Two-colour high-speed asynchronous optical sampling based on offset-stabilized Yb:KYW and Ti:sapphire oscillators

N. Krauß,1* G. Schäfer,1 J. Flock,1 O. Kliebisch,1 C. Li,1 H. G. Barros,1,2 D. C. Heinecke,1 and T. Dekorsy1

1 Department of Physics and Center of Applied Photonics, University of Konstanz, D-78457, Germany
2 Current address: Department für Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany
*nico.krauss@uni-konstanz.de

Abstract: We present a high-speed asynchronous optical sampling system, based on two different Kerr-lens mode-locked lasers with a GHz repetition rate: An Yb:KYW oscillator and a Ti:sapphire oscillator are synchronized in a master-slave configuration at a repetition rate offset of a few kHz. This system enables two-colour pump-probe measurements with resulting noise floors below $10^{-6}$ at a data acquisition time of 5 seconds. The measured temporal resolution within the 1 ns time window is below 350 fs, including a timing jitter of less than 50 fs. The system is applied to investigate zone-folded coherent acoustic phonons in two different semiconductor superlattices in transmission geometry at a probe wavelength far below the bandgap of the superlattice constituents. The lifetime of the phonon modes with a zero wave vector and frequencies in the range from 100 GHz to 500 GHz are measured at room temperature and compared with previous work.

References and links
1. Introduction

Ultrafast laser spectroscopy systems have drawn great attention during the last decades due to their versatile applications in solid-state physics, biology and medicine. Modern spectroscopy techniques rely on ultrashort laser pulses and offer femtosecond temporal resolution. This enables studying the dynamics of fundamental ultrafast excitations in semiconductors like charge carriers, phonons, plasmons, excitons and many more [1, 2]. Understanding these processes is essential to identify the basic limitations in todays semiconductor-based high-speed communication systems.

Ultrafast phenomena are typically studied in a conventional pump-probe configuration composed of a single laser to excite and probe the reflectivity (or the transmission) of the sample for different time delays. The measured sample response is a unique mixture of different excitation and detection mechanisms. In order to resolve weak signal contributions (the relative change in the reflectivity $\Delta R/R$ due to acoustic phonons is in the order of $10^{-4} - 10^{-7}$), different beam modulation techniques for lock-in amplification need to be applied to reduce noise contributions from the implemented light sources [3]. Still, these techniques suffer from long data acquisition times. In addition to that, beam size modulation and beam pointing from mechanical delay stages influence the measurement. These limitations can be overcome by implementing high-speed asynchronous optical sampling (ASOPS), where the repetition rate of two gigahertz lasers is synchronized at an offset of several kHz [4]. This way, the time delay between successive pulse pairs from both lasers is linearly ramped between zero and the inverse repetition rate within a fraction of a millisecond. The high scanning speed allows for shot-noise limited noise floors below $\Delta R/R \approx 10^{-6}$ within seconds of trace averaging. A feedback loop is applied to stabilize the repetition rate offset, thus enabling measurements with sub-50 fs time resolution [4]. Asynchronous optical sampling can also be applied to oscillators with lower repetition rates, however the corresponding scanning rate needs to be decreased in these measurements to maintain the temporal resolution. In recent experiments, asynchronous optical sampling was applied to study ultrafast dynamics in a variety of structured materials [5–9]. In addition to that, several ASOPS-variants have been demonstrated [10–13].

Up to now, Ti:sapphire lasers with a central wavelength around 800 nm (corresponding to a photon energy of 1.55 eV) are the work horse for ultrafast pump-probe experiments due to the broad emission bandwidth and the commercial availability of these lasers. During the last years, a huge progress in the development of femtosecond solid state lasers (SSLs) with GHz repetition rates, based on the ytterbium doped double tungstates Yb:KYW and Yb:KGW, was noticeable [14–18]. These lasers are cost-efficient and compact, as they are pumped with high-power semiconductor laser diodes. Also, several alternative host crystals for ytterbium are currently investigated. Only recently, pulses with an energy of 1.6 nJ and a duration of about 60 fs at a 1.8 GHz repetition rate have been demonstrated, utilizing an Yb:CALGO crystal [19]. The emission wavelength of these Yb-based SSLs is around 1.05 $\mu$m (corresponding to a photon energy of 1.18 eV), which offers the possibility to probe III-V semiconductors like GaAs and AlAs below the bandgap, while other compound semiconductors like In$_{x}$Ga$_{1-x}$As or GaN$_{y}$As$_{1-y}$ can be studied around the bandgap, given the appropriate composition.

Here, we present an ASOPS implementation that combines the titanium and the ytterbium laser technology: An Yb:KYW laser is synchronized to a Ti:sapphire laser at a repetition-frequency offset of a few kHz and a fundamental frequency of 1 GHz. This way, dual-wavelength measurements at high scanning speed and temporal resolution with largely separated pump- and probe wavelengths are made possible. In particular, ultrafast phenomena in utmost important semiconductors with a bandgap in the energy range from 1.18 eV to 1.55 eV can be pumped above the bandgap and probed in transmission below the bandgap. In combination with the high signal resolution associated to high-speed ASOPS, this system is ideal to...
investigate laser-induced coherent acoustic phonons and their corresponding scattering mechanisms.

The paper is organized as follows: First, the Kerr-lens mode-locked (KLM) lasers are described. Second, the synchronization scheme is presented and the two-colour ASOPS system is characterized in terms of temporal resolution and detection sensitivity. Third, the system is applied to measure acoustic phonons in a GaAs/AlAs and a GaAs/AlGaAs superlattice. The resulting lifetimes of the folded zone-center modes are discussed.

2. Kerr-lens mode-locked Yb:KYW and Ti:sapphire oscillator

The schematic layout of the Yb:KYW laser is shown in Fig. 1(a). A similar oscillator was demonstrated previously in Ref. [20]. We demonstrate a three-fold improvement in terms of output power by use of an increased pump power and optimized resonator elements. As pump source, a fiber-Bragg grating stabilized single-mode fiber-coupled pump laser with a maximum delivered output power of about 750 mW at a center wavelength of about 980 nm (Model 3CN01511GL, 3SPGroup) is used. The $M^2$-value of the collimated pump beam is measured with a beam profiler (ModeMaster, Coherent Inc.) to about 1.06. A $f = 30$ mm lens is used to focus the pump beam into the Yb:KYW crystal. The crystal (EKSMA OPTICS) is cut at Brewster angle with a doping concentration of 10 at. % and a thickness of 1 mm. The pump beam polarization is parallel to the $N_m$ axis of the crystal. The crystal is mounted on a copper holder without any active cooling. The resonator consists of four mirrors (LayerTec), positioned in a symmetric ring-configuration. The radius of curvature (ROC) of the two curved mirrors is 30 mm. Given the thickness of the crystal and the ROC of the mirrors, the angle $\Theta$ is adjusted for astigmatism compensation to about 13.5° [21]. Dispersion management is done by inserting two GTI mirrors that produce a total group delay dispersion (GDD) of -2400 fs$^2$, leading to a net dispersion of about -2200 fs$^2$. This is much more than in Ti:sapphire lasers (net GDD is less than -100 fs$^2$ in our case), which is due to the higher nonlinear index of refraction of the Yb:KYW laser crystal. An amount of 0.5 % of the laser power is coupled out of the oscillator. The laser is mounted in an aluminum housing to prevent any lasing disturbance due to air turbulences. Kerr-lens mode-locking can be easily initiated by knocking on a mirror or the housing.

The measurement results of the Yb:KYW laser are summarized in Fig. 2. The radio fre-
Fig. 2. Characterization results of the Yb:KYW laser. (a) RF spectrum, inset: zoom into the fundamental repetition rate $f_0 = 996$ GHz. (b) Laser output power versus pump power. (c) Optical spectrum and sech$^2$ fit. (d) Interferometric auto-correlation, yielding a pulse duration of about 180 fs.

The frequency (RF) spectrum is measured within a 13 GHz bandwidth at a 30 kHz resolution and shows a fundamental repetition rate $f_0$ at around 1 GHz and corresponding higher harmonics with only little amplitude modulation. This modulation could be a sign for multipulsing. In section 3, however, we will give a direct proof of the CW mode-locked operation of the laser with no multipulsing. The pump dependency of the output power is measured by decreasing the pump power. The result is shown in Fig. 2(b). The most striking feature is the sudden reduction in output power to half the value at a pump power of 550 mW where the laser jumps from the KLM regime into the CW regime. At the highest incident pump power of about 710 mW, the output power is about 340 mW. The optical-to-optical efficiency in this case is more than 45%. The high conversion efficiency can be attributed to the Gaussian-like pump beam and the high absorption cross-section of the Yb:KYW crystal. The slope efficiency in the KLM regime is 45%. The optical spectrum and an exemplary interferometric auto-correlation at maximum power is displayed in Fig. 2(c) and Fig. 2(d), respectively. The central wavelength is $(1052 \pm 1)$ nm with a bandwidth of $(7.2 \pm 1.0)$ nm. The error is given by the optical resolution of the implemented spectrometer. The resulting bandwidth corresponds to a bandwidth-limited pulse duration of roughly $(161 \pm 23)$ fs, if a squared hyperbolic secant (sech$^2$) shape is assumed. Evaluating the measured auto-correlation yields a pulse duration of about 180 fs. If the amount of dispersive optics between the laser and the nonlinear crystal in the auto-correlator (about 2000 fs$^2$) is taken into account, a pulse duration of $(172 \pm 18)$ fs can be estimated. Thus, the measured pulse duration corresponds to the expected value within the given measurement accuracy. The laser was running for several hours without any further necessary adjustments. The relative intensity noise (measured within a 1 Hz to 100 kHz bandwidth) is below 0.1%. The measured $M^2$-value of the output beam is 1.04 and 1.01 in the tangential and sagittal plane, respectively, and thus close to a perfect Gaussian beam. These measurements demonstrate the feasibility of the given Yb:KYW laser for ultrafast spectroscopy experiments. By implementing
the latest pump laser modules with output powers approaching 1 Watt, the output power of the Yb:KYW laser should be scalable to the 500 mW level.

The schematic layout of the Ti:sapphire oscillator is displayed in Fig. 1(b). The oscillator (GigaJet, Laser Quantum Ltd.) is pumped by a frequency doubled Nd:YVO₄ (Finesse Pure, Laser Quantum Ltd.) laser with a pump power of about 5 W. In comparison to the Yb:KYW resonator, an additional folding of the cavity is applied for dispersion management (broadband chirped reflectors with about -40 fs² for each mirror). The radius of curvature of the curved mirrors as well as the focal length of the focusing lens is 30 mm. The crystal is actively cooled, the crystal thickness is about 2 mm in order to obtain good absorption of the pump beam. The laser delivers an output power of 900 mW at a bandwidth of around 30 nm, corresponding to a bandwidth-limited pulse duration of about 23 fs assuming a sech² pulse shape. Further details about high-repetition-rate Ti:sapphire lasers can also be found in Ref. [22].

3. Two-colour high-speed ASOPS characterization

The setup for two-colour ASOPS experiments is schematically drawn in Fig. 3(a). About 10 mW of both laser beams is used for measuring the tenth harmonic of the fundamental repetition rate in the photodiodes P1 and P2. These signals are fed into a feedback loop (TL-1000-ASOPS, Laser Quantum Ltd.) to offset-lock the Ti:sapphire lasers repetition rate to the free-running Yb:KYW laser at a frequency difference of a few kHz. The working principle of the phase-locked loop is described in detail in Ref. [4]. For the repetition frequency regulation, two of the Ti:sapphire laser mirrors are mounted on top of piezo crystals. Anti-reflection coated polarizing beam splitters as well as low- and highpass dielectric filters were implemented for superimposing and separating the beams from both lasers. The two-colour ASOPS data acquisition is triggered by a two photon absorption (TPA) cross-correlation signal, that is generated by focusing about 200 mW of both beams onto a 1 mm thick ZnTe crystal. This represents a power loss of about 60% in the Yb:KYW beam. A more efficient optical trigger could be realized for example by apllying sum-frequency generation in a nonlinear crystal instead of two-photon ab-
sorption in combination with an optimized detection scheme. The remaining power of the two beams was sufficient for the targeted experiments.

First, the time resolution of the two-colour ASOPS system is studied via a TPA cross-correlation measurement, similar to the generation of the trigger signal. Both beams are collinearly overlapped with a polarizing beam splitter and focussed in a 0.5 mm thick GaP crystal, that is placed at the sample position. The resulting change in transmission versus time delay is displayed in Fig. 3(b). A time window of more than the pulse-to-pulse distance is chosen to resolve the subsequent pulses. The frequency offset for this measurement is 5 kHz. The measured signal shows distinct peaks at a distance of the inverse repetition rate. The width of the first TPA signal is about 320 fs. The shape of a pure TPA signal represents a convolution of pump- and probe pulses. The slowly oscillating tail of the TPA signal is a filtering effect from the frequency response of the photodiode P4 that is used for the experiment and has no further influence on the following measurement results. The duration of the pump pulses at the GaP crystal are estimated to about 210 fs by taking into account a total GDD of 2400 fs² from dispersive optics in the beam path of the Ti:sapphire oscillator. The estimated duration of the probe pulses is (172 ± 18) fs, taken from the discussion above. The width of the calculated convolution function assuming sech² pulses is then roughly (296 ± 14) fs, which is close to the measured width of 320 fs. The remaining difference between the estimated and the measured width could be explained by jitter due to different optical path lengths in the trigger channel and the measurement channel. The width of the second- and the third TPA signal is about 350 fs and 370 fs, respectively. From these measurement results we conclude, that the temporal resolution within the 1 ns time window is limited to below 350 fs mainly by the duration of the implemented laser pulses and an accumulated timing jitter that amounts to less than 50 fs. It should be possible to improve the temporal resolution to below 250 fs by avoiding dispersive effects or by implementing dispersion compensating optics.

The given experiment clearly demonstrates the CW mode-locking (CWML) of the Yb:KYW laser. When less GDD or a smaller outcoupling rate is chosen for the mirrors in the Yb:KYW oscillator, a multipeak structure is visible in the same cross-correlation measurement. Thus, CWML or multipulse operation of the Yb:KYW laser can directly be observed and distinguished by the given ASOPS cross-correlation measurement. Usually, the optical spectrum or the RF spectrum is used to verify a clean mode-locking of the laser. These methods, however, do not directly reveal the CWML operation of a laser and are limited by the resolution of the spectrometer. Auto-correlation measurements are a direct proof of the pulsed operation of the laser but the time window of auto-correlators is limited by the maximum mirror displacement.

In a second experiment, we characterize the detection sensitivity of the two-colour ASOPS system. Previous studies proofed, that the detection sensitivity in ASOPS measurements is at the shot-noise level if low-noise Ti:sapphire oscillators are implemented. In any ASOPS experiment, however, high-frequency amplitude noise in the probe beam will be overlayed with the pump-probe data, as soon as the laser noise surpasses the noise of the photoreceiver. Due to the kHz scanning speed associated to high-speed ASOPS, AC-coupled photoreceivers with a typical gain of 40 V/mA and noise equivalent powers of a few pW/√Hz can be used. The bandwidth of the implemented photoreceivers covers the range from 25 kHz to 130 MHz. The upper frequency limit in this study is limited to 100 MHz by the analog-to-digital converter. So, the relevant frequency range for the targeted ASOPS measurements reaches from 25 kHz to 100 MHz. In order to estimate any noise contributions from the oscillators to the ASOPS pump-probe data, the noise power spectral density (PSD) of both lasers was measured. To resolve noise contributions with frequencies below 25 kHz, a DC-coupled photodetector with a 150 MHz bandwidth (Thorlabs, PDA10A) was used only for this particular experiment. The results are shown in Fig. 4(a). At low frequencies the noise PSD of the Yb:KYW laser is larger.
Fig. 4. Noise characterization using the Ti:sapphire (black) and the Yb:KYW oscillator (red). Blue straight lines correspond to the calculated shot-noise limit of the photoreceivers used for the ASOPS measurements with a bandwidth from 25 kHz to 130 MHz (AC-Det). (a) noise power spectral density, measured with a DC-coupled photodiode (DC-Det). The blue dashed line corresponds to the noise level of the DC-coupled photodiode. (b) Averaged ASOPS time traces at zero pump power at a data acquisition time of about 1 s and 1000 s. (c) corresponding power spectral density of the data in (b). (d) noise floor for different data acquisition times.

than that of the Ti:sapphire laser, whereas at high frequencies both lasers are comparable. At a frequency of about 1 MHz, the Ti:sapphire laser has larger noise PSD than the Yb:KYW laser. The broad feature at around 150 MHz stems from the limited bandwidth of the photodetector used for the noise detection. Since no special care was taken to reduce the laser noise in the Yb:KYW oscillator, the comparatively low noise is quite surprising at first glance. Though it can be explained by the lifetime of the upper laser level of the Yb:KYW crystal (0.3 ms), which acts as a low-pass filter with a cut-off frequency of 3 kHz. By chance this is below the detection bandwidth, thus making the Yb:KYW laser well suited for low-noise high-speed ASOPS experiments. Correspondingly, the relative intensity noise (RIN) of the Ti:sapphire and the Yb:KYW laser within the relevant detection bandwidth are in the same order of magnitude (0.042% and 0.053%, respectively). Comparing the calculated shot-noise limit of the detector to the noise PSD, the laser noise is above the shot-noise, thus it should be visible when conducting ASOPS. Figure 4(b) compares ASOPS measurements with zero pump power, using the Yb:KYW oscillator or the Ti:sapphire laser as probe laser at a data acquisition time of about 1 s and 1000 s and an offset frequency of 5 kHz. The time to measure a single trace is 0.2 ms. For an actual pump-probe measurement, the time axis is divided by a factor of f₀/Δf to obtain the time delay between the pulses. From the data in Fig. 4(b) it can be clearly seen, that averaging reduces the amplitude of the noise background. The power spectral density of the time-domain data is calculated via fast Fourier transform (FFT) and displayed in Fig. 4(c). For both lasers, a direct mapping of the above-shot-noise laser noise is observed, in good agreement with the
measurements in Fig. 4(a). The averaging process reduces most of the spectral content equally despite some frequencies at 10 kHz and a high-frequency structure at 10 MHz in the measurement with the Ti:sapphire laser. We attribute this circumstance to an electronic artefact from the control of the piezos in the Ti:sapphire laser. The square root of the integrated data shown in Fig. 4(c) yields the noise floor, which is equal to the standard deviation of the time-domain traces. Figure 4(d) compares the noise floor in the ASOPS measurements with the shot-noise limit of the photoreceiver for different data acquisition times. The points indicate a clear increase in detection sensitivity with increasing acquisition time. A saturation occurs in the noise floor of the Ti:sapphire oscillator for large data acquisition times because of the electronic artefact visible in Fig. 4(c), which can not be further averaged. Although the noise floor in our system is in excess of the shot-noise by a factor of about 2, a noise floor below $10^{-6}$ is achieved within seconds of trace averaging. Reduction of noise components above the shot-noise in the given two-colour ASOPS system could be realized with balanced detection schemes.

4. Two-colour high-speed ASOPS experiments

To demonstrate the capabilities of the two-colour pump-probe system, we investigate coherent acoustic phonons in two different semiconductor superlattices (SLs). The dispersion of a SL is back-folded due to the periodicity of the structure. Thus, high-frequency acoustic phonons close to the center of the Brillouin zone can be investigated by means of CW Raman and time-resolved pump-probe experiments. In the latter, the excitation and detection of these modes was proofed to be based on impulsive stimulated Raman scattering and the acoustic deformation potential, respectively [23]. Throughout the past, SLs based on GaAs/AlAs has evolved as a useful material system to investigate high-frequency ultrasonic [24–27] and potential applications like phonon cavities [28]. This is partly due to the perfect lattice-matching of both materials and the consequential growth control in molecular beam epitaxy techniques. Moreover, Ti:sapphire lasers can be used to pump and probe around the first interband transition of the superlattice, leading to enhanced acoustic signal contributions. Finally, the short penetration depth at 800 nm ($\alpha^{-1} \approx 1 \mu$m) enables a spatial decoupling of the generation and detection of the acoustic waves, that can be used for example in remote detection [29–31]. On the other hand, the absorption limits the above-mentioned studies to reflection geometries or to the use of thin samples. In this study, we give results on resonant pumping at around 800 nm, while probing with the Yb:KYW laser far below the bandgap of the SL at 1.05 $\mu$m. We use the low absorption of the probe beam to measure the lifetime of the first-branch zone-folded acoustic mode in transmission geometry.

The first investigated sample consists of 40 GaAs/AlAs superlattice periods, grown on a (001) oriented GaAs substrate. The substrate is wet-etched to measure the structure at 800 nm in reflection and transmission, which was done in a previous study [23]. The individual layer thickness is 19 monolayers. The experimental setup is described above and displayed in Fig. 3(a). The Ti:sapphire laser is used as a pump beam with a central wavelength of about 810 nm, whereas the Yb:KYW laser serves as probe beam. Pump- and probe power are adjusted to 100 mW and 5 mW, respectively. Both beams are focused onto the sample by the same lens to a spot size of about 30 $\mu$m. The frequency offset is set to $\Delta f = 5$ kHz and about 5 million measurement scans are averaged, resulting in a measurement time of about 17 minutes. The measurement is done at room temperature.

The resulting time-dependent change in the relative transmission of the Yb:KYW beam is depicted in Fig. 5(a). The background from carrier dynamics is already removed for clarity. The signal shows a decaying oscillation at a frequency of around 460 GHz. The fast Fourier transform spectrum of the oscillation is given in Fig. 5(b) together with the calculated Rytov dispersion of the superlattice. The value for the sound velocity and the density of the materials is
Fig. 5. (a) Measured acoustic phonons in the GaAs/AlAs superlattice after subtraction of the background. (b) upper part: calculated dispersion relation. Straight horizontal lines represent the double wavevector of the probe laser. Straight vertical lines indicate the expected backscattered acoustic phonon frequencies. lower part: FFT spectrum of the data in (a) and result of a measurement in reflection at a probe wavelength of 800 nm. (c) zoom into the first 200 ps of the data in (a) and exponentially damped sinusoidal fit.

taken from Ref. [32]. The individual layer thickness in the calculation was adjusted to 5.28 nm to match the experimental data. For comparison, a spectrum obtained in reflection geometry at a probe wavelength of 800 nm is displayed as well. By comparing the measurement results with the calculations, the strong acoustic feature at 460 GHz can be attributed to the lower first-branch zone-center phonon mode. The upper first-branch zone-center mode cannot be detected due to symmetry reasons [23]. The phonons at twice the laser wave-vector $q = 2k_{\text{laser}}$ are attributed to the back-scattered Raman process, thus they are not visible in transmission. For the same reason, no low-frequency Brillouin oscillation is visible in the transmission data. The missing back-scattered Raman-contributions explain, why the transmission time-domain data has a more simple envelope than in the reflection experiments, where the two back-scattered folded modes lead to a strong beating of the acoustic oscillations.

The data in Fig. 5 also allows for the extraction of phonon lifetimes. Phonon lifetimes and the corresponding scattering mechanisms are of high importance, since they directly influence the speed of many nanoscaled electronic devices. Figure 5(c) shows an exponentially damped sinusoidal fit to the data. An additional constant phase was introduced in the argument of the sinusoidal to match the data. The first 20 ps after excitation were not taken into account, because the background substraction leads to an artefact. The fit yields a decay time of $(76 \pm 1)$ ps. Recent pump-probe studies on a different GaAs/AlAs superlattice revealed room temperature decay times of 1020 ps and 300 ps at frequencies of 320 GHz and 640 GHz, respectively [34]. This indicates a strong difference in the extrinsic scattering rates, which are the driving mechanisms for phonon decay at room temperature.
In an additional experiment, acoustic phonons in a GaAs/Al$_{0.3}$Ga$_{0.7}$As superlattice are studied. The structure was grown on a 1 mm thick GaAs substrate with an individual layer thickness of 15 nm and 30 nm, respectively. The pump power for this sample was adjusted to 200 mW, while all other measurement parameters are analogue to the previous measurement. The data are taken in transmission through the GaAs substrate. In reflection geometry this would lead to a strong contribution from Brillouin oscillations from the substrate, which are completely absent in transmission geometry. The results are displayed in Fig. 6. A clear acoustic feature is visible in the time-domain trace. The according frequency spectrum reveals a dominating frequency of 118 GHz with a smaller contribution at a frequency of 233 GHz. Comparing with the Rytov-dispersion (the parameters of Al$_{0.3}$Ga$_{0.7}$As were assumed to be the bulk values), these features can be assigned to the first- and second zone-folded center mode. Zone-folded modes of third and higher orders are not visible within the accuracy of our measurement. Based on the phonon spectrum, the time-domain data is fitted by a sum of two exponentially decaying sinusoidal functions. The result is shown in Fig. 6(c) and yields a decay time of (295 ± 2) ps and (78 ± 4) ps for the first and the second folded mode, respectively. The decay times are in agreement with the three-phonon scattering model for high-frequency acoustic phonons insofar as the second folded phonon mode decays faster than the first folded phonon mode. Additional measurements are necessary to further investigate the frequency-dependence of the acoustic phonon lifetimes in the demonstrated superlattice.
5. Conclusion

In summary, we introduced a high-speed pump-probe system, based on an Yb:KYW and a Ti:sapphire oscillator with a gigahertz repetition rate. An offset of a few kHz between both lasers, stabilized by a feedback loop, enables two-colour asynchronous optical sampling experiments at several kHz scanning speed. Noise floors of the pump-probe data below $10^{-6}$ are achieved within seconds of trace averaging in close proximity to the shot-noise level. A temporal resolution of 350 fs, including a timing jitter of less than 50 fs, was measured in accordance to the duration of the implemented laser pulses. As a showcase experiment, zone-folded coherent acoustic phonons in semiconductor superlattices were probed in transmission. The demonstrated system opens new possibilities for high-speed pump-probe experiments at wavelength configurations of 800 nm and 1050 nm for pump or probe pulses, respectively.

Acknowledgments

The authors gratefully acknowledge financial support by the Center for Applied Photonics at the University of Konstanz. This work is partially funded by the Deutsche Forschungsgemeinschaft (DFG) through the SFB 767 and by the Ministry of Science, Research and Arts of Baden-Württemberg (Germany). H. G. Barros and C. Li acknowledge funding by the Alexander-von-Humbold Foundation and the Chinese Scholarship Council, respectively.