temperature distribution upon the transmission grating at a diode current of 140 A, which corresponds to an incident free-running laser power of 1.17 kW.
transmitted light at the grating, the radial temperature profile upon the grating is disturbed and not completely resolved in the thermographic camera image. According to Eq. (3.7), the observed spectral shift can be induced by a change of the grating groove spacing or a changed AOI of the emitter sub-beams upon the grating. Since the CTE of fused silica glasses is in the order of $10^{-6}/K$ [137], the impact of the heating of the grating on the change of the groove spacing due to thermal expansion is comparatively low ($\approx 0.002\%$). A greater impact on the wavelength shift is expected from a changed AOI of the emitter sub-beams upon the grating. A changed beam angle in FA with increasing diode current can be the result of thermally induced beam pointing errors of the emitter sub-beams due to a heating of the FAC, as discussed in section 3.2.3.2.

Figure 4.9a shows the output power characteristics and the related e-o conversion efficiencies of the free-running laser diode module and the combined output beam as a function of diode current. At a diode current of 180A, the combined output power is 1.19kW with a corresponding e-o conversion efficiency of 41.3%. The WBC efficiency with respect to the free-running optical output power of the laser diode module is depicted in Fig. 4.9b. Furthermore, the corresponding measured overall relative power loss at the grating with respect to the free-running optical output power is shown. The free-running optical output power of the laser diode module is measured behind transform lens 2. The relative power loss in the op-

![Fig. 4.9:](a) Left axis, optical output power vs. diode current for the free-running laser diode module and the combined output beam. Right axis, corresponding e-o conversion efficiencies vs. diode current. (b) Left axis, WBC efficiency vs. diode current. Right axis, relative power losses at the transmission grating with reference to the free-running optical output power vs. diode current.
tics of the laser module and the transform optics with reference to the aggregated free-running optical output power of the individual laser diode bars are in the order of 4% at a diode current of 180 A and consequently not incorporated in the following considerations. The WBC efficiency is 80% at a diode current of 180 A. At low currents the WBC efficiency is significantly lower due to the discussed decreased modal gain overlap of the long-wave diode bars. As a consequence, the combined output power below 120 A shows a reduced slope efficiency compared to the free-running laser diode module operation and a significantly reduced e-o conversion efficiency. The measured overall relative power loss in the three discussed loss channels at the grating is about 13%. In a good approximation, the grating losses stay constant with diode current variation but are significantly higher compared to the presented results in case of the individual-bar experiment for bar A (see Fig. 3.10b). The higher grating losses can be related to the lower DOP of the deployed diode bars (bar C; insulating layer) and the increased stabilized spectral interval, for which the transmission grating exhibits a lower average diffraction efficiency into the -1st order (see Fig. 3.4). The remaining relative power loss with reference to the free-running optical output power is most likely caused by material absorption and reflection losses at the optical interfaces of the non-high-power optimized coatings and substrates of the optical components inside the external resonator, the output coupling losses at the OC and furthermore by the spectral cross-talk filtering, as discussed in section 3.2.3.3.

The BPP of the combined output beam as a function of diode current is depicted in Fig. 4.10a. The presented BPP values correspond to a power content of 95%. The SA-BPP of the combined cavity output lies within a range of 3.9 to 6.3 mm × mrad and shows a typical linear dependency on diode current. Compared to the results of the individual-bar experiment for bar C presented in Fig. 3.11b, the SA-BPP is about 1 mm × mrad larger at a diode current of 180 A. This deviation can be explained by alignment tolerances of the beam pointing angles in SA in the far field of the output beams of the diode bars compared to each other. At a diode current of 60 A, the FA-BPP is about 0.9 mm × mrad. The FA-BPP shows a linear dependency on diode current and increases to a value of 1.7 mm × mrad at a diode current of 180 A. Consequently, the FA-BPP is deteriorated by a factor $\Delta = 5.7$ compared to the diffraction-limited ($M^2 = 1$) BPP in FA of an individual free-running emitter ($BPP_{FA,em} \approx 0.30 \text{ mm} \times \text{ mrad}$ at $\lambda = 955 \text{ nm}$). Reasons for the dependency of the FA-BPP on diode current have already been discussed in section 3.2.3 for DWBC of an individual diode bar and can be related to the increasing residual spectral emitter linewidth, a potential beam tilt at the location of the grating induced by the BTS and thermo-optically induced beam pointing errors of the emitter sub-beams in FA. In case of DWBC
**Fig. 4.10:** (a) FA- and SA-BPP of the combined cavity output vs. diode current. (b) FA-BPP of the combined cavity output of the laser diode module and selected individual bars at a diode current of 100 A and 180 A, respectively. (c) FA-BPP at a diode current of 180 A and measured smile value of selected individual bars of the laser diode module.

of multiple-bar arrangements, thermo-optical effects in the resonator optics are expected to have an additional impact on the beam quality of the combined cavity output, since the intra-cavity power is one order of magnitude higher. Figure 4.10b shows the FA-BPP of the combined cavity output of the laser diode module and selected individual bars at a diode current of 100 A and 180 A, respectively. For the measurement of the individual bars, the output beams of nine of the ten diode bars are blocked in front of the laser diode module. In this case, only one individual bar is present inside the external cavity and the intra-cavity power is correspondingly small. At both diode currents, the mean value of the
4.2. Transmission grating approach

The presented data of the FA-BPP of the individual bars is in good agreement with the measured FA-BPP of the combined cavity output of the complete laser diode module. This implies that beam combination of the diode bar ensemble inside the external cavity is successfully performed and the increase of the FA-BPP is dominated by the increase of the FA-BPP of the individual diode bar. Hence, the present data show no thermo-optical impacts on the beam quality, e.g. due to the heating of the grating. In theory, one would expect a significantly lower FA-BPP mean value of the individually operated diode bars compared to the FA-BPP of the entire diode bar ensemble if thermo-optical effects are present, since the thermal heat load on the optical components inside the resonator is by one order of magnitude smaller for only an individual diode bar being present inside the external cavity. A possible explanation for this discrepancy is the alignment of the cross-talk filtering telescope which is optimized for maximal output power and locking performance of the entire wavelength beam-combined diode laser module at a diode current of 140 A. As discussed in section 3.2.3.3, in this configuration, the FA-BPP of the individual bars is not necessarily at their minimal values due to residual cross-talk. Due to this fact, the impact of thermo-optics on the beam quality can not be monitored by the data presented in Fig. 4.10b. However, comparing the presented data with the beam quality results which have been achieved in case of the individual-bar experiment for bar C (see Fig. 3.11a), the FA-BPP deviates by a factor of 2 over the whole diode current range, although a higher magnification of the cross-talk filtering telescope \( f_{X1}/f_{X2} = 10 \) has been used in the external cavity of module Ia. The higher FA-BPP of the combined output beam can be related to thermo-optical effects in the transmission grating, as for example thermo-optically induced wavefront front aberrations [138, 139], due to the heating of the optical component. As expected from theory, the FA-BPP of the individual bars of the laser diode module correlates to the measured smile value. Figure 4.10c shows the measured FA-BPP at a diode current of 180 A and the corresponding smile value of selected individual bars of the laser diode module. For low-smile \((\approx 1 \mu m)\) bars, as for instance bar 7 and bar 8, the FA-BPP is about \(1.3 \text{ mm} \times \text{ mrad}\). Bars with larger smile values \((\geq 1.5 \mu m)\), as for instance bar 3 and bar 4, exhibit a FA-BPP in the range of \(1.9 \text{ mm} \times \text{ mrad}\).

4.2.2. Module II

The schematic setup of the external laser cavity in case of laser diode module II is shown in Fig. 4.11. As in case of laser diode module Ia, the module is assembled with ten actively cooled BAL diode bars (bar C) which exhibit an emitter design with an insulating dielectric layer as current aperture. The diode bars are assembled on the module according to the epitaxial placement presented in Fig. 4.2b.
Although different diode bars and a different epitaxial diode bar placement are used for both laser diode modules, the diode bars exhibit similar characteristics in terms of free-running output power, DOP and spectral locking range. In the beam-combining FA, the transform optics design of the module provides an effective focal length of \( f_{\text{TL},\text{eff}} = 1060 \text{ mm} \) (see Table 4.1). The telescope for cross-talk suppression consists of two cylindrical lenses with focal lengths \( f_{X1} = 200 \text{ mm} \) and \( f_{X2} = -35 \text{ mm} \). Thus, the telescope provides a magnification of about 5.7, which is smaller than the magnification of 10 as in case of the external cavity of laser diode module Ia. The telescope is placed in a non-telecentrical configuration. The distance of the first lens of the telescope from the grating is \( z_1 = 40 \text{ mm} \). The distance between the two lenses is given by \( z_2 = f_{X1} + f_{X2} = 165 \text{ mm} \) and the distance from second lens to the HR is \( z_3 = z_{3a} + z_{3b} = 195 \text{ mm} \). The SA imaging of the emitter sub-beams onto the HR is performed by a cylindrical lens telescope with focal lengths \( f_{SA1} = 401 \text{ mm} \) and \( f_{SA2} = -361 \text{ mm} \). The first lens of the SA telescope is integrated into transform lens 2 which exhibits a cross-cylindrical design. As in case of module Ia, all emitter sub-beams share a zero-order HWP which is placed in front of the transform lens 2. For the output coupling of the combined output beam, the polarization-dependent output coupling scheme, which has been discussed in section 3.2.1, is used. The TFP is operated at an
angle of 20° with reference to the optical axis in order to realize an AOI of 70° of the combined beam. The rotation angle of the QWP and thus the optical feedback strength is optimized such that a maximal output power and a stable locking performance is achieved at diode current of 140 A.

Figure 4.12 shows the spectrum of the combined output beam of the external grating cavity at a diode current of 180 A. The measured spectral interval of the wavelength-stabilized laser diode module is $\Delta \lambda = 47.6$ nm and therefore in good agreement with the theoretically calculated value (see Table 4.2). The same applies to the position of the stabilized central wavelength of the diode bars which are consistent with the calculated spectral channels presented in Fig. 4.2b. The spectral channel spacing of adjacent emitters is $\Delta \lambda_{em} = 174$ pm which can be seen in the extract of the stabilized spectrum in the lower part of Fig. 4.12. The spectral linewidth of the stabilized emitters is $\delta \lambda = 65$ pm (FWHM). The spectrum shows a high modulation depth and the spectral lines of the individually wavelength-stabilized emitters are completely resolved, which implies that emit-

![Figure 4.12: Spectrum of the combined output beam of the external grating cavity at a diode current of 180 A. The lower part shows an extract of the spectrum to provide a higher resolution of the spectral lines of the individually wavelength-locked emitters.](image-url)
ter cross-talk is mostly suppressed, although the magnification of the cross-talk filtering telescope is smaller compared to laser diode module Ia.

Figure 4.13a shows the output power characteristics and the related e-o conversion efficiencies of the free-running laser diode module and the combined output beam as a function of diode current. At a diode current of 180 A, the combined output power is 1.32 kW with a corresponding e-o conversion efficiency of 46.4%. The WBC efficiency and the measured relative power losses at the grating and the TFP with respect to the free-running optical output power of the laser diode module are shown in Fig. 4.13b. The free-running optical output power of the laser diode module is measured in front of the HWP. The relative power loss in the optics of the laser module and the transform optics with reference to the aggregated free-running optical output power of the individual laser diode bars are about 5% at a diode current of 180 A and therefore only insignificantly larger than in case of laser diode module Ia. The WBC efficiency is larger than 80% over the whole diode current range and reaches a value of 89% at a diode current of 180 A. The maximum WBC efficiency of about 90% is achieved at a diode current of 140 A which is consistent with the theoretically predicted diode current value for a maximal WBC efficiency in the analysis of epitaxial diode bar placement for laser diode module II in section 4.1.2. The measured relative power loss at the grating is about 8% at a diode current of 180 A. The grating losses are 5% lower than in case of module Ia which can not be explained by a higher degree of TE polarization of the diode bars of the laser diode module, since the average DOP of the diode bars of both modules does not significantly differ. The average DOP of the diode bars of module Ia is 93.5% and 94.3% for the diode bars of module II at a diode current of 160 A, respectively. An explanation for the lower power losses at the grating is that the transmission grating is operated in Littrow configuration with reference to the optical axis in case of module II, which was not the case for laser diode module Ia. The relative power loss at the TFP is approximately 3% at a diode current of 180 A and shows only a minor fluctuation, when the diode current is varied. This additional loss channel is related to the transmission of residual TM-polarized power fractions of the emitter sub-beams at the first pass of the TFP. The BPP of the combined output beam as a function of diode current is depicted in Fig. 4.13c. At a diode current of 180 A, the FA-BPP amounts to 1.6 mm × mrad and is therefore in the same range as in case of laser diode module Ia. Due to different smile values of the used laser diode bars and deviating magnifications of the cross-talk filtering telescope, the results of both module configurations are not directly comparable in terms of the achieved FA-BPP. The SA-BPP of the combined cavity output is 4.7 mm × mrad at a diode current of 180 A. This value is 1.6 mm × mrad (25%) smaller than in
4.2. Transmission grating approach

Fig. 4.13: (a) Left axis, optical output power vs. diode current for the free-running laser diode module and the combined output beam. Right axis, corresponding e-o conversion efficiencies vs. diode current. (b) Left axis, WBC efficiency vs. diode current. Right axis, relative power losses at the transmission grating and the TFP with reference to the free-running optical output power vs. diode current. (c) FA- and SA-BPP of the combined cavity output vs. diode current.

Such a significant deviation of the SA-BPP is not expected, since diode bars with the identical lateral emitter design are used for the experiments which should yield a comparable beam quality in the SA direction. A potential explanation for the observed deviation is an optimized CCD camera based alignment procedure which is used in case of laser diode module II. The alignment setup allows for a more precise control of the beam positions and beam pointing angles in SA in the near and far field of the output beams of the diode bars compared to each other, which is crucial for a sufficient beam quality.
preservation in the non-beam-combining axis.

A further improvement of the laser performance in terms of the combined output power and e-o conversion efficiency could be achieved by the replacement of the diode bars of the module with an insulating dielectric layer as current aperture by diode bars which exhibit an ion implantation for lateral emitter separation. As discussed in section 2.2, the diode bars with ion implantation provide

![Graphs showing (a) combined output beam parameters, (b) WBC efficiency, and (c) FA- and SA-BPP vs. diode current.]

**Fig. 4.14:** Comparison of the combined output beam parameters and the WBC performance for module II which is assembled with diode bars exhibiting an emitter design with an insulating dielectric layer as current aperture or ion implantation. (a) Left axis, optical output power vs. diode current for the combined output beam. Right axis, corresponding e-o conversion efficiency vs. diode current. (b) WBC efficiency vs. diode current. (c) FA- and SA-BPP of the combined cavity output vs. diode current.
a higher degree of TE polarization. The free-running output power of both diode bar variants are comparable. Figure 4.14a shows a comparison of the achieved combined output power and the corresponding e-o conversion efficiency for laser diode module II assembled with both diode bar variants. At a diode current of 180 A, the combined output power for the ion-implanted emitter design of the diode bars is 1.38 kW. The corresponding e-o conversion efficiency is 48.4%. The combined output power is about 60 W (5%) higher than for the diode bars which exhibit an insulating dielectric layer as current aperture and the e-o conversion efficiency is increased by about 2%. The higher output power results in an increased WBC efficiency which can be seen from Fig. 4.14b. At a diode current of 180 A, the WBC efficiency is 95%. The observed improved performance of the wavelength beam-combined laser diode module can be related to the increased average degree of TE polarization of the diode bars which results in lower power losses at the transmission grating and the TFP in the output coupling unit. The average DOP of the output beams of the laser diode module amounts to 97.1% for the ion-implanted diode bars at 160 A which is 2.8% higher than the value measured for the diode bars exhibiting an insulating dielectric layer as current aperture. For a further comparison, Fig. 4.14c shows the measured beam quality of both laser diode module implementations. A minor improvement of the SA-BPP could be achieved using the diode bars with ion implantation. The SA-BPP is 4.4 mm × mrad at a diode current of 180 A. This value is 0.3 mm × mrad (6%) smaller than in case of the diode bars with an insulating dielectric layer as current aperture. In a good approximation, the presented data of the FA-BPP show a similar course with diode current variation with a more or less constant offset which is approximately 0.2 mm × mrad at a diode current of 140 A. The deviating FA-BPP can be related to dissimilar smile values of the used diode bars. Consequently, the observed deviation is not a generic effect resulting from the different diode bar implementations of the laser diode module.

4.2.3. Conclusion

A kW-class direct diode laser was successfully realized using both laser diode module configurations based on the transmission grating approach for DWBC. The achieved results at a diode operation current of 180 A in terms of combined output power, e-o conversion efficiency and beam quality are listed and compared in Table 4.3. The listed values for module Ia correspond to the presented data for output coupling via an OC with a reflectivity of about 5%, whereas the listed values for module II were achieved using the polarization-dependent output coupling unit which provides an optical feedback ratio between 3% to 7% in the relevant spectral interval from 930 nm to 980 nm. Both modules are sta-
Tab. 4.3: Comparison of the output beam characteristics of the wavelength beam-combined laser diode modules using the transmission grating approach for DWBC at a diode current of 180 A.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Module</th>
<th>Ia</th>
<th>II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined output power (kW)</td>
<td></td>
<td>1.19</td>
<td>1.38</td>
</tr>
<tr>
<td>e-o conversion efficiency ηeo (%)</td>
<td></td>
<td>41.3</td>
<td>48.4</td>
</tr>
<tr>
<td>FA-BPP or BPPx (mm × mrad)</td>
<td></td>
<td>1.7</td>
<td>1.5</td>
</tr>
<tr>
<td>SA-BPP or BPPy (mm × mrad)</td>
<td></td>
<td>6.3</td>
<td>4.4</td>
</tr>
<tr>
<td>Symmetrized BPP (mm × mrad)</td>
<td></td>
<td>3.3</td>
<td>2.6</td>
</tr>
<tr>
<td>Spatial brightness B_CB (MW/cm²/sr)</td>
<td></td>
<td>1126</td>
<td>2119</td>
</tr>
<tr>
<td>BPP deterioration factor Δ</td>
<td></td>
<td>5.7</td>
<td>5.0</td>
</tr>
<tr>
<td>WBC efficiency η_WBC (%)</td>
<td></td>
<td>80</td>
<td>95</td>
</tr>
<tr>
<td>Optical feedback ratio (%)</td>
<td></td>
<td>5 – 6</td>
<td>3 – 7</td>
</tr>
</tbody>
</table>
BPP of the combined cavity output is about $1.5 \text{ mm} \times \text{ mrad}$ which corresponds to a deterioration factor of $\Delta = 5.0$ compared to the diffraction-limited ($M^2 = 1$) BPP in FA of an individual free-running emitter ($\text{BPP}_{\text{FA,em}} \approx 0.30 \text{ mm} \times \text{ mrad}$ at $\lambda = 955 \text{ nm}$). Besides the beam quality deterioration mechanisms which have been discussed in terms of DWBC of individual diode bars in section 3.2.3, the resulting FA-BPP of the wavelength beam-combined laser diode module is affected by thermo-optical effects in the transmission grating, as for example thermo-optically induced wavefront front aberrations, which limit the minimal achievable FA-BPP. An impact of the wavelength stabilization in the external cavity and the thermo-optical effects in the transmission grating on the SA-BPP could not be observed. Depending on the alignment procedure of the output beams of the laser diode module in the non-beam-combining direction, a SA-BPP of the combined cavity output could be achieved which is in a good approximation consistent with the SA-BPP of an individual diode bar emitter. In conjunction with the achieved FA-BPP, the overall symmetrized BPP of the combined cavity output amounts to $3.3 \text{ mm} \times \text{ mrad}$ for laser diode module Ia and $2.6 \text{ mm} \times \text{ mrad}$ for module II. The resulting spatial brightness of the combined beam equals to $1126 \text{ MW/cm}^2/\text{sr}$ resp. $2119 \text{ MW/cm}^2/\text{sr}$ according to Eq. (1.1). The achieved beam quality of module II is sufficient for fiber coupling into commonly used beam delivery fibers for high-brightness laser applications with a core diameter of 100$\mu$m and a numerical aperture (NA) of 0.12 without significant power losses. Hereto, a BPP of less than $6 \text{ mm} \times \text{ mrad}$ in either beam dimension is required. Furthermore, the achieved beam parameters allow for further spatial brightness scaling towards the multi-kW power level by SBC and PBC, as proposed by the modular concept shown in Fig. 1.3. The necessary key beam parameters of a 1-kW direct diode laser module, which can serve as a building block for a potential 4-kW high-brightness direct diode laser system, could be demonstrated using the transmission grating approach for DWBC. The presented beam parameter values of Table 4.3 serve as a benchmark for the experimental results which have been achieved using the TFF approach for DWBC. The results of the wavelength beam-combined laser diode modules in case of the TFF approach are presented in the following sections.

4.3. Thin-film filter approach

4.3.1. Module Ib

The first high-power experiments, based on the TFF approach for DWBC, were performed using laser diode module Ib. The module is assembled with ten actively cooled BAL diode bars (bar C), which exhibit an emitter design with an insulating
dielectric layer as current aperture, according to the epitaxial placement presented in Fig. 4.2. The diode bars are identical to the diode bars which were used for the high-power experiments, based on the transmission grating approach for DWBC, in case of laser diode module Ia. Hence, due to the identical diode bar placement and similar stabilized spectral intervals, equivalent experimental conditions are realized. Consequently, the achieved results of both DWBC approaches are directly comparable. The schematic setup of the external TFF multi-laser cavity and the grating combiner are shown in Fig. 4.15. In the beam-combining FA, the transform optics design provides an effective focal length of $f_{TLEff} = 565$ mm (see Table 4.1). In the feedback branch behind the TFF, a cylindrical lens with a focal length of $f_{FB} = 200$ mm is used for feedback re-imaging in FA. In order to image the beam waist of the emitter sub-beams in SA onto the HR, subsequent to the SAC lens of the laser diode module, two additional cylindrical lenses with focal lengths $f_{S_{A1}} = 500$ mm and $f_{S_{A2}} = 250$ mm are used. As in case of laser diode module Ia, all emitter sub-beams share a zero-order HWP which is placed in front of the TFF. The dispersion-matching telescope consists of two cylindrical lenses with a focal length of $f_{C1} = 100$ mm and $f_{C2} = 194$ mm which are placed

![Schematic setup of the external TFF multi-laser cavity and the grating combiner based on laser diode module Ib.](image)

**Fig. 4.15:** Schematic setup of the external TFF multi-laser cavity and the grating combiner based on laser diode module Ib.
in 4f-configuration. Hence, the telescope provides an magnification of $M = 1.94$ which corresponds to the theoretical optimal value for minimal beam quality deterioration at a stabilized central wavelength of $\lambda_c = 955\,\text{nm}$, which was deduced in section 3.3.2.

Figure 4.16 shows the spectrum of the output beams out of the TFF multi-laser cavity at a diode current of 40 A. The spectrum was measured using a high-resolution spectrometer (HighFinesse HDSA; 40-pm spectral resolution at $\lambda = 960\,\text{nm}$). The 230 emitters of the laser diode module are stabilized within a spectral bandwidth of $\Delta\lambda = 42.3\,\text{nm}$ around a central wavelength of $\lambda_c = 954.5\,\text{nm}$. This value is in good agreement with the theoretically calculated value (see Table 4.2). The spectral channel spacing of adjacent emitters is $\Delta\lambda_{em} = 153\,\text{pm}$. Each emitter is stabilized at a unique wavelength. The spectrum shows a high modulation depth and the spectral lines of the individually wavelength-stabilized emitters are completely resolved in the spectrum without any appearance of spectral emitter cross-talk. The spectral linewidth of the stabi-

![Figure 4.16](image-url) Fig. 4.16: Spectrum of the output beams out of the TFF multi-laser cavity at a diode current of 40 A. The lower part shows an extract of the spectrum to provide a higher resolution of the spectral lines of the individually wavelength-locked emitters.
lized emitters is $\delta \lambda = 76 \text{ pm}$ (FWHM). With increasing diode current a thermooptically induced wavelength shift can be observed in the stabilized spectrum. Figure 4.17 shows the spectrum of the output beams out of the TFF multi-laser cavity at a diode current of 180 A. The extract in the lower part of Fig. 4.17 shows the spectrum of three bars of the laser diode module at a diode current of 40 A and 180 A, respectively. The absolute wavelength shift is about 550 pm corresponding to a relative shift of 0.6 pm/W with reference to the combined output power of the laser diode module. The reason for this observation is a heating of the TFF to a peak temperature of 53°C at high power levels, due to the residual absorption of the incident laser power by the substrate of the filter. The heating of the TFF leads to thermal expansion of the spacer layer and a thermooptically induced change of the effective refractive index of the filter which results in a shift of the resonant wavelengths to higher values according to Eq. (3.28). Figure 4.18a shows a measurement of the central wavelength of the stabilized spectrum and the thermographically measured peak temperature of the TFF as a function of diode current. Both quantities show a linear dependency on diode current.
current which shows that the observed wavelength shift is clearly correlated to the temperature increase of the TFF. Figure 4.18b shows the correlation between the central wavelength of the stabilized spectrum and the peak temperature of the TFF. Furthermore, the theoretically expected temperature dependence of

![Graphs showing the correlation between central wavelength, current, and peak temperature.](a) Central wavelength $\lambda_c$ of the stabilized spectrum and thermographically measured peak temperature of the TFF vs. diode current. (b) Measured and calculated correlation between the central wavelength $\lambda_c$ of the stabilized spectrum and the peak temperature of the TFF.

Tab. 4.4: Material parameter values of the layer materials of the TFF at room temperature used for the calculation of the thermo-optically induced wavelength shift of the stabilized spectrum [137, 140–142].

<table>
<thead>
<tr>
<th>Material</th>
<th>Parameter</th>
<th>$\text{SiO}_2$</th>
<th>$\text{Ta}_2\text{O}_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\text{CTE} \ (10^{-6}/\text{K})$</td>
<td>0.54</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>$dn/dT \ (10^{-5}/\text{K})$</td>
<td>1.29</td>
<td>12</td>
</tr>
</tbody>
</table>

the stabilized central wavelength, based on the Eqs. (3.33) and (3.31), is plotted. For the calculations both the temperature-dependent thermal expansion of the low-index SiO$_2$ spacer thickness $d_{FP}(T)$ and the temperature-dependent increase of the effective index of the filter $n_{TFF,eff}(T)$ are determined using the material
parameter values of the layer materials of the TFF listed in Table 4.4. By use of Eq. (3.33), the resulting wavelength shift can be deduced assuming a constant angle between the surface normal of the filter and the optical axis. A good matching is achieved between the measured data and the theoretically deduced values. Besides the discussed thermo-optically induced wavelength shift, the spectra in Fig. 4.17 show a significant broadening of the stabilized emitter linewidth with increasing diode current, which is accompanied by a reduced modulation depth of the spectral emitter lines. The linewidth at 180 A is $\delta \lambda = 119$ pm (FWHM). This effect is potentially related to higher order lateral modes of the radiated electric field in SA with increasing emitter current, as explained in section 3.2.3.1.

Figure 4.19a shows the output power characteristics and the related e-o conversion efficiencies of the free-running laser diode module, the wavelength-stabilized cavity output and the combined output beam as a function of diode current. At a diode current of 180 A, the combined output power is 1.14 kW with a corresponding e-o conversion efficiency of 39.6%. The maximal e-o conversion efficiency of 41.8% is reached at a diode current of 140 A, where the combined output power is about 920 W. The WBC efficiency with respect to the free-running optical output power of the laser diode module is depicted in Fig. 4.19b. Furthermore, the corresponding measured relative power losses at the location of TFF, the dispersion-matching telescope and the combiner grating with reference to the free-running optical output power are shown which represent the main loss channels. The free-running optical output power of the laser diode module is measured behind transform lens 2 and is consistent with the optical power measured in case of laser diode module Ia. This is the reason why the relative power loss in the optics of the laser module and the transform optics are identical and amount to 4% at a diode current of 180 A. The WBC efficiency is 77% at a diode current of 180 A. The relative power loss of 10% of the stabilized cavity output compared to free-running laser diode module operation can be related to the measured power ratio of about 8% which is reflected out of the cavity towards the beam block at the location of the TFF in the feedback branch. The measured overall relative power loss at the grating is about 13%. Furthermore, a relative power loss of 2% is caused by the dispersion-matching telescope. Compared to the results which have been achieved in case laser diode module Ia using the transmission grating approach for DWBC (see Fig. 4.9), the combined output power is 50 W (4%) lower at a diode current of 180 A which results in a deviation of the e-o conversion efficiency of both lasers of 1.7%. A significantly (15%) improved WBC efficiency is achieved at low diode currents which can be explained by a better locking performance of the diode bars of the laser diode module. Since the epitaxial diode bar placement of both configurations is identical, a better locking
4.3. Thin-film filter approach

Fig. 4.19: (a) Left axis, optical output power vs. diode current for the free-running laser diode module, the wavelength-stabilized cavity output and the combined output beam. Right axis, corresponding e-o conversion efficiencies vs. diode current. (b) Left axis, WBC efficiency vs. diode current. Right axis, relative power losses at the TFF, the dispersion-matching telescope and the combiner grating with reference to the free-running optical output power vs. diode current.

Performance can be the result of an increased locking range of the diode bars due to a higher optical feedback ratio. Differing optical feedback conditions can furthermore explain the decreased combined output power and WBC efficiency at a diode current of 180 A which have been achieved in case of laser diode module Ib. As expected, the measured relative power losses at the grating are consistent for both configurations at a diode current of 180 A, since identical diode bars with identical DOP are used and no change of the DOP is expected due to the wavelength stabilization inside the external cavity [143].

In order to determine the wavelength-dependent optical feedback ratio inside the external cavity during ongoing laser diode module operation, a measurement setup is used which is shown in Fig. 4.20. The setup and measurement configuration are identical to the setup presented in Fig. 3.28, which has been used for the investigation of the optical feedback characteristics in case of individual-bar experiments in section 3.3.4. A beam block in front of the laser diode module is used to block the output beams of nine of the ten diode bars in order to realize individual-bar operation inside the external cavity. Again, Eq. (3.37) is applied to deduce the optical feedback ratio from the measured optical powers of the PMs at the three indicated measurement locations in conjunction with the known spectral transmission coefficient for TE polarization of the PRM. Figure 4.21a shows
the deduced feedback ratio as a function of diode current for six individual bars of the laser diode module. For the central bars (bar 5 and bar 6), the deduced feedback ratio is in the range of 4% to 5% at a diode current of 120 A. In a good approximation, the feedback ratio stays constant, when the diode current is varied. The outer bars of the laser diode module show a different behavior. The feedback ratio for bar 1 and bar 2, exhibiting a smaller stabilized wavelength, is higher (6% resp. 8%) at low currents, but approaches the value of the central bars at a diode current of 120 A. For bar 8 and bar 10, exhibiting a larger stabilized wavelength, the feedback ratio is significantly higher both at low and high diode currents and shows a dependency on diode current. At 120 A, the feedback ratio of bar 8 is 11 % and the feedback ratio of bar 10 is 9 %. This deviation can be explained by an incomplete rotation of the polarization of the outer bars, due to larger AOI upon the HWP compared to the central bars. Consequently, the outer bars exhibit larger TM-polarized power fractions, for which the TFF has significantly broader transmission bandwidth of 440 pm (FWHM) (see Fig. 3.19b) resulting in an increased optical feedback strength. Figure 4.21b shows the deduced feedback ratio data of Fig. 4.21a plotted as a function of the stabilized wavelength of the diode bars at a diode current of 40 A and 120 A, respectively. The data clearly show that the feedback ratio inside the external resonator exhibits a wavelength dependency. At both presented diode currents, the feedback ratio strongly increases for wavelengths larger than the central wavelength of the stabilized laser diode module. For wavelengths below the central wavelength, the feedback ratio increases at a diode current of 40 A as well but shows a significantly lower increase at 120 A. The wavelength-dependent optical feedback affects the stabilized output power of the bars, as can be seen from Fig. 4.21c. The higher feedback ratio for the long-wave diode bars results in a lower stabilized output.
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Fig. 4.21: (a) Deduced optical feedback ratio vs. diode current for six individual bars of the laser diode module. (b) Deduced optical feedback ratio vs. wavelength at a diode current of 40 A and 120 A, respectively. (c) Normalized stabilized output power of the TFF multi-laser cavity vs. wavelength at a diode current of 120 A.

power compared to the diode bars which are stabilized at smaller wavelengths.

The BPP of the combined output beam as a function of diode current is depicted in Fig. 4.22a. The presented BPP values correspond to a power content of 95% and were measured using a camera based automatic laser beam profiler (Ophir Photonics M2-200s). The SA-BPP of the combined cavity output lies within a range of 3.0 to 5.7 mm × mrad and shows a typical linear dependency on diode current. At a diode current of 20 A, the FA-BPP is about 3.2 mm × mrad and is consequently deteriorated by a factor Δ = 10.7 compared to the diffraction-limited BPP in FA of an individual free-running emitter ($BPP_{FA,em} \approx 0.30$ mm × mrad
at $\lambda = 955\,\text{nm}$). This value is much larger than the factor $\Delta \approx 3.5$ predicted by the theoretical considerations in section 3.3.5 for the optimal configuration of the grating combiner ($M = 1.94; \Lambda^{-1} = 1600\,\text{lines/mm}$) and the presented experimental parameters. An explanation for this deviation is a slightly detuned telescope magnification and beam quality deterioration due to smile of the laser diode bars. As the simulation of Fig. 3.43 shows, the deterioration factor due to the dispersion mismatch sensibly reacts on the magnification of the dispersion-

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**Fig. 4.22:** (a) FA- and SA-BPP of the combined cavity output vs. diode current. (b) FA-BPP of the combined cavity output of the laser diode module and selected individual bars vs. diode current. (c) FA-BPP at a diode current of 40 A and smile measurement of selected individual bars of the laser diode module. (d) FA-BPP of the combined cavity output of the laser diode module vs. thermographically measured peak temperature of the TFF.
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matching telescope. A variation of the ideal magnification value by ±0.04 leads to an increase of the deterioration factor to a value of $\Delta_{dm} \geq 5$ resulting in an overall deterioration factor of $\Delta \geq 10$. Such a deviation is very likely to occur, since it lies in between the manufacturing tolerances of the telescope lenses and the alignment errors of the grating combiner setup. Furthermore, smile of the laser diode bars significantly affects the BPP of an individual bar in the beam-combining axis, as discussed in section 3.2.3.2. For the theoretical calculations, low-smile values ($\approx 1 \mu m$) have been assumed, which is not the case for all deployed diode bars of the laser diode module. Figure 4.22b shows the FA-BPP of the combined output beam as a function of diode current for selected individual bars of the laser diode module. The smile measurement of the corresponding bars is shown in Fig. 4.22c. For low-smile ($\approx 1 \mu m$) bars, as for instance bar 1, the FA-BPP is around $1.5 \text{ mm} \times \text{mrad}$. For bars with larger smile, the BPP is significantly increased. For example bar 5, exhibiting 2.2-µm smile, has a FA-BPP of $3 \text{ mm} \times \text{mrad}$. The FA-BPP of the individual bars correlates to the smile value, as can be seen from Fig. 4.22c. Depending on the smile value, the FA-BPP differs from the value of a stabilized individual emitter of the diode bar, which lies in the range of 0.6 to $1.1 \text{ mm} \times \text{mrad}$. In summary, the interaction of diode bar smile and an imperfect telescope magnification cause the FA-BPP to be larger than the expected theoretical minimum for the optimal configuration. Furthermore, the measured data in the Figs. 4.22a and 4.22b show that the FA-BPP of the combined output beam has a linear dependency on diode current and reaches a value of $6.6 \text{ mm} \times \text{mrad}$ at a diode current of 180 A. Since the FA-BPP of an individual bar stays constant over the whole diode operation current range, the increasing BPP of the complete laser diode module must be related to a thermo-optical effect. For the measurement of the FA-BPP of the individual bars, the output beams of nine of the ten diode bars were blocked directly in front of the laser diode module. Hence, only one individual diode bar is present inside the external cavity and the thermal heat load on the TFF is correspondingly small. Furthermore, due to the small stabilized spectral interval of the individual bar of $\Delta \lambda < 4 \text{ nm}$, the influence of the dispersion mismatch on the FA-BPP is negligible in this case. Thus, besides the discussed beam quality deterioration mechanisms, thermo-optically induced effects in the resonator optics, mainly in the TFF, have to be considered. Both the observed spectral shift of the stabilized spectrum due to the heating of TFF and the increased emitter linewidth can not explain the strongly increased BPP at large operation currents. The spectral shift results in a deviation from the Littrow condition at the combiner grating and a changed diffraction angle of the combined output beam into the -1st order. The resulting beam pointing deviation is about 1 mrad from 40 A to 180 A, which corresponds to only 5% of the far-field divergence of the combined output beam in FA direction. The increased
linewidth of the stabilized emitters results in a higher beam divergence of the emitter sub-beams behind the grating, governed by the Eqs. (3.48) and (3.19). If both effects are included into the simulation of beam quality deterioration, a deterioration factor \( \Delta \) results which is only a factor of 1.3 larger than the value for the optimal configuration and the experimental parameters at low currents. The experimentally observed increase of the FA-BPP from 3.2 to \( 6.6 \text{ mm} \times \text{mrad} \) corresponds to a factor of 2.1 which is much larger than the theoretically predicted increase. A possible explanation for the increasing FA-BPP with increasing diode current are thermo-optically induced wavefront aberrations [138, 139] due to the heating of the TFF, which additionally deteriorate the beam quality in FA. Figure 4.22d shows the measured FA-BPP of the combined cavity output of the laser diode module as a function of the peak temperature of the TFF. The data show that both quantities show a strong linear correlation. Besides, thermo-optically induced effects in the combiner grating can have an additional impact on the FA-BPP, as briefly mentioned in section 4.2.1 using the example of DWBC based on the transmission grating approach. A more detailed investigation of beam quality deterioration due to thermo-optically induced wavefront aberrations is presented in the following section 4.3.2 using laser diode module II.

### 4.3.2. Module II

In order to improve the laser performance in terms of output power, e-o conversion efficiency and beam quality of the combined cavity output, an external laser cavity based on laser diode module II was built up. The schematic setup of the external TFF multi-laser cavity and the grating combiner are shown in Fig. 4.23. The module is assembled with ten actively cooled BAL diode bars, which exhibit an ion-implanted lateral emitter design, providing an average degree of TE polarization of the free-running laser diode module of 98% at a diode current of 160 A. This value is 3.5% larger than in case of laser diode module Ib which is equipped with diode bars exhibiting an emitter design with an insulating dielectric layer as current aperture. The free-running output power of both laser diode modules is comparable and amounts to about 1.5 kW at a diode current of 180 A. Furthermore, the diode bars of both modules exhibit similar characteristics in terms of the spectral locking range. In the beam-combining FA, the transform optics design of the module provides an effective focal length of \( f_{\text{TL,eff}} = 1060 \text{ mm} \) (see Table 4.1). Due to the larger effective transform focal length, the spectral interval is significantly reduced which is the reason why a lower impact of the dispersion mismatch between the TFF and the combiner grating on the FA-BPP is expected. Compared to the external cavity in case of module Ib, some minor modifications have been performed. In the feedback branch behind the TFF, a cylindrical lens
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with a focal length of $f_{FB} = 250\, \text{mm}$ is used for feedback re-imaging in FA. The telescope for SA imaging subsequent to the SAC consists of two cylindrical lenses with focal lengths $f_{SA1} = 500\, \text{mm}$ and $f_{SA2} = 300\, \text{mm}$. As in case of laser diode module Ib, all emitter sub-beams share a zero-order HWP which is placed in front of the TFF. The dispersion-matching telescope remains unchanged and consist of two cylindrical lenses with a focal length of $f_{C1} = 100\, \text{mm}$ and $f_{C2} = 194\, \text{mm}$ which are placed in 4f-configuration. Hence, the telescope provides an identical magnification of $M = 1.94$.

Figure 4.24 shows the spectrum of the output beams out of the TFF multi-laser cavity at a diode current of 40 A. The diode bars of the laser diode module are stabilized within a spectral interval of $\Delta \lambda = 24.2\, \text{nm}$ around a central wavelength of $\lambda_c = 955.2\, \text{nm}$. This value is in good agreement with the theoretically calculated value (see Table 4.2). Due to the compressed stabilized spectral interval, the channel spacing of adjacent emitters is smaller than the spectral resolution provided by the used spectrometer (HighFinesse HDSA; 40-pm spectral resolution at $\lambda = 960\, \text{nm}$). This is the reason why the spectral lines of the individually wavelength-stabilized emitters can not be resolved in the spectrum and no com-
Fig. 4.24: Spectrum of the output beams out of the TFF multi-laser cavity at a diode current of 40 A. The extract in the lower part shows the spectrum of three bars of the laser diode module at a diode current of 40 A and 160 A, respectively.

Measurements about the locking performance of the emitters and the residual stabilized emitter linewidth can be given. As in case of laser diode module Ib, a thermooptically induced wavelength shift with increasing diode current can be observed in the stabilized spectrum due to the heating of the TFF. The extract in the lower part of Fig. 4.24 shows the spectrum of three bars of the laser diode module at a diode current of 40 A and 160 A, respectively. The absolute wavelength shift is about 415 pm from 40 A to 160 A, which is consistent with the results obtained in case of laser diode module Ib. Due to a higher achieved combined output power, the relative shift with reference to the combined output power of the laser diode module amounts to 0.4 pm/W, which is 0.2 pm/W (33%) smaller than in case of laser diode module Ib. Figure 4.25a shows a measurement of the central wavelength of the stabilized spectrum and the thermographically measured peak temperature of the TFF as a function of diode current. As in case of laser diode module Ib, both quantities show a linear dependency on diode current. The wavelength shift is clearly correlated to the temperature increase of the TFF, as can be seen from Fig. 4.25b, and a good agreement between the measured data and
Fig. 4.25: Wavelength shift of the stabilized spectrum of the TFF multi-laser cavity. (a) Central wavelength $\lambda_c$ of the stabilized spectrum and thermographically measured peak temperature of the TFF vs. diode current. (b) Measured and calculated correlation between the central wavelength $\lambda_c$ of the stabilized spectrum and the peak temperature of the TFF.

the theoretically deduced values is obtained.

Figure 4.26a shows the output power characteristics and the related e-o conversion efficiencies of the free-running laser diode module, the wavelength-stabilized cavity output and the combined output beam as a function of diode current. At a diode current of 180 A, the combined output power is 1.34 kW with a corresponding e-o conversion efficiency of 47.0%. The maximal e-o conversion efficiency of 49.2% is reached at a diode current of 120 A, where the combined output power is about 890 W. The WBC efficiency with respect to the free-running optical output power of the laser diode module is depicted in Fig. 4.26b. Furthermore, the corresponding measured relative power losses at the location of the TFF and the combiner grating with reference to the free-running optical output power are shown. The free-running optical output power of the laser diode module is measured in front of the HWP. The measured relative power loss of 5% in the optics of the laser module and the transform optics with reference to the aggregated free-running optical output power of the individual laser diode bars is consequently not incorporated in the following discussion. In a good approximation, the WBC efficiency shows a current-independent course and is 88% at a diode current of 180 A. The improved current-dependent locking performance compared to laser diode module Ib is related to both the compressed stabilized spectral interval and the optimized epitaxial diode bar placement. An overall
higher WBC efficiency is achieved due to the lower overall relative power loss at the grating of only 1.4\%. The losses are significantly (>10\%) lower than in case of laser diode module Ib. The reasons for the reduced grating losses are related to the higher degree of TE polarization of the used diode bars with ion-implanted lateral emitter design and the significantly smaller stabilized spectral bandwidth, for which the grating exhibits a higher average diffraction efficiency into the -1\textsuperscript{st} order (see Fig. 3.4). Due to the higher WBC efficiency, the combined output power is 200 W (18\%) higher at a diode current of 180 A compared to laser diode module Ib. The corresponding increase of the e-o conversion efficiency is 7\%. The main loss channel is related to the power ratio of 6\% which is reflected out of the cavity towards the beam block at the location of the TFF in the feedback branch. Since the identical dispersion matching telescope has been used, a similar additional relative power loss of 2\% is expected. Compared to the results which have been achieved in case laser diode module II, using the transmission grating approach for DWBC and diode bars exhibiting an ion-implanted lateral emitter design (see Fig. 4.14a), the combined output power is 40 W (3\%) lower at a diode current of 180 A, which results in a deviation of the e-o conversion efficiency of both lasers by 1.4\%. Although a different epitaxial diode bar placement is used in both cases due to differing stabilized spectral bandwidths, the used
diode bars with ion-implanted lateral emitter design exhibit similar characteristics in terms of the free-running optical output power, the spectral locking range and the degree of TE polarization, which justifies a comparison of the achieved results.

The BPP of the combined output beam as a function of diode current is depicted in Fig. 4.27a. The SA-BPP of the combined cavity output shows a typical linear dependency on diode current and is 4.2 mm × mrad at a diode current of 180 A. This value is 1.5 mm × mrad (26%) lower than in case of laser diode module Ib. The reason for the significantly improved SA-BPP is an optimized CCD camera based alignment procedure which is used in case of laser diode module II. The measured SA-BPP is consistent with the achieved result in case of laser diode module II using the transmission grating approach for DWBC and diode bars exhibiting an ion-implanted lateral emitter design (see Fig. 4.14c). At a diode current of 20 A, the FA-BPP is about 4.3 mm × mrad and is consequently deteriorated by a factor $\Delta = 14.3$ compared to the diffraction-limited BPP in FA of an individual free-running emitter ($BPP_{F.A,em} \approx 0.30 \text{ mm} \times \text{ mrad at } \lambda = 955 \text{ nm}$). Consequently, contrary to the theoretical expectation, no improvement of the FA-BPP could be achieved compared to laser diode module Ib due to the compressed stabilized spectral interval. Specifically, the FA-BPP is 1.1 mm × mrad (34%) larger. Furthermore, the measured data show that the FA-BPP of the combined output beam has a linear dependency on diode current and reaches a value of 10.9 mm × mrad at a diode current of 180 A. Due to the stronger current-dependent increase, the deviation of the FA-BPP of both lasers at 180 A is even larger and amounts to 4.3 mm × mrad. In order to investigate the beam quality deterioration in the beam-combining FA in more detail, Fig. 4.27b shows the FA-BPP of the combined cavity output of the laser diode module and individual bars at a diode current of 40 A. Furthermore, the smile measurement of the corresponding diode bars is shown. For the measurement of the individual bars, the output beams of nine of the ten diode bars are blocked in front of the laser diode module. In this case, only one individual bar is present inside the external cavity. Due to the small stabilized spectral bandwidth of the individual diode bar of about 2 nm, the influence of the dispersion mismatch on the beam quality of the combined output beam can be completely neglected in this case. Furthermore, due to the comparatively small intra-cavity power, thermo-optically induced effects in the TFF are negligible for the presented data of the individual bars. From the presented data one can see that the mean value of the FA-BPP of the individual bars is 4.3 mm × mrad. With the exception of bar 10, no significant deviations from the mean value are observable. A correlation between the measured FA-BPP of the individual bars and the corresponding smile value is not observable,
Fig. 4.27: (a) FA- and SA-BPP of the combined cavity output vs. diode current. (b) Left axis, FA-BPP of the combined cavity output of the laser diode module and selected individual bars at a diode current of 40 A. Right axis, measured smile value of selected individual bars of the laser diode module. (c) Beam waist location in FA of the combined cavity output of the laser diode module and selected individual bars at a diode current of 40 A after beam propagation through a spherical lens with a focal length of 300 mm. (d) Correlation between the measured FA-BPP of the combined cavity output of the laser diode module and the thermographically measured peak temperature of the TFF.

which shows that another effect dominates the beam quality deterioration in this case. Compared to the FA-BPP of the individual bars, which have been presented in Fig. 4.22c for laser diode module Ib, diode bars with similar smile values exhibit a significantly larger BPP which deviates by a factor of about 2. An explanation for the increased FA-BPP of the individual bars in case of laser diode module II
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is the stronger impact of beam quality deterioration due to the diffraction of the emitter sub-beams at the TFF. Due to the larger transform focal length, provided by the transform optics design, the far-field divergence of the emitter sub-beams which are reflected at the TFF is a factor of 1.9 smaller. According to the discussion in section 3.3.5.1, this results in an increased deterioration factor of the same magnitude. Furthermore, Fig. 4.27b shows that the mean value of the FA-BPP of the individual diode bars and the FA-BPP of the combined cavity output of the complete laser diode module deviate by about $1.5 \text{ mm} \times \text{ mrad}$ (26%). Assuming that the dispersion mismatch has a minor impact on the FA-BPP, due to the compressed stabilized spectral interval, the deviating results can be related to spherical and chromatic aberrations in the dispersion matching telescope or, as already proposed in section 4.3.1, thermo-optically induced wavefront aberrations due to the heating of the TFF. In order to check the argument of lens aberrations, Fig. 4.27c shows the beam waist location in FA of the combined cavity output of the laser diode module and individual bars at a diode current of 40A after beam propagation through a spherical lens with a focal length of 300 mm. The presented data are extracted from the corresponding beam caustic measurement using the camera based automatic laser beam profiler. The measurement results show that the beam waist location of the individual bars has a parabolic-like dependency. Originating from the central bars, the beam waist location decreases for adjacent bars and is lowest for the outer bars of the module which have the largest distance from the optical axis of the telescope. The decreasing beam waist location with increasing distance of the beam from the optical axis is a typical effect which results from spherical aberrations. However, the observed shift of the beam waist location of the corresponding bar with reference to the mean value lies within the range of the Rayleigh length $z_R$, what implies that the observed lens aberrations have only a minor impact on beam quality in the beam-combining FA. The same applies to the thermo-optically induced beam waist shift, since the deviation of the mean value of the beam waist locations of the individual bars compared to the beam waist location of the complete diode bar ensemble lies also within this range. Figure 4.27d shows the measured FA-BPP of the combined cavity output of the laser diode module as a function of the peak temperature of the TFF. As in case of laser diode module Ib, the data show a strong linear correlation between both quantities, which supports the hypothesis that thermo-optically induced effects in the TFF significantly influence the resulting FA-BPP.

In order to validate this hypothesis, the dependency of the FA-BPP of an individual bar of the laser diode module on the peak temperature of the TFF is investigated. For this purpose, two experimental configurations are used which are depicted in Fig. 4.28. In configuration A, the output beams of nine of the
Fig. 4.28: Experimental configurations A and B for the investigation of the influence of thermo-optical effects in the TFF on the FA-BPP of the combined cavity output of the laser diode module.

ten diode bars are blocked in front of the laser diode module as in case of the individual-bar measurements presented in Fig. 4.27. In configuration B, the output beams of the diode bars are blocked behind the TFF. Consequently, the complete output power of the module is incident on the TFF. Figure 4.29a shows a thermographic camera image of the temperature distribution upon the TFF in configuration B at a diode current of 20 A and 120 A, respectively. The corresponding incident free-running laser power is 58 W and 1.02 kW, respectively. The thermographic camera image is taken from the back side of the filter, where the substrate is located. The front side of the filter, where the layered stack is located, shows a similar temperature distribution and consistent peak temperatures. The measured FA-BPP as a function of diode current and the corresponding peak temperature of the TFF for both configurations are shown in Fig. 4.29b. Figures 4.29c and 4.29d show the corresponding correlation between the measured FA-BPP and the peak temperature of the TFF. The data show that the FA-BPP of the individual bar correlates to the peak temperature of the TFF in both cases. The results prove that thermo-optically induced effects in the TFF are
Fig. 4.29: (a) Thermographic camera image of the temperature distribution upon the TFF at a diode current of 20 A and 120 A, respectively. The corresponding incident free-running laser power is 58 W and 1.02 kW, respectively. (b) Left axis, FA-BPP vs. diode current for the combined cavity output of an individual bar of the laser diode module vs. diode current for the experimental configurations A and B (see Fig. 4.28). Right axis, corresponding thermographically measured peak temperature of the TFF vs. diode current. Correlation between the measured FA-BPP and the thermographically measured peak temperature of the TFF for (c) experimental configuration A and (d) experimental configuration B.

the reason for the dependency of the FA-BPP on diode current. Besides the thermo-optically induced effects in the TFF, thermo-optically induced wavefront front aberrations at the combiner grating can have an additional impact on the FA-BPP. The presented results in Fig. 4.29 only incorporate the FA-BPP deterioration due to thermo-optically induced wavefront front aberrations in the TFF,
since, in both experimental configurations, only one individual bar is incident on the combiner grating. Hence, the thermal heat load on the combiner grating is comparatively small and no thermo-optically induced effects are expected. If one compares the FA-BPP of the individual bar in experimental configuration B from Fig. 4.29b with the FA-BPP of the combined cavity output of the complete diode laser module, which is shown in Fig. 4.27a, the measured FA-BPP values deviate by 3 mm × mrad (33%) at a diode current of 120 A. Assuming that neither the dispersion mismatch nor spherical or chromatic lens aberrations in the dispersion-matching telescope affect the FA-BPP of the combined output beam of the entire bar ensemble, the larger FA-BPP of the complete laser diode module can be related to the additional thermo-optically induced effects in the combiner grating. In order to carry out which thermo-optical effect in the TFF leads to the beam quality deterioration, an interferometer was built up which enables the measurement of thermo-optically induced wavefront aberrations. The schematic setup of the interferometer is shown in Fig. 4.30. As laser source for the experiment, the collimated output beam of a wavelength-tunable fiber-coupled single-mode diode laser (Sacher Lasertechnik LION) is used. The laser is operated at a wavelength of 976.5 nm, where the output power is about 30 mW. Due to the small linewidth of the laser in the MHz-range, the coherence length is well above the beam propagation distances inside the interferometer. The collimated output beam is expanded by a spherical telescope with a magnification of 2, in order to increase the laser beam diameter upon the TFF for a sufficiently large probe area. Behind the telescope, the laser beam is split into a probe and a reference beam by use of a non-polarizing beamsplitter (NPBS). The probe beam is directed towards the TFF by a HR. The AOI upon the TFF is close to 0°, which is the reason why the probe beam is off-resonantly operated compared to the resonant

![Fig. 4.30: Schematic setup of the interferometer for the measurement of thermo-optically induced wavefront aberrations in the TFF.](image_url)
transmission wavelength of the filter. Consequently, the probe beam is completely reflected by the TFF. Two additional HRs redirect the probe beam towards a second NPBS, where the probe beam is superimposed with the reference beam. Both beams exhibit a small angle in the horizontal FA dimension compared to each other, in order to probe the wavefront aberrations in the FA beam direction by the resulting two-beam interference pattern. The angle between both beams determines the spacing of the fringes of the interference pattern [144] and therefore the lateral spatial resolution of the wavefront disturbance. The interference pattern is detected by a CCD camera at the location where both beams overlap. Figure 4.31 shows the CCD camera image of the two-beam interference pattern resulting from the back side of the TFF in case of a turned-off laser and at a diode current of 120 A, which corresponds to an incident free-running laser power on the TFF of 1.02 kW. As a reference, the area of the TFF, which is irradiated by the incident laser beam of the laser diode module, is indicated in the CCD camera image. As one can see, the interference pattern is strongly disturbed, when the output beam of the laser diode module is incident on the TFF and the TFF heats up. The fringes of the interference pattern exhibit a strong curvature in the center of the area, where the incident laser beam of the laser diode module hits the TFF. In this region the incident intensity and consequently the temperature

![CCD Camera Image](image)

**Fig. 4.31:** CCD camera image of the two-beam interference pattern resulting from the back side of the TFF in case of a turned-off laser and at a diode current of 120 A which corresponds to an incident free-running laser power on the TFF of 1.02 kW. As a reference, the area of the TFF which is irradiated by the incident laser beam of the laser diode module is indicated.
of the TFF is highest. According to the lateral temperature distribution in the TFF, the curvature of the fringes decreases towards the borders of the irradiated area. From the detected two-beam interference pattern, the thermo-optically induced OPD along the lateral direction on the TFF is extracted and plotted as a function of the horizontal FA position $x$ in Fig. 4.32. The OPD in the center of the irradiated area amounts to 0.6 $\mu$m which corresponds to 0.6$\lambda$ with reference to the wavelength of the single-mode diode laser. The extracted OPD data are used for a polynomial curve fit of the form:

$$OPD = A_0 + A_1 \cdot x^2 + A_2 \cdot x^4.$$  

(4.3)

According to the definition of wavefront aberrations, given by Seidel, the terms of the polynomial curve fit of Eq. (4.3) contain both the impact of thermal lensing ($\propto x^2$) and the impact of spherical aberrations ($\propto x^4$) on the wavefront disturbance. As one can see from Fig. 4.32, the polynomial curve fit is in good agreement with the extracted data. In the center region of the illuminated area ($-2 \text{ mm} \leq x \leq 2 \text{ mm}$), the wavefront disturbance is mainly caused by thermal lensing which results in a defocus of the incident emitter sub-beams of the laser diode module. In the outer regions of the illuminated area ($2 \text{ mm} < x \leq 5 \text{ mm}; -5 \text{ mm} < x \leq -2 \text{ mm}$), spherical aberrations dominate the thermo-optically induced OPD which cause a deterioration of beam quality in this direction.

![Fig. 4.32](image.png)

**Fig. 4.32:** Extracted thermo-optically induced OPD from the CCD camera image of the two-beam interference pattern resulting from the back side of the TFF vs. lateral position on the TFF along the horizontal FA direction and polynomial curve fit of the extracted OPD data.
impact of both effects on the beam parameters of the probe beam are shown in Fig. 4.33. Figure 4.33a shows the measured BPP and Fig. 4.33b the measured beam waist location after beam propagation through a spherical lens with a focal length of 300 mm in the horizontal FA direction as a function diode current of the wavelength beam-combined laser diode module, with and without a 2x telescope for input beam shaping. The presented BPP values correspond to a power content of 95% and were measured using a camera based automatic laser beam profiler (Ophir Photonics M2-200s). The beam waist locations are extracted from the corresponding measured beam caustic. Without the telescope, the beam diameter of the probe beam upon the TFF in the horizontal FA direction is about 3.6 mm. Consequently, based on the presented OPD data in Fig. 4.32, the beam is only affected by the thermal lens in the TFF which dominates the thermo-optically induced wavefront disturbance in the center of the irradiated area. Accordingly, the presented data in Fig. 4.33 show a significant shift of the beam waist location due to the defocus resulting form the thermal lens in the TFF and no significant deterioration of the beam quality of the probe beam. By using the 2x telescope, the beam diameter of the probe beam is increased to about 7.1 mm. In this case, the probe beam additionally experiences thermo-optically induced spherical aberrations in the TFF which result, besides the defocus due to the thermal lens, in a

Fig. 4.33: Measured beam parameters of the probe beam of the single-mode diode laser in the horizontal FA direction after the reflection at the back side of the TFF. (a) Measured BPP and (b) measured beam waist location after beam propagation through a spherical lens with a focal length of 300 mm vs. diode current of the wavelength beam-combined laser diode module, with and without 2x telescope for input beam shaping.
significant deterioration of beam quality. Specifically, the FA-BPP is deteriorated by a factor of more than 2 at a diode current of 120 A, which is in the same order of magnitude as the measured increase of the FA-BPP of the individual bar of the laser diode module presented in Fig. 4.29b. Hence, a current-dependent increase of the FA-BPP is mainly related to thermo-optically induced spherical aberrations in the TFF. Since the beam diameter of the incident emitter sub-beams of the laser diode module on the TFF \(2\omega_{TFF,FA} = 9.9 \text{ mm}\) is larger than the probe beam diameter, the impact of thermo-optically induced spherical aberrations on the FA-BPP of the combined cavity output is expected to be even larger than the measurement results presented for the probe beam in Fig. 4.33. Up to now, only the thermo-optically induced wavefront disturbance resulting from the back side of the filter, where the substrate is located, has been investigated. In the external cavity, only the frequency-filtered emitter sub-beams of the optical feedback propagate through the substrate of the filter and experience the associated thermo-optically induced wavefront aberrations. The part of the emitter sub-beam which is reflected at the TFF undergoes multiple reflections inside the layered stack and only experiences the thermo-optically induced wavefront disturbance resulting from the front side of the filter, since the beam does not penetrate into the substrate. Due to the fact that the front side of the TFF shows a similar temperature distribution and consistent peak temperatures compared to the back side of the filter and multiple reflections of the resonant stabilized emitter sub-beams occur inside the layered stack, a comparable wavefront disturbance and beam quality deterioration for the reflected emitter sub-beams resulting from the front side of the filter is expected, although the layered stack and the substrate of the TFF differ in thickness by three orders of magnitude. The interferometric measurement of the thermo-optically induced wavefront aberrations resulting from the front side of the TFF are not directly experimentally accessible. Since the probe beam is off-resonantly tuned with reference to the resonant transmission wavelength of the TFF, the thermo-optically induced wavefront aberrations which are exclusively induced by the front side of the filter can not be monitored. As shown in Fig. 4.34, the probe beam can not penetrate into the layered stack. The beam only experiences the Fresnel reflection at the optical interface. This is the reason why the resulting interference pattern can only image the thermomechanically induced surface curvature of the filter. In order to investigate the thermo-mechanically induced wavefront aberrations resulting from the front side of the TFF, where the layered stack is located, the identical interferometer setup to the one shown in Fig. 4.30 has been used. Figure 4.35 shows the CCD camera image of the two-beam interference pattern resulting from the front side of the TFF in case of a turned-off laser and at a diode current of 160 A, which corresponds to an incident free-running laser power on the TFF of 1.37 kW.
Fig. 4.34: Schematic layer setup of the TFF and the incident probe beam of the interferometer.

Fig. 4.35: CCD camera image of the two-beam interference pattern resulting from the front side of the TFF in case of a turned-off laser and at a diode current of 160 A which corresponds to an incident free-running laser power on the TFF of 1.37 kW. As a reference, the area of the TFF which is irradiated by the incident laser beam of the laser diode module is indicated.

reference, the area of the TFF which is irradiated by the incident laser beam of the laser diode module is indicated in the CCD camera image. As one can see, the interference pattern shows only a week disturbance, when the output beams of the laser diode module are incident upon the TFF. The fringes of the interference pattern exhibit only a small curvature in the center of the area, where the incident laser beam of the laser diode module hits the TFF. From the detected two-beam
interference pattern, the thermo-mechanically induced OPD along the lateral direction on the TFF is extracted and plotted as a function of the horizontal FA position $x$ in Fig. 4.36a. The OPD in the center of the irradiated area amounts to 0.1 µm, which corresponds to $\lambda/10$ with reference to the wavelength of the single-mode diode laser. This value constitutes the contribution of the thermo-mechanically induced surface curvature of the TFF to the OPD measured at the

![Graphs showing OPD vs. FA, BPP vs. Current, and Beam Waist Location vs. Current](image)

**Fig. 4.36:** (a) Comparison of the extracted OPD from the CCD camera image of the two-beam interference pattern resulting from the front and the back side of the TFF vs. lateral position on the TFF along the horizontal FA direction. (b) Measured BPP and (c) measured beam waist location after beam propagation through a spherical lens with a focal length of 300 mm of the probe beam of the single-mode diode laser in the horizontal FA direction vs. diode current of the wavelength beam-combined laser diode module for the front and the back side of the TFF.
4.3. Thin-film filter approach

back side of the TFF and is a factor of 6 lower compared to the measured OPD in the center at the back side of the TFF. Consequently, in contrast to the back side of the filter, both the measured BPP and the beam waist location of the probe beam in the horizontal FA direction are only insignificantly affected by the thermo-mechanically induced surface curvature of the TFF, as can be seen from the data presented in the Figs. 4.36b and 4.36c.

4.3.3. Conclusion

The TFF approach for DWBC was successfully applied to realize a kW-class direct diode laser using both laser diode module configurations. The achieved results at a diode operation current of 180 A in terms of combined output power, e-o conversion efficiency and beam quality are listed and compared in Table 4.5. Both modules are stabilized at a central wavelength of about \( \lambda_c = 955 \text{ nm} \) within a spectral interval of \( \Delta \lambda < 50 \text{ nm} \). As in case of the experiments using the transmission grating approach for DWBC, a current-independent WBC efficiency and locking performance could be achieved by the proposed epitaxial diode bar placement of the modules in conjunction with the spectral locking range of the diode bars at the corresponding optical feedback ratio. The external cavity of module Ib provides a wavelength-dependent feedback ratio between 4% to 11% in the relevant spectral interval from 930 nm to 980 nm. Consequently, the wavelength-dependent feedback ratio deviation within the stabilized spectral interval is larger (4% resp. 6%) than in case of the external transmission grating based cavity with either output coupling via an OC or the polarization-dependent output coupling unit. A spectrally varying feedback ratio is disadvantageous in terms of lifetime of the diode bar emitters under external feedback [71–73], since diode bars with increased optical feedback are expected to show premature power degradation due to a higher probability of COMD of the diode bar emitters. The measured thermo-optically induced wavelength shift in the range of 0.4 pm/W to 0.6 pm/W is significantly larger than the spectral shift, which was measured in case of the external transmission grating based cavity (<0.1 pm/W) and affects the FA beam pointing angle of the combined output. The induced beam pointing deviation amounts to 5% at the maximal diode operation current of 180 A compared to the corresponding far-field divergence of the combined output beam. Hence, the beam pointing deviation is expected to be critical in terms of fiber coupling of the combined output beam into a beam delivery fiber. The achieved combined output power lies above the kW power level for both modules. The corresponding e-o conversion efficiencies are larger than 39%. As in case of the transmission grating approach, the combined output power is limited by the output power and the DOP of the wavelength-stabilized diode bar emitters. The main loss channels
Tab. 4.5: Comparison of the output beam characteristics of the wavelength beam-combined laser diode modules using the TFF approach for DWBC at a diode current of 180 A.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined output power (kW)</td>
<td>Ib</td>
</tr>
<tr>
<td>e-o conversion efficiency η eo (%)</td>
<td>39.6</td>
</tr>
<tr>
<td>FA-BPP or $BPP_e$ (mm × mrad)</td>
<td>6.6</td>
</tr>
<tr>
<td>SA-BPP or $BPP_y$ (mm × mrad)</td>
<td>5.7</td>
</tr>
<tr>
<td>Symmetrized BPP (mm × mrad)</td>
<td>6.1</td>
</tr>
<tr>
<td>Spatial brightness $B_{CB}$ (MW/cm²/sr)</td>
<td>307</td>
</tr>
<tr>
<td>BPP deterioration factor $\Delta$</td>
<td>22</td>
</tr>
<tr>
<td>WBC efficiency $\eta_{WBC}$ (%)</td>
<td>77</td>
</tr>
<tr>
<td>Optical feedback ratio (%)</td>
<td>4 – 11</td>
</tr>
</tbody>
</table>

are related to the power losses at the TFF in the feedback branch of the external cavity and the losses of depolarized power fractions at the combiner grating. The achieved combined output power in case of laser diode module Ib is 4% smaller compared to the results of laser diode module Ia (see Table 4.3), where the transmission grating approach for DWBC has been applied to the identical diode bar array. The resulting deviation of the e-o conversion efficiency equals to 1.7%. The deviations are mainly caused by differing optical feedback conditions and the additional loss channel in the external TFF multi-laser cavity. The FA-BPP of the combined cavity output is 6.6 mm × mrad which corresponds to a deterioration factor of $\Delta = 22$ compared to the diffraction-limited ($M^2 = 1$) BPP in FA of an individual free-running emitter ($BPP_{FA,em} \approx 0.30 \text{ mm} \times \text{ mrad}$ at $\lambda = 955 \text{ nm}$). Hence, the FA-BPP is a factor of about 4 larger compared to the FA-BPP of the combined cavity output of laser diode module Ia, which was assembled with the identical diode bars. The larger FA-BPP is caused by two effects. First, besides the beam quality deterioration mechanisms which have been discussed in section 3.3.5 in terms of DWBC of an individual diode bar, the resulting FA-BPP of the wavelength beam-combined laser diode module is affected by the dispersion mismatch between the TFF and the combiner grating due to the
increased stabilized spectral bandwidth. The accompanied beam quality deterioration is a generic effect of the open-loop architecture of the cavity. Although the theoretically predicted configuration of the grating combiner for optimal beam quality preservation is used, a significantly larger FA-BPP is measured compared to the theoretical simulations. The discrepancy between the theoretically calculated BPP deterioration factor in the beam-combining axis and the experimental results can be explained by an imperfect telescope alignment and diode bar smile. Second, thermo-optimally induced wavefront aberrations in the TFF and the combiner grating limit the minimal achievable FA-BPP and are proven to be the reason for a strongly increased FA-BPP at the kW power level of the combined output beam. A significant improvement in terms of the combined output power and e-o conversion efficiency could be achieved using laser diode module II, which was assembled with diode bars with ion-implanted lateral emitter design. Due to the improved DOP compared to the diode bars exhibiting an emitter design with an insulating dielectric layer as current aperture, which have been used in case of module Ib, the combined output power could be increased to 1.34 kW with an e-o conversion efficiency of 47.0%. In this configuration, a maximal WBC efficiency of 88% could be achieved. Due to the larger effective transform focal length, the stabilized spectral interval is significantly reduced which is the reason why a lower impact of the dispersion mismatch between the TFF and the combiner grating on the FA-BPP was expected in case of laser diode module II. But in contrast to the theoretical expectation, no improvement of the FA-BPP could be achieved, since, as a consequence of the larger beam diameter of the emitter sub-beams upon the TFF and the combiner grating, the impact of thermo-optimally induced wavefront aberrations on the FA-BPP is simultaneously increased. The resulting FA-BPP amounts to $10.9 \text{ mm} \times \text{mrad}$ ($\Delta = 36$). In a good approximation, the achieved SA-BPP of the combined output beam of both modules is consistent with the achieved SA-BPP in case of using the transmission grating approach for DWBC. With the exception of the alignment procedure of the output beams of the laser diode module in the non-beam-combining direction, no further impact on the SA-BPP due to the wavelength stabilization in the external cavity or thermo-optical effects in the dispersive optical elements could be observed. The overall symmetrized BPP of the combined cavity output amounts to $6.1 \text{ mm} \times \text{mrad}$ for laser diode module Ib and $6.8 \text{ mm} \times \text{mrad}$ for module II. The resulting brightness of the combined beam equals to $307 \text{ MW/cm}^2/\text{sr}$ resp. $297 \text{ MW/cm}^2/\text{sr}$ according to Eq. (1.1). The achieved beam quality of both modules is not sufficient for fiber coupling into commonly used beam delivery fibers for high-brightness laser applications (100-µm core diameter; 0.12 NA) without significant power losses, since the FA-BPP exceeds in either case the required BPP of $\leq 6 \text{ mm} \times \text{mrad}$ for efficient fiber coupling. Furthermore, due to a FA-BPP above $5 \text{ mm} \times \text{mrad}$
of both modules, no space for further power scaling by spatial stacking is left. The output power could be doubled by applying PBC of the combined output beam of two modules. Higher laser output powers can only be addressed at the cost of a decrease in beam quality. Due to the mentioned constraints in beam quality, wavelength beam-combined laser diode modules based on the TFF approach for DWBC are not yet suited as optical engine for building an efficient high-brightness multi-kW direct diode laser, as proposed by the modular concept shown in Fig. 1.3. The necessary key beam parameters of a 1-kW direct diode laser module, which can serve as a building block for a potential 4-kW high-brightness direct diode laser system, could not be demonstrated using the TFF approach for DWBC. However, the presented results show that the approach provides comparable combined output powers and e-o conversion efficiencies compared to the transmission grating approach for DWBC. This is the reason why the TFF approach is already well suited for building efficient direct diode laser systems of lower spatial brightness, with a beam quality in the region of $14 \text{mm} \times \text{mrad}$ at the multi-kW power level.
In this thesis, two different approaches for either open- or closed-loop DWBC were investigated and compared with regard to an efficient spatial brightness scaling of high-power BAL diode bars towards the kW power level with minimal beam quality deterioration in order to realize a 1-kW high-brightness direct diode laser module with largest possible e-o conversion efficiency. The module shall serve as a building block for a potential high-brightness direct diode laser system with an output power of 4 kW and a BPP below $5 \text{ mm} \times \text{ mrad}$. These beam parameters match the sweet spot for high-brightness industrial laser applications, as e.g. laser cutting and remote welding, where presently less efficient diode-pumped solid-state thin-disk or fiber lasers dominate the market.

For the experiments, state-of-the-art high-power 9xx-nm BAL diode bars have been deployed whose architecture, radiation characteristics and micro-optical components for shaping of the output beams were explained in Chapter 2. Key beam parameters for the usage of BAL diode bars as radiation source for DWBC in both investigated external laser cavities are found to be the spectral locking range, the DOP and the SA-BPP of the output beams of the diode bar emitters. A high DOP of the diode bar emitters is crucial to achieve a large WBC efficiency, since depolarized power fractions mainly determine the power losses at the combiner grating in the external cavity. The spectral locking range, provided by the AR coating of the front facet of the diode bar chip, has to be large enough to compensate for the temperature-dependent wavelength shift of the spectrum of the diode bar emitters which is determined by the thermal resistance of the diode bar package. In order to realize a current-independent locking performance of the diode bar emitters, a sufficiently large locking range is needed. The SA-BPP of the diode bar emitters limit the achievable BPP in the non-beam-combining dimension in case of FA-DWBC by use of a micro-optical BTS. In order to achieve the claimed beam parameters of the 1-kW high-brightness direct diode laser module, the SA-BPP may not exceed the level of $5 \text{ mm} \times \text{ mrad}$ at the corresponding operation current.
The theoretical background and the functional principle of both investigated DWBC approaches have been explained in Chapter 3. Furthermore, based on theoretical considerations and results of individual-bar experiments, the capability of both external cavity designs for an efficient spatial brightness scaling of BAL diode bars and the dominant mechanisms of beam quality deterioration, which limit the achievable spatial brightness of the combined output beam, have been discussed and investigated. The external cavity of the closed-loop transmission grating approach is based on a single intra-cavity diffraction grating for simultaneous wavelength stabilization and beam combination. The presented results of the individual-bar experiments demonstrate the capability of this approach for an efficient spatial brightness scaling of BAL diode bars. The WBC efficiency with respect to the free-running output power of the diode bar is in the range of 90%. The main loss channels in the external cavity are related to the transmission of depolarized power fractions at the grating, the limited diffraction efficiency of the grating and the power fraction which is reflected into the -1<sup>st</sup> diffraction order. Depending on the deployed diode bar type, a power of the combined output beam between 100 W to 150 W could be achieved with a corresponding e-o conversion efficiency of about 50%. The dominant effects which limit the minimal achievable BPP of the combined output beam in the beam-combining axis could be identified. In case of beam combining in the fundamental-mode FA beam dimension by use of a micro-optical BTS, beam quality deterioration is related to three main mechanisms. These are the residual spectral linewidth of the stabilized emitters, diode bar smile and spectral emitter cross-talk. Based on theoretical considerations and results of individual-bar experiments, a minimal value of $\Delta \cdot BPP_{FA,em} \approx 0.53 \text{ mm} \times \text{mrad (} M^2 \approx 1.7)$ for the resulting BPP in the beam-combining axis could be deduced for low-smile ($\approx 1 \mu\text{m}$) diode bars. Deviations from the minimal value with increasing diode current are due to an incomplete beam rotation of the micro-optical BTS and thermally induced beam pointing errors of the emitter sub-beams in the beam-combining axis. An influence of the wavelength stabilization in the external cavity on the beam quality in the non-beam-combining axis, which corresponds to the SA beam dimension, could not be observed. In a good approximation, the SA-BPP of the combined output beam corresponds to the SA-BPP of an individual stabilized diode bar emitter. The presented novel cavity architecture of the open-loop TFF approach is based on a single customized ultra-narrowband TFF as dispersive optical element inside the resonator. Individual cross-talk free spectral stabilization of the diode bar emitters in the external cavity could be successfully demonstrated. Subsequent spectral beam combination of the cavity output has been performed in a grating combiner setup consisting of a diffraction grating and cylindrical telescope which is used for linear dispersion-matching between the TFF and the
combiner grating. Compared to the individual-bar experiments using the transmission grating approach, a reduced WBC efficiency of about 80% is achieved at comparable optical feedback strengths due to an additional loss channel in the feedback branch behind the TFF in the external resonator, which consequently results in both a lower power and e-o conversion efficiency of the combined output beam. Regarding beam quality preservation, the effects which have been deduced for the transmission grating approach can be directly transferred concerning the residual spectral linewidth of the stabilized emitters and diode bar smile. Two additional effects could be identified to be the reason for an increased BPP in the beam-combining axis compared to the closed-loop transmission grating based cavity. First, beam distortion by the spectral filtering of the TFF. Second, beam pointing errors of the emitter sub-beams with respect to each other after beam combining due the dispersion mismatch between the TFF and the combiner grating in case of large stabilized spectral bandwidths (Δλ > 5 nm) or a telescope magnification which differs from the ideal value. As a result, the deduced minimal achievable beam parameter product in the beam-combining axis at the 100-W power level is \( \Delta \cdot BPP_{FA,em} \approx 0.9 \text{ mm} \times \text{ mrad} \) assuming a negligible impact of the dispersion mismatch and low smile values (≈1 μm) of the diode bars.

Both investigated cavity architectures have been applied to two different laser diode module configurations, each consisting of ten horizontally stacked actively cooled 150-W BAL diode bars, in order to realize a high-brightness kW-class direct diode laser module which potentially serves as a building block for a 4-kW direct diode laser system. The setup of the used laser diode modules and the achieved results by employing both DWBC approaches have been presented in Chapter 4. Using the transmission grating approach, the demanded key beam parameters for the 1-kW module platform (\( P = 1 \text{ kW}; \Delta \lambda \leq 50 \text{ nm}; BPP_x = BPP_{FA} \leq 1.5 \text{ mm} \times \text{ mrad}; BPP_y = BPP_{SA} \leq 5 \text{ mm} \times \text{ mrad} \)) could be successfully demonstrated with excellent e-o conversion efficiency of up to 48%. Besides the beam quality deterioration mechanisms which have been identified in terms of individual-bar experiments, the resulting BPP in the beam-combining axis of the wavelength beam-combined laser diode module is affected by thermo-optical effects in the transmission grating which limit the minimal achievable beam quality. In case of the TFF approach, the required key beam parameters could have not yet been achieved with regard to the claimed beam quality of the combined output beam in the beam-combining axis. An output power above the kW power level could be demonstrated with an electrical-to-optical conversion efficiency of about 40% resp. 47%. The BPP of the combined output beam in the beam-combining axis is larger than 1.5 mm × mrad and consequently exceeds
the required value. Thermo-optically induced wavefront aberrations due to the heating of the TFF and the combiner grating and furthermore an imperfect magnification of the dispersion-matching telescope are identified to be the reason for a degrading beam quality in the beam-combining axis in high-power operation beyond the observed value in individual-bar experiments, where an order of magnitude lower intra-cavity power and stabilized spectral bandwidth are present. A future improvement of the laser performance is possible by using TFF substrates with lower absorption in order to reduce thermo-optical effects inside the filter and thereby solving the issues of BPP deterioration. In this context, a shift of the stabilized spectrum above the strong OH absorption band of fused silica glasses at a wavelength of 940 nm [145, 146] is beneficial to further reduce absorption of the filter. Additionally, in order to achieve better beam quality preservation, a cylindrical zoom lens telescope for dispersion-matching could be employed which enables a more precise adjustment of the magnification. However, due to the additional beam quality deterioration resulting from the beam distortion by the spectral filtering of the TFF, a comparable beam quality in the beam-combining axis or spatial brightness as in case of the transmission grating approach can generically not be achieved.

Regardless of the specific DWBC approach, the presented results in this thesis show that the spatial brightness provided by BAL diode emitters of state-of-the-art high-power laser diode bars is sufficient for the realization of highly efficient high-brightness kW-class direct diode lasers by use of DWBC in external laser cavities. The limiting brightness degrading mechanisms using this technique in either open-loop or closed-loop cavity architectures have been generally deduced and show that, as of today, the closed-loop transmission grating approach exhibits the greatest potential for realizing multi-kW direct diode laser systems with highest spatial brightness. The future success of this technology strongly depends on the reliability and lifetime of laser diode emitters under external optical feedback and further improvements concerning output power and beam quality in the lateral multi-transverse-mode SA beam dimension of diode bar emitters. Only if these prerequisites are fulfilled, high-brightness direct diode lasers can compete with well established high-power solid-state thin-disk or fiber lasers and successfully exploit their advantage of a superior e-o conversion efficiency.
Calculations for the measurement of the optical feedback ratio

Locking-range setup

According to the measurement setup of Fig. 2.11, the power of the optical feedback $P_{FB}$ can be expressed as

$$P_{FB} = P_{in} \cdot T_{TM,PRM}^2 \cdot T_{rem} \, ,$$

(A.1)

where $P_{in}$ is the input laser power and $T_{TM,PRM}^2(\lambda)$ being the spectral transmission coefficient of the PRM for TM-polarized power fractions. The unknown spectral transmission of the remaining optical components of the external cavity behind the PRM during one roundtrip is denoted by $T_{rem}$. The power $P_1$, measured by the first PM (PM 1), is given by:

$$P_1 = P_{in} \cdot [1 - T_{TM,PRM}(\lambda)] \, .$$

(A.2)

The power $P_2$, measured by the second PM (PM 2), is given by:

$$P_2 = P_{in} \cdot T_{TM,PRM}(\lambda) \cdot T_{rem} \cdot [1 - T_{TM,PRM}(\lambda)] \, .$$

(A.3)

Solving Eq. (A.2) for $P_{in}$ and inserting the resulting expression into Eq. (A.2) yields:

$$T_{rem} = \frac{P_2}{P_1} \cdot T_{TM,PRM}^2(\lambda)^{-1} \, .$$

(A.4)

By using the Eqs. (A.1) and (A.4), the feedback ratio with reference to the incident laser power is given by:

$$\frac{P_{FB}}{P_{in}} = \frac{P_2}{P_1} \cdot T_{TM,PRM}(\lambda) \, .$$

(A.5)
The result of the upper equation represents the expression from Eq. (2.8) which was used to deduce the optical feedback ratio for the corresponding measurement of the spectral locking range.

**Thin-film filter multi-laser cavity**

According to the measurement setup of Fig. 3.28, the input laser power $P_{in}$ at the location of the TFF can be expressed as

$$P_{in} = P_1 + P_2 \cdot T_{TE,PRM}(\lambda)^{-1},$$

(A.6)

where $P_1$ is the measured stabilized output power and $P_2$ being the power which is measured behind the PRM. The spectral transmission coefficient of the PRM for TE-polarized power fractions is denoted by $T_{TE,PRM}(\lambda)$. The power of the optical feedback $P_{FB}$ is given by:

$$P_{FB} = \frac{P_2 \cdot T_{TE,PRM}(\lambda)^{-1} \cdot [1 - T_{TE,PRM}(\lambda)] - P_3}{1 - T_{TE,PRM}(\lambda)}.$$

(A.7)

The expression in the nominator, corresponds to the optical feedback power in case of the presence of a PRM instead of a HR. The factor $[1 - T_{TE,PRM}(\lambda)]^{-1}$ is used to correct the optical feedback power for the case, if a HR is present instead of a PRM. Consequently, this factor is needed to deduce the actual optical feedback power which is present inside the external cavity under normal operation. By using the Eqs. (A.6) and (A.7), the feedback ratio with reference to the incident laser power simplifies to:

$$\frac{P_{FB}}{P_{in}} = \frac{P_2 \cdot \tau - P_3}{[P_1 \cdot T_{TE,PRM}(\lambda) + P_2] \cdot \tau} \quad \text{with} \quad \tau := T_{TE,PRM}(\lambda)^{-1} - 1.$$

(A.8)

The result of the upper equation represents the expression from Eq. (3.37) which was used to experimentally deduce the wavelength-dependent optical feedback ratio provided by the TFF multi-laser cavity.
Assuming two adjacent emitters which exhibit an AOI $\alpha_i$ and $\alpha_{i+1}$ upon the transmission grating, respectively. Without loss of generality $\alpha_i > \alpha_{i+1}$ is assumed. From Eq. (3.7) it follows that the corresponding stabilized wavelengths $\lambda_i$ and $\lambda_{i+1}$ have to fulfill the following conditions:

$$\sin (\alpha_i) + \sin [\beta_L(\lambda_c)] = \frac{\lambda_i}{\Lambda} \quad \text{(B.1)}$$
$$\sin (\alpha_{i+1}) + \sin [\beta_L(\lambda_c)] = \frac{\lambda_{i+1}}{\Lambda} \quad \text{(B.2)}$$

In this way, both emitters sub-beams are diffracted into the combined beam which exhibits the Littrow angle $\beta_L(\lambda_c)$ of the stabilized central emitter of the diode bar. Adding both upper equations yields:

$$\sin (\alpha_i) + \sin (\alpha_{i+1}) + 2\sin [\beta_L(\lambda_c)] = \frac{\lambda_i + \lambda_{i+1}}{\Lambda} \quad \text{(B.3)}$$

In the following, it is assumed that the feedback sub-beam has a small angle deviation $\Delta \beta$ compared to the combined output beam, as depicted in Fig. 3.16a. A resonator roundtrip is enabled if the feedback sub-beam of the $i^{th}$ emitter is diffracted at the grating into the direction of the incident sub-beam of the neighboring emitter after the propagation through the optics in the feedback branch of the external cavity. This condition can mathematically be expressed in terms of the grating equation as

$$\sin (\alpha_i) + \sin [\beta_L(\lambda_c) + \Delta \beta] = \frac{\lambda_X}{\Lambda} \quad \text{(B.4)}$$
$$\sin (\alpha_{i+1}) + \sin [\beta_L(\lambda_c) - \Delta \beta] = \frac{\lambda_X}{\Lambda} \quad \text{(B.5)}$$
where $\lambda_X$ denotes the wavelength of the spectral cross-talk channel, which enables the described resonator roundtrip, and $\Delta\beta > 0$ is assumed. By applying the sine addition theorem and adding the Eqs. (B.4) and (B.5), the following expression is obtained:

$$\sin (\alpha_i) + \sin (\alpha_{i+1}) + 2 \sin [\beta_L(\lambda_c)] \cos (\Delta\beta) = \frac{2\lambda_X}{\Lambda} .$$

(B.6)

The first two summands of the upper equation can be expressed in terms of the stabilized wavelengths $\lambda_i$ and $\lambda_{i+1}$ of the adjacent emitters by use of Eq. (B.3). In this way, the upper equation simplifies to:

$$\lambda_X = \frac{\lambda_i + \lambda_{i+1}}{2} + \sin [\beta_L(\lambda_c)] \cdot [\cos (\Delta\beta) - 1] .$$

(B.7)

The upper equation corresponds to the expression for the wavelength $\lambda_X$ of the spectral cross-talk channel presented in Eq. (3.21).
Calculation of the effective angle of incidence $\Theta_{eff}$ upon the thin-film filter

Based on Fig. 3.34, an auxiliary geometry can be defined which is shown in Fig. C.1. The auxiliary geometry consists of three rectangular triangles which are constructed in the plane of incidence of the emitter sub-beam at the location of the TFF. Using the law of cosine and the definitions of the auxiliary geometry,

\[
\Theta_{eff} = \arccos \left( \frac{-a^2 + b^2 + c^2}{2bc} \right). 
\]  

(C.1)
In the following, expressions for the values of $a$, $b$, $c$ and $d$ as a function of the known angles $\Theta$ and $\theta_{TFF,SA}$ are deduced, where without loss of generality $b \equiv 1$ is assumed. From the Pythagorean theorem it follows:

$$a = \sqrt{a'^2 + a''^2}.$$  \hfill (C.2)

The value $a''$ in the upper equation results from the following trigonometric relation:

$$\sin(\Theta) = \frac{a''}{b} \quad \overset{b \equiv 1}{\Longrightarrow} \quad a'' = \sin(\Theta).$$  \hfill (C.3)

Using again the Pythagorean theorem in combination with Eq. (C.3), an expression for the value of $d$ as a function of the AOI $\Theta$ can be deduced:

$$b^2 = d^2 + a''^2 = d^2 + \sin^2(\Theta) \quad \overset{b \equiv 1}{\Longrightarrow} \quad d = \sqrt{1 - \sin^2(\Theta)} = \cos(\Theta).$$  \hfill (C.4)

The remaining expression for the value of $a'$ in Eq. (C.2) can be deduced by use of the following trigonometric relation in combination with Eq. (C.4):

$$\tan(\theta_{TFF,SA,em}) = \frac{a'}{d} \quad \Longrightarrow \quad a' = \tan(\theta_{TFF,SA,em}) \cdot \cos(\Theta).$$  \hfill (C.5)

Consequently, Eq. (C.2) simplifies to

$$a = \sqrt{a'^2 + a''^2} = \sqrt{\tan^2(\theta_{TFF,SA,em}) \cos^2(\Theta) + \sin^2(\Theta)},$$  \hfill (C.6)

where the expressions of the Eqs. (C.3) and (C.5) have been employed. The remaining expression for the value of $c$ in Eq. (C.1) is given by

$$c = \sqrt{a'^2 + d^2} = \sqrt{\tan^2(\theta_{TFF,SA,em}) \cos^2(\Theta) + \cos^2(\Theta)},$$  \hfill (C.7)

where the Pythagorean theorem in combination with the Eqs. (C.4) and (C.5) have been used. Inserting the deduced expressions of the Eqs. (C.4), (C.6) and (C.7) into Eq. (C.1) yields:

$$\Theta_{eff} = \arccos \left\{ \frac{\cos(\Theta)}{\sqrt{1 + \tan^2(\theta_{TFF,SA,em})}} \right\}.$$  \hfill (C.8)

The result of the upper equation represents the expression from Eq. (3.44) which was used for the calculation of the effective AOI $\Theta_{eff}$ of the incident emitter sub-beam upon the TFF.
ABCD matrix analysis of the transform optics design

The ABCD matrix analysis is a ray tracing technique of geometrical optics which enables the calculation of the propagation of paraxial light rays in an arbitrary optical imaging system [131, 132]. Hereby, the impact of the optical system on a light ray, which enters the input plane, is described by a ray transfer matrix. The input light ray is characterized by its distance \( \omega_{in} \) from the optical axis and its angle \( \theta_{in} \) to the optical axis at the input plane, which are composited in a ray vector \((\omega_{in}, \theta_{in})\). The ray transfer matrix \(M\) describes the transformation of the input light ray parameters from the input plane to the output plane by the relation

\[
\begin{pmatrix}
\omega_{out} \\
\theta_{out}
\end{pmatrix} = \begin{pmatrix}
A & B \\
C & D
\end{pmatrix} \cdot \begin{pmatrix}
\omega_{in} \\
\theta_{in}
\end{pmatrix},
\]

(D.1)

where \((\omega_{out}, \theta_{out})\) represent the ray vector at the output plane. The ray transfer matrix \(M_{tc}\) for the telecentrical imaging (2\(f\)-configuration) of a single ideal lens with focal length \(f\) in paraxial approximation is given by

\[
M_{tc} = \begin{pmatrix}
1 & d \\
0 & 1
\end{pmatrix} \begin{pmatrix}
1 & 0 \\
-1/f & 1
\end{pmatrix} \begin{pmatrix}
1 & d \\
0 & 1
\end{pmatrix} \overset{d=f}{=} \begin{pmatrix}
0 & f \\
-1/f & 0
\end{pmatrix},
\]

(D.2)

where \(d\) is the propagation distance of the light ray before and after the lens. From the upper equation one can see that for a telecentrical imaging \((d = f)\), the transfer matrix elements has to fulfill the following conditions:

\[
A \wedge D = 0 \quad \text{and} \quad B = -1/C.
\]

(D.3)
The ray transfer matrix $M_{ml}$ for the multiple-lens transform optics design, which is presented in Fig. 4.1, is given by:

$$M_{ml} = \begin{pmatrix} 1 & d_3 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f_{TL2} & 1 \end{pmatrix} \begin{pmatrix} 1 & d_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f_{TL1} & 1 \end{pmatrix} \begin{pmatrix} 1 & d_1 \\ 0 & 1 \end{pmatrix}. \quad (D.4)$$

Carrying out the matrix multiplication yields the following matrix elements of $M_{ml}$:

$$A = \left(1 - \frac{d_3}{f_{TL2}}\right) \cdot \left(1 - \frac{d_2}{f_{TL1}}\right) - \frac{d_3}{f_{TL1}}, \quad (D.5)$$

$$B = \left(1 - \frac{d_3}{f_{TL2}}\right) \cdot \left(d_1 + d_2 - \frac{d_1 d_2}{f_1}\right) + d_3 - \frac{d_1 d_3}{f_{TL1}}, \quad (D.6)$$

$$C = -\frac{1}{f_{TL1}} - \frac{1}{f_{TL2}} + \frac{d_2}{f_{TL1} f_{TL2}}, \quad (D.7)$$

$$D = -\frac{d_1}{f_{TL2}} - \frac{d_2}{f_{TL2}} + \frac{d_1 d_2}{f_{TL1} f_{TL2}} + 1 - \frac{d_1}{f_{TL1}}. \quad (D.8)$$

By comparison with the transfer matrix of Eq. (D.2) it is clear that the matrix element $C$ of Eq. (D.7) represents the resulting negative inverse effective transform focal length $f_{TL,eff}$ of the two-lens transform optics configuration and is consequently given by:

$$f_{TL,eff} = -C^{-1} = \frac{f_{TL1} \cdot f_{TL2}}{f_{TL1} + f_{TL2} - d_2}. \quad (D.9)$$

This is the result for the effective transform focal length $f_{TL,eff}$ presented in Eq. (4.1). In order to provide a telecentrical imaging, the other matrix elements have to fulfill the conditions of Eq. (D.3). Using the condition $A = 0$, it follows from Eq. (D.5):

$$A = 1 - \frac{d_2}{f_{TL1}} - d_3 \left(\frac{1}{f_{TL1}} + \frac{1}{f_{TL2}} - \frac{d_2}{f_{TL1} f_{TL2}}\right) \equiv 0 \quad \Rightarrow d_3 = f_{TL,eff} \cdot \left(1 - \frac{d_2}{f_{TL1}}\right). \quad (D.10)$$
Using furthermore the condition \( D = 0 \), it follows from Eq. (D.8):
\[
D = 1 - d_1 \left( \frac{1}{f_{TL1}} + \frac{1}{f_{TL2}} - \frac{d_2}{f_{TL1}f_{TL2}} \right) - \frac{d_2}{f_{TL2}} = 0
\]
\[
= \frac{1}{f_{TL,eff}}
\]
\[
\Rightarrow d_1 = f_{TL,eff} \left( 1 - \frac{d_2}{f_{TL2}} \right).
\] (D.11)

The deduced results of the Eqs. (D.10) and (D.11) correspond to the distance \( d_1 \) of transform lens 1 to the front facet of the diode bar and the distance \( d_3 \) of transform lens 2 to the dispersive optical element presented in Eq. (4.2) for a telecentrical imaging of the two-lens transform optics configuration.
Hiermit bedanke ich mich bei allen Personen, die am Gelingen dieser Arbeit ihren Anteil hatten. Mein besonderer Dank gilt:

**Herrn Prof. Dr. Thomas Dekorsy** für die Möglichkeit an diesem hochinteressanten Forschungsthema im Rahmen einer Promotion arbeiten zu können, seine Unterstützung und hilfreichen Ratschläge durch die er diese Arbeit gefördert hat.

**Herrn apl. Prof. Dr. Johannes Boneberg** für die freundliche Übernahme des Zweitgutachtens.

**Herrn Dr. Alexander Killi** für die Möglichkeit an diesem hochinteressanten Forschungsthema in der Entwicklungsabteilung der Firma TRUMPF Laser GmbH arbeiten zu können.

**Herrn Dr. Hagen Zimer** für die hilfreichen Ratschläge, die engagierte Betreuung der Arbeit und das offene Ohr bei vielen Problemen.

**Herrn Prof. Dr. Uwe Detlef Zeitner und Herrn Dr. Frank Fuchs** für die Bereitstellung der Simulationsdaten der Beugungseffizienz der verwendeten Transmissionsgitter.

**Herrn Simon Rauch und Herrn Simon Nagel** für die vielen spannenden und hilfreichen physikalischen Diskussionen, das Korrekturlesen der Paper und die Aktivitäten abseits der Firma.

**Herrn Lukas Irmler** für die geniale Fahrgemeinschaft, sein offenes Ohr bei vielen Problemen und die vielen hilfreichen Diskussionen während den Fahrten in den Schwarzwald.

**Herrn Markus Ginter** für die super Zusammenarbeit im Labor während der Anfangszeit der Diodenlaser-Gruppe.

**Herrn Rolf Beißwanger und Herrn Dietmar Biehler** für das Lensing der Mikrooptiken.

Allen Kollegen der Enwicklungs- und Forschungsabteilung der Firma
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TRUMPF Laser GmbH für die gute Zusammenarbeit und das angenehme Arbeitsklima.

Meinen Eltern für ihre Unterstützung.

Ein ganz besonderer Dank gebührt meiner Frau Tanja für ihre Unterstützung und ihr Verständnis, welches sie meiner Arbeit entgegengebracht hat.
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