Zuerst ersch. in: Optics Express ; 20 (2012), 9. - S. 9698-9704

Mode-locked Yb:YAG thin-disk oscillator with 41 µJ pulse energy at 145 W average infrared power and high power frequency conversion

Dominik Bauer,[1,2,*] Ivo Zawischa,[2] Dirk H. Sutter,[2] Alexander Killi,[2] and Thomas Dekorsy[1]

[1] *Department of Physics and Center of Applied Photonics, University of Konstanz, 78465 Konstanz, Germany*
[2] *TRUMPF-Laser GmbH + Co. KG, Aichhalder Str. 39, 78713 Schramberg, Germany*
[*] *dominik.bauer@de.trumpf.com*

Abstract: We demonstrate the generation of 1.1 ps pulses containing more than 41 µJ of energy directly out of an Yb:YAG thin-disk without any additional amplification stages. The laser oscillator operates in ambient atmosphere with a 3.5 MHz repetition rate and 145 W of average output power at a fundamental wavelength of 1030 nm. An average output power of 91.5 W at 515 nm was obtained by frequency doubling with a conversion efficiency exceeding 65%. Third harmonic generation resulted in 34 W at 343 nm at 34% efficiency.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3580) Laser, solid state; (140.4050) Mode-locked lasers; (190.2620) Harmonic generation and Mixing.

References and links

1. F. Brunner, E. Innerhofer, S. V. Marchese, T. Südmeyer, R. Paschotta, T. Usami, H. Ito, S. Kurimura, K. Kitamura, G. Arisholm, and U. Keller, "Powerful red-green-blue laser source pumped with a mode-locked thin disk laser," Opt. Lett. **29**(16), 1921–1923 (2004).
2. L. Shah, M. E. Fermann, J. W. Dawson, and C. P. J. Barty, "Micromachining with a 50 W, 50 µJ, sub-picosecond fiber laser system," Opt. Express **14**(25), 12546–12551 (2006).
3. P. Baum and A. H. Zewail, "Attosecond electron pulses for 4D diffraction and microscopy," Proc. Natl. Acad. Sci. U.S.A. **104**(47), 18409–18414 (2007).
4. D. H. Sutter, J. Kleinbauer, D. Bauer, M. Wolf, C. Tan, R. Gebs, A. Budnicki, P. Wagenblast, and S. Weiler, "Ultrafast disk lasers and amplifiers," Proc. SPIE **8235**, 82350X, 82350X-9 (2012).
5. J. Aus der Au, G. J. Spühler, T. Südmeyer, R. Paschotta, R. Hövel, M. Moser, S. Erhard, M. Karszewski, A. Giesen, and U. Keller, "16.2-W average power from a diode-pumped femtosecond Yb:YAG thin disk laser," Opt. Lett. **25**(11), 859–861 (2000).
6. C. R. Saraceno, O. H. Heckl, C. R. Baer, C. Schriber, M. Golling, K. Beil, C. Kränkel, T. Südmeyer, G. Huber, and U. Keller, "Sub-100 femtosecond pulses from a SESAM modelocked thin disk laser," Appl Phys B published online (2012) DOI 10.1007/s00340-012-4900-5
7. C. R. Baer, C. Kränkel, C. J. Saraceno, O. H. Heckl, M. Golling, R. Peters, K. Petermann, T. Südmeyer, G. Huber, and U. Keller, "Femtosecond thin-disk laser with 141 W of average power," Opt. Lett. **35**(13), 2302–2304 (2010).
8. O. Pronin, J. Brons, C. Grasse, V. Pervak, G. Boehm, M.-C. Amann, V. L. Kalashnikov, A. Apolonski, and F. Krausz, "High-power 200 fs Kerr-lens mode-locked Yb:YAG thin-disk oscillator," Opt. Lett. **36**(24), 4746–4748 (2011).
9. S. V. Marchese, T. Südmeyer, M. Golling, R. Grange, and U. Keller, "Pulse energy scaling to 5 microJ from a femtosecond thin disk laser," Opt. Lett. **31**(18), 2728–2730 (2006).
10. C. Y. Teisset, H. Fattahi, A. Sugita, L. Turi, X. Gu, O. Pronin, V. Pervak, F. Kraus, and A. Apolonski, "700 nJ broad-band MHz optical parametric amplifier," in Ultra Fast Optics (UFO VII) and High Field Short Wavelength (HFSW XIII) Conference Program, Arcachon, (2009), Conf. Proc., pp. 1–3.
11. E. Innerhofer, T. Südmeyer, F. Brunner, R. Häring, A. Aschwanden, R. Paschotta, C. Hönninger, M. Kumkar, and U. Keller, "60-W average power in 810-fs pulses from a thin-disk Yb:YAG laser," Opt. Lett. **28**(5), 367–369 (2003).
12. S. V. Marchese, C. R. Baer, A. G. Engqvist, S. Hashimoto, D. J. Maas, M. Golling, T. Südmeyer, and U. Keller, "Femtosecond thin disk laser oscillator with pulse energy beyond the 10-microjoule level," Opt. Express **16**(9), 6397–6407 (2008).
13. J. Neuhaus, J. Kleinbauer, A. Killi, S. Weiler, D. Sutter, and T. Dekorsy, "Passively mode-locked Yb:YAG thin-disk laser with pulse energies exceeding 13 microJ by use of an active multipass geometry," Opt. Lett. **33**(7), 726–728 (2008).

#164191 - $15.00 USD Received 6 Mar 2012; revised 2 Apr 2012; accepted 3 Apr 2012; published 12 Apr 2012

14. J. Neuhaus, D. Bauer, J. Zhang, A. Killi, J. Kleinbauer, M. Kumkar, S. Weiler, M. Guina, D. H. Sutter, and T. Dekorsy, "Subpicosecond thin-disk laser oscillator with pulse energies of up to 25.9 microjoules by use of an active multipass geometry," Opt. Express **16**(25), 20530–20539 (2008).
15. F. X. Kärtner and U. Keller, "Stabilization of solitonlike pulses with a slow saturable absorber," Opt. Lett. **20**(1), 16–18 (1995).
16. J. Neuhaus, D. Bauer, J. Kleinbauer, A. Killi, D. H. Sutter, and T. Dekorsy, "Numerical analysis of a sub-picosecond thin-disk laser oscillator with active multipass geometry showing a variation of pulse duration within one round trip," J. Opt. Soc. Am. B **27**(1), 65–71 (2010).

1. Introduction

Laser pulses of around one picosecond duration with pulse energies in the microjoule regime allow for micromachining with negligible heat affects, they enable pumping of optical energetic parametric oscillators and are useful for applications in basic research, e.g. in high-field physics and the generation of attosecond electron pulses [1–4]. These parameter ranges become increasingly accessible with mode-locked laser oscillators at reduced complexity and cost compared to amplifier systems [4].

The first microjoule level pulses directly from a mode-locked oscillator reaching 16 W of average output power were realized more than a decade ago, providing a major technology break through based on the use of a Yb:YAG thin-disk as the gain material [5]. The thin-disk laser geometry is the ideal choice for high power mode-locking as it can be scaled to high average TEM_{00} powers due to the good thermal management of the gain medium. Additionally, the nonlinearities introduced by the thin-disk itself are very small due to the large spot size in the disk allowing for rather high pulse energies. Employing sesquioxide gain materials supporting broader spectra, either very short pulses with only 96 fs at low output powers of 5.1 W using $Yb:LuScO_3$ [6] or 141 W of average power at <2.5 µJ pulse energy and 738 fs pulse duration using $Yb:Lu_2O_3$ [7] have been obtained from SESAM assisted soliton mode-locked oscillators. Using Kerr-lens mode-locking in combination with an Yb:YAG thin-disk, 200 fs long pulses have been obtained at 17 W output power recently [8]. All these lasers employ short resonators with high repetition rates where the beam passes the disk twice per round-trip.

However, higher pulse energies above 10 µJ are needed for processing of many materials [4]. In addition, limited scanning speeds ask for low repetition rates below 10 MHz to assure cold material processing by reducing the pulse overlap on the work piece. With mode-locked oscillators the above parameter range is only accessible with long resonator thin-disk lasers (see Fig. 1). Long resonators, with or without extended resonator cavities, where the beam passes the disk twice per round-trip allow for pulse energies below 6 µJ in ambient air [9,10]. The main limiting factor for the attainable peak intensities stems from the significant self-phase modulation (SPM) introduced by propagation through air during the long intra-cavity beam distance [11]. One approach to overcome this limitation is to evacuate the resonator or to flush it with a gas of low nonlinearity such as helium. With Helium flooding, energies as high as 11 µJ have been generated directly from a disk oscillator with this resonator type [12].

Another approach to overcome the limitations of SPM is to use a larger output coupling rate and hence to reach higher external power at similar (or even lower) intra-cavity powers. For efficient laser operation under high output coupling a high round-trip gain is needed. However, a thin-disk has a low single pass gain. Hence we increased the round-trip gain by passing the gain medium successively under different angles within one round-trip. With this active multipass cell (AMC) approach output coupling ratios above 70% can be tolerated. Hence the nonlinearities can be kept low while still being able to operate the laser at high output power TEM_{00} [13]. This scheme obviously relies on a good surface quality of the disk, as wavefront distortions add up for each pass through the AMC. Using this approach pulse energies of 25.9 µJ with 3 MHz repetition rate directly from an unamplified mode-locked oscillator operated in ambient air were demonstrated [14]. The chronologic development of pulse energies of unamplified mode-locked oscillators over the past decade is summarized in Fig. 1. Pulse energies above 11 µJ were only obtained using the AMC concept.

#164191 - $15.00 USD Received 6 Mar 2012; revised 2 Apr 2012; accepted 3 Apr 2012; published 12 Apr 2012

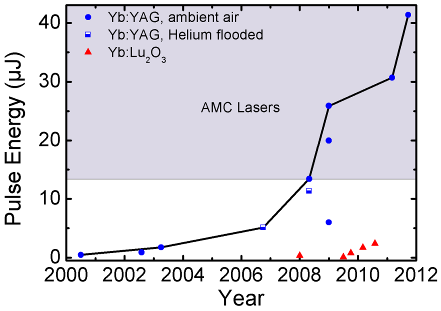

Fig. 1. Development of pulse energies in the past 12 years directly from unamplified mode-locked oscillators. All pulse energies above 11 µJ in ambient air were obtained using the active multipass cell and Yb:YAG as gain medium. Recent high power Yb:Lu$_2$O$_3$ thin-disk results are at significantly lower pulse energies and shorter pulse length.

Here we report higher output powers than [7] using the AMC concept with a simplified and optimized setup compared to [14]. At maximum 41.4 µJ pulse energy at 145 W output power and 3.51 MHz repetition rate were generated in ambient atmosphere.

Especially for material processing frequency conversion to shorter wavelengths is interesting. In a second harmonic generation (SHG) setup we were able to generate 91.5 W of 515 nm picosecond pulses at full oscillator output power. In a standard third harmonic generation (THG) setup 34.4 W of 343 nm light were generated at a reduced oscillator output power of 99 W.

2. Mode-locked AMC laser

Figure 2 shows a schematic layout of an AMC disk oscillator with angular multiplexing. It can be divided into the beam forming part (red and blue) and the AMC (green) that reimaged the spot on the thin-disk. With the beam forming part an appropriate resonator with the desired TEM$_{00}$ mode sizes on the thin-disk and the semiconductor saturable absorber mirror (SESAM) was formed.

The strong SPM mainly introduced by air was balanced by large amounts of negative group delay dispersion (GDD) resulting in soliton mode-locking as the predominant pulse shaping mechanism [15]. Only the multipass cell contained six Gires–Tournois interferometer (GTI) type dispersive mirrors, each having less than –2500 fs^2 that stabilized the soliton pulses. In contrast to [13,14] the mirrors were more dispersive and the beam forming part contained no dispersive mirrors. The resonator was aligned for 11 passes through the AMC (corresponding to 44 passes through the gain medium) within one round-trip, resulting in a total GDD of approximately –346500 fs^2 per round-trip and a total resonator length of 42.7 m, comparable to [13]. The overall SPM factor of this resonator was approximately $\gamma_{SPM} \approx 0.0375$ MW^{-1}, which was mainly introduced by air. The high round-trip gain allowed for an optimum output coupling of approximately 72% adjustable with a quarter wave plate and a thin-film polarizer. Hence the resonator enhancement was low and nonlinear effects and potential damaging effects were greatly reduced. Additionally, the output beam was linearly polarized.

A SESAM was used to start and to stabilize the soliton mode-locking of this laser [5–15]. The measured modulation depth of the InGaAsN quantum well based SESAM was 3.5% and the saturation fluence was 61 µJ/cm^2, both sufficiently high to suppress double pulsing at high pulse energies. The maximum pump power could be increased compared to [14] by using a slightly larger pump spot diameter of 2.4 mm on the thin-disk and a mode radius of 550 µm on the SESAM. The pump light was aligned for 20 passes through the Yb:YAG thin-disk with similar parameters as in [14], leading to below 80% absorption of the fiber-coupled pump power of up to 571 W at a center wavelength of 940 nm.

Received 6 Mar 2012; revised 2 Apr 2012; accepted 3 Apr 2012; published 12 Apr 2012

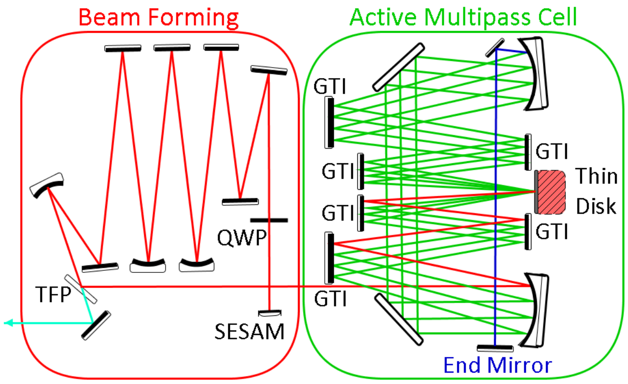

Fig. 2. Schematic of the AMC laser setup. The beam forming part (red and blue) is shown on the left, containing the thin-film polarizer (TFP), a quarter wave plate (QWP) and the semiconductor saturable absorber mirror (SESAM). The right part shows the AMC (green) that reimaged the thin-disk onto itself, where for simplicity of view only 4 passes are shown. It contained the 6 GTI type mirrors that are the only source for negative dispersion.

At the oscillator's maximum average output power of 145 W and a corresponding pump power of 571 W, pulses with energies of 41.4 µJ at 3.511 MHz repetition rate were obtained. With the output coupling ratio of 72% the corresponding maximum intra-cavity pulse energy was 57.5 µJ. A pulse duration of 1120 fs assuming an ideal sech^2 shape and a full width half maximum (FWHM) spectral bandwidth of 1.06 nm at a center wavelength of 1030.0 nm were measured at 41.4 µJ, as shown in Fig. 3. The optical spectrum showed a clean sech^2 shape as expected for soliton mode-locking. The resulting time bandwidth product of 0.336 is within 10% of the transform limit for soliton pulses. In the logarithmic scale of the optical spectrum (right part of Fig. 3) Kelly sidebands were visible at around 1026.7 nm and 1033.2 nm.

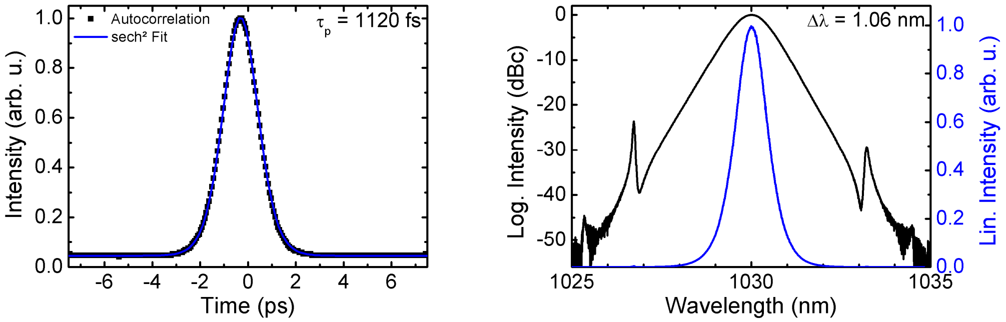

Fig. 3. *Left*: Autocorrelation (AC) trace and sech^2 fit of the measured pulses with 41.4 µJ pulse energy at 11 passes through the multipass cell. The output power was 145 W at 571 W of pump power and 3.511 MHz repetition rate. Assuming an ideal sech^2 pulse the corresponding pulse width is 1120 fs. *Right*: Spectrum of the 41.4 µJ pulses on a logarithmic and linear scale. The FWHM spectral width is 1.06 nm at a center wavelength of 1030.0 nm. The sech^2 shape indicates for clean soliton mode-locking

These Kelly sidebands were suppressed by 23.6 dBc and 29.3 dBc, respectively. The good suppression shows potential for further pulse energy scaling and the difference in suppression indicated for third order dispersion introduced by the dispersive mirrors. Second order Kelly sidebands were visible at the very low intensity parts of the spectrum.

The pulse to pulse energy fluctuations were measured by means of a fast photodiode and an oscilloscope. The standard deviation of the area below the pulse trace is a measure for these fluctuations and showed a standard deviation of 1.1% for 2740 sweeps. A radio frequency analyzer showed a noise suppression of 40 dB, without any visible side lobes. This is an improvement compared to [13,14], where small relaxation oscillations were present.

In the left part of Fig. 4 the output power and the efficiency are drawn versus pump power, whereas in the right part the FWHM spectral width and the pulse length are drawn versus output power. In contrast to the 141 W Yb:Lu_2O_3 laser [7], this laser was stable over the whole pump power range without adjusting resonator arms, although the stability zone was significantly smaller with respect to variations of the focal power of the disk, indicating much better control of the residual thermal lens. The laser showed an efficiency drop at pump powers above 450 W, which was mainly due to the spectral shift of our pump diode to wavelengths above 940 nm. Therefore higher pump powers than 571 W were not possible. The laser operated CW mode-locked as indicated from 73 to 145 W of output power with pulse durations from 2.37 to 1.12 ps (see Fig. 4 right). The FWHM spectral width increased linearly when the laser was operated mode-locked. Soliton mode-locking was confirmed by the reciprocal dependence of the pulse width on the pulse energy. The optical efficiency of the setup could be improved by the use of a better adapted pump chamber with more pump beam passes. Obviously, similar resonators could also be realized with other gain media than Yb:YAG.

Over the whole mode-locking range no CW-background was observable and the laser emitted a nearly diffraction limited beam. Single pulse operation was confirmed using a long range autocorrelator, a fast photodiode and second harmonic generation in the low conversion regime. The OC was adjusted for optimum pulse energy at maximum available pump power. Turning the OC to higher pulse energies, resulted in double pulsing. The rather long pulses before the onset of double pulsing instabilities are in good agreement with our pulse propagation simulations [16]. They showed that for a given SESAM modulation depth the minimum possible pulse length increases with pulse energy. To ensure shorter pulses at high pulse energies a higher SESAM modulation depth or a gain medium with a broader emission cross section is needed.

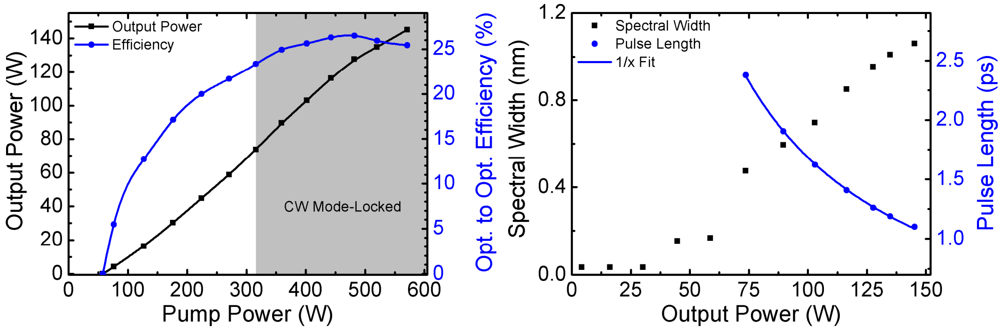

Fig. 4. *Left*: Output power and optical to optical efficiency versus pump power. *Right*: Spectral width and pulse length versus output power. The pulse length is inversely proportional to the output power, indicating for soliton mode-locking as the predominant pulse shaping mechanism. In mode-locked operation the spectral width increases with output power.

To our knowledge, the reported pulse energies are the highest ever obtained directly from an unamplified mode-locked solid-state laser oscillator. This laser architecture appears to be the least complex for generating high energy ultrafast pulses, as there are no active switches inside the resonator.

3. Frequency conversion

Many micromachining applications show better performance and wider process windows in the green or UV spectral range. Silicon for example has a significantly shorter absorption length at wavelengths of 515 nm or 343 nm than at 1030 nm. Hence the ablation at these wavelengths is cleaner and less heat is introduced deeper in the material.

Received 6 Mar 2012; revised 2 Apr 2012; accepted 3 Apr 2012; published 12 Apr 2012

In order to demonstrate the capability of the laser to provide these short wavelengths we set up nonlinear second harmonic generation (SHG) and third harmonic generation (THG) experiments.

For the SHG experiment we used a 4 mm long BBO crystal cut for critically phase matching (CPM) at 515 nm. Using a lens zoom objective the spot diameter in the nonlinear crystal was set to approximately 1.7 mm. The infrared input power was varied by changing the output power of the mode-locked oscillator and accordingly the pulse length (see right part of Fig. 4). The green light was separated from residual IR light by means of dichroic mirrors. In the left part of Fig. 5 the SHG output power and conversion efficiency is shown for this setup. At 141 W output power that was available for frequency conversion output powers up to 91.5 W at 515 nm wavelength with conversion efficiencies beyond 64% have been obtained. Losses in the delivery optics and the telescope have not been included in the efficiency calculation. The SHG conversion results are in good agreement with simulations at similar input parameters, indicating single pulse behavior. At 71 W input power the calculated efficiency for single pulsing is 49.0%, whereas for double pulsing 32.6% would be expected. After frequency conversion the beam still had a Gaussian shape without noticeable distortions.

For the THG experiment we used a 2.5 mm long BBO crystal cut for SHG in combination with a 2.0 mm long BBO crystal cut for sum frequency generation. The spot diameter inside the CPM nonlinear crystals was adjusted to around 1.1 mm. For the results shown in Fig. 5 we set the oscillator to a fixed pulse length of 1.4 ps at reduced output power (see Fig. 4) and varied the infrared power in the nonlinear crystals by means of a half wave plate and a polarizer. At the maximum infrared input power of 99.2 W at the nonlinear crystal we obtained 34.4 W of 343 nm light corresponding to a conversion efficiency of 34.7%. The resulting UV beam had a Gaussian shape similar to the fundamental output of the oscillator. Using higher oscillator powers and hence shorter pulses than 1.4 ps resulted in a reduced power at 343 nm. This can be explained by temporal separation of the fundamental and the converted pulse due to different group velocities inside the nonlinear crystals and may be compensated by shorter nonlinear crystals or to a certain extend by retardation of the infrared pulses between SHG and THG.

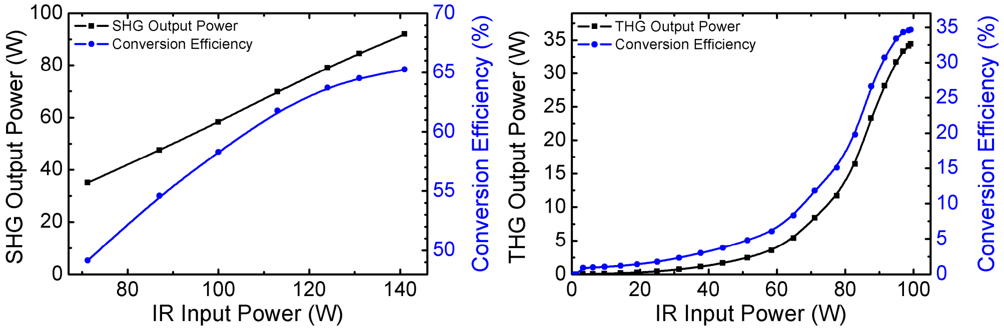

Fig. 5. *Left*: Second harmonic output power and conversion efficiency versus oscillator output power. *Right*: Third harmonic output power and conversion efficiency at different input powers but fixed pulse length.

3. Conclusion and outlook

In conclusion we demonstrated to the best of our knowledge the highest pulse energies of 41.4 µJ and also the highest average output power of 145 W ever obtained directly from an unamplified mode-locked oscillator. At a pulse duration of about one picosecond the corresponding peak power of several tens of megawatt is well suited for high precision micromachining. The repetition rate of 3.5 MHz can be handled with state-of-the-art scanning optics, while higher repetition rates would result in excessive pulse overlap and lead to degradation of machining results. The simplicity of an oscillator setup compared to more sophisticated master oscillator power amplifier systems offers advantages in terms of overall system cost and reliability.

The presented high energy transform limited picosecond pulses are well suited for efficient frequency conversion, as the available peak intensities are very high and the spectral width is comparably small. The experiments show high efficiencies for both SHG with 64.0% and THG with 34.7%. For THG the optimum minimum pulse length and therefore the input power are limited with our conversion crystals. Using shorter nonlinear crystals the full oscillator output power should be usable, giving rise for significantly higher UV output powers.

SESAMs with higher modulation depth and improved dispersive mirrors should allow for even higher pulse energies using the AMC approach.

Acknowledgment

The authors thank the European Union for partial funding of this work within the SOLASYS collaborative project 219050.

#164191 - $15.00 USD Received 6 Mar 2012; revised 2 Apr 2012; accepted 3 Apr 2012; published 12 Apr 2012