Femtosecond diode-pumped solid-state laser with a repetition rate of 4.8 GHz

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Abstract: We report on a diode-pumped Yb:KGW (ytterbium-doped potassium gadolinium tungstate) laser with a repetition rate of 4.8 GHz and a pulse duration of 396 fs. Stable fundamental modelocking is achieved with a semiconductor saturable absorber mirror (SESAM). The average output power of this compact diode-pumped solid state laser is 1.9 W which corresponds to a peak power of 0.9 kW and the optical-to-optical efficiency is 36%. To the best of our knowledge, this is the femtosecond DPSSL with the highest repetition rate ever reported so far.

OCIS codes: (140.4050) Mode-locked lasers; (140.3615) Lasers, ytterbium; (140.3480) Lasers, diode-pumped; (140.3580) Lasers, solid-state; (320.7090) Ultrafast lasers; (120.3940) Metrology.

References and links

1. H. R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, and U. Keller, "Carrier-envelope offset phase control: A novel concept for absolute optical frequency measurement and ultrashort pulse generation," Appl. Phys. B **69**(4), 327–332 (1999).
2. D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, "Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis," Science **288**(5466), 635–639 (2000).
3. S. A. Diddams, D. J. Jones, J. Ye, S. T. Cundiff, J. L. Hall, J. K. Ranka, R. S. Windeler, R. Holzwarth, T. Udem, and T. W. Hänsch, "Direct link between microwave and optical frequencies with a 300 THz femtosecond laser comb," Phys. Rev. Lett. **84**(22), 5102–5105 (2000).
4. D. C. Heinecke, A. Bartels, and S. A. Diddams, "Offset frequency dynamics and phase noise properties of a self-referenced 10 GHz Ti:sapphire frequency comb," Opt. Express **19**(19), 18440–18451 (2011).
5. D. Hillerkuss, R. Schmogrow, T. Schellinger, M. Jordan, M. Winter, G. Huber, T. Vallaitis, R. Bonk, P. Kleinow, F. Frey, M. Roeger, S. Koenig, A. Ludwig, A. Marculescu, J. Li, M. Hoh, M. Dreschmann, J. Meyer, S. Ben Ezra, N. Narkiss, B. Nebendahl, F. Parmigiani, P. Petropoulos, B. Resan, A. Oehler, K. Weingarten, T. Ellermeyer, J. Lutz, M. Moeller, M. Huebner, J. Becker, C. Koos, W. Freude, and J. Leuthold, "26 Tbit s^{-1} line-rate super-channel transmission utilizing all-optical fast Fourier transform processing," Nat. Photonics **5**(6), 364–371 (2011).
6. R. Aviles-Espinosa, G. Filippidis, C. Hamilton, G. Malcolm, K. J. Weingarten, T. Südmeyer, Y. Barbarin, U. Keller, S. I. C. O. Santos, D. Artigas, and P. Loza-Alvarez, "Compact ultrafast semiconductor disk laser: targeting GFP based nonlinear applications in living organisms," Biomed. Opt. Express **2**(4), 739–747 (2011).
7. S.-W. Chu, T.-M. Liu, C.-K. Sun, C.-Y. Lin, and H.-J. Tsai, "Real-time second-harmonic-generation microscopy based on a 2-GHz repetition rate Ti:sapphire laser," Opt. Express **11**(8), 933–938 (2003).
8. R. Paschotta, A. Schlatter, S. C. Zeller, H. R. Telle, and U. Keller, "Optical phase noise and carrier-envelope offset noise of mode-locked lasers," Appl. Phys. B **82**(2), 265–273 (2006).
9. A. Schlatter, B. Rudin, S. C. Zeller, R. Paschotta, G. J. Spühler, L. Krainer, N. Haverkamp, H. R. Telle, and U. Keller, "Nearly quantum-noise-limited timing jitter from miniature Er:Yb:glass lasers," Opt. Lett. **30**(12), 1536–1538 (2005).
10. A. E. H. Oehler, T. Südmeyer, K. J. Weingarten, and U. Keller, "100 GHz passively mode-locked Er:Yb:glass laser at 1.5 µm with 1.6-ps pulses," Opt. Express **16**(26), 21930–21935 (2008).
11. L. Krainer, R. Paschotta, S. Lecomte, M. Moser, K. J. Weingarten, and U. Keller, "Compact Nd:YVO_4 lasers with pulse repetition rates up to 160 GHz," IEEE J. Quantum Electron. **38**(10), 1331–1338 (2002).

#160525 - $15.00 USD Received 23 Dec 2011; revised 30 Jan 2012; accepted 2 Feb 2012; published 6 Feb 2012

12. A. E. H. Oehler, M. C. Stumpf, S. Pekarek, T. Südmeyer, K. J. Weingarten, and U. Keller, "Picosecond diode-pumped 1.5 µm Er,Yb:glass lasers operating at 10–100 GHz repetition rate," Appl. Phys. B **99**(1-2), 53–62 (2010).
13. P. Wasylczyk, P. Wnuk, and C. Radzewicz, "Passively modelocked, diode-pumped Yb:KYW femtosecond oscillator with 1 GHz repetition rate," Opt. Express **17**(7), 5630–5635 (2009).
14. S. Yamazoe, M. Katou, T. Adachi, and T. Kasamatsu, "Palm-top-size, 1.5 kW peak-power, and femtosecond (160 fs) diode-pumped mode-locked Yb^{+3}:$KY(WO_4)_2$ solid-state laser with a semiconductor saturable absorber mirror," Opt. Lett. **35**(5), 748–750 (2010).
15. D. Li, U. Demirbas, J. R. Birge, G. S. Petrich, L. A. Kolodziejski, A. Sennaroglu, F. X. Kärtner, and J. G. Fujimoto, "Diode-pumped passively mode-locked GHz femtosecond Cr:LiSAF laser with kW peak power," Opt. Lett. **35**(9), 1446–1448 (2010).
16. S. Pekarek, T. Südmeyer, S. Lecomte, S. Kundermann, J. M. Dudley, and U. Keller, "Self-referenceable frequency comb from a gigahertz diode-pumped solid-state laser," Opt. Express **19**(17), 16491–16497 (2011).
17. S. Pekarek, C. Fiebig, M. C. Stumpf, A. E. H. Oehler, K. Paschke, G. Erbert, T. Südmeyer, and U. Keller, "Diode-pumped gigahertz femtosecond Yb:KGW laser with a peak power of 3.9 kW," Opt. Express **18**(16), 16320–16326 (2010).
18. U. Keller, J. A. Valdmanis, M. C. Nuss, and A. M. Johnson, "53ps pulses at 1.32 µm from a harmonic mode-locked Nd:YAG laser," IEEE J. Quantum Electron. **24**(2), 427–430 (1988).
19. M. F. Becker, D. J. Kuizenga, and A. E. Siegman, "Harmonic Mode Locking of the Nd:YAG laser," IEEE J. Quantum Electron. **8**(8), 687–693 (1972).
20. C. Fiebig, G. Blume, C. Kaspari, D. Feise, J. Fricke, M. Matalla, W. John, H. Wenzel, K. Paschke, and G. Erbert, "12W high-brightness single-frequency DBR tapered diode laser," Electron. Lett. **44**(21), 1253–1255 (2008).
21. U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, "Semiconductor saturable absorber mirrors (SESAMs) for femtosecond to nanosecond pulse generation in solid-state lasers," IEEE J. Sel. Top. Quantum Electron. **2**(3), 435–453 (1996).
22. M. Haiml, R. Grange, and U. Keller, "Optical characterization of semiconductor saturable absorbers," Appl. Phys. B **79**(3), 331–339 (2004).
23. C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, "Q-switching stability limits of continuous-wave passive mode locking," J. Opt. Soc. Am. B **16**(1), 46–56 (1999).
24. F. X. Kärtner, I. D. Jung, and U. Keller, "Soliton Mode-Locking with Saturable Absorbers," IEEE J. Sel. Top. Quantum Electron. **2**(3), 540–556 (1996).
25. R. Paschotta and U. Keller, "Passive mode locking with slow saturable absorbers," Appl. Phys. B **73**(7), 653–662 (2001).
26. F. Druon, S. Chénais, P. Raybaut, F. Balembois, P. Georges, R. Gaumé, G. Aka, B. Viana, S. Mohr, and D. Kopf, "Diode-pumped $Yb:Sr_3Y(BO_3)_3$ femtosecond laser," Opt. Lett. **27**(3), 197–199 (2002).

1. Introduction

A wide range of applications benefits from lasers combining short pulses in the femtosecond regime and high repetition rates in the gigahertz regime. For instance, in case of frequency combs [1–4] from high repetition rate modelocked lasers, the lines are less densely spaced and hence, the average power is divided by less lines. Therefore, such combs provide an increased power per mode for the same overall optical bandwidth and total power. Another advantage is the simplified access to individual optical lines in comparison to low repetition rate sources. Moreover, high repetition rate femtosecond lasers are also beneficial for example for fast data transmission [5] or nonlinear biophotonic applications [6]. In the latter case, a higher repetition rate laser reduces the photodamage possibility [7].

Ultrafast diode-pumped solid-state lasers (DPSSLs) are excellent compact sources for these purposes. They combine the favorable properties of cost-efficient diode-pumping and an intrinsic low quantum noise level [8, 9]. In the picosecond regime, DPSSLs have proven to operate at repetition rates in the regime of tens of gigahertz [10–12]. But so far, there were only a few demonstrations of DPSSLs combining gigahertz repetition rates and femtosecond pulse durations. A Kerr-lens modelocked laser based on $Yb:KY(WO_4)_2$ (Yb:KYW) with a repetition rate of 1 GHz and an average output power of 115 mW was demonstrated [13]. Its pulse duration was estimated from the optical spectrum to be 200 fs, but no autocorrelation was provided. A semiconductor saturable absorber mirror (SESAM) modelocked Yb:KYW laser was operated at a repetition rate of 2.8 GHz delivering 162-fs pulses at an average output power of 680 mW [14]. Short pulses with a duration of 55 fs were obtained from a 1-GHz Cr:LiSAF laser with an average output power of 110 mW [15]. Recently, the first self-

#160525 - $15.00 USD Received 23 Dec 2011; revised 30 Jan 2012; accepted 2 Feb 2012; published 6 Feb 2012

referenceable frequency comb from a gigahertz DPSSL was demonstrated with an Yb:KGd(WO_4)$_2$ (Yb:KGW) laser which delivered an average output power of 2.2 W in 290-fs pulses [16]. An overview on fundamentally modelocked DPSSLs with a repetition rate >1 GHz is given in Table 1.

Table 1. Overview on fundamentally modelocked diode-pumped solid-state lasers (DPSSLs) with a repetition rate >1 GHz with f_{rep}: repetition rate, τ_p: pulse duration, P_{av}: average output power, E_p: pulse energy, P_0: peak power and λ_0: center wavelength. The reference is a state of the art Ti:sapphire laser.

f_{rep}	τ_p	P_{av}	E_p	P_0	gain material	λ_0	reference
10 GHz	42 fs	1.06 W	50 pJ	3.5 kW	Ti:sapphire	788 nm	[4]
160 GHz	2.7 ps	110 mW	0.69 pJ	0.25 W	Nd:YVO_4	1064 nm	[11]
100 GHz	1.1 ps	35 mW	0.35 pJ	0.32 W	Er:Yb:glass	1550 nm	[10, 12]
4.8 GHz	396 fs	1900 mW	0.40 nJ	0.9 kW	Yb:KGW	1043 nm	here
2.8 GHz	162 fs	680 mW	0.23 nJ	1.5 kW	Yb:KYW	1045 nm	[14]
1 GHz	55 fs	110 mW	0.11 nJ	1.8 kW	Cr:LiSAF	865 nm	[15]
1 GHz	*200 fs	115 mW	0.12 nJ	0.5 kW	Yb:KYW	1047 nm	[13]
1 GHz	290 fs	2200 mW	2.20 nJ	6.7 kW	Yb:KGW	1042 nm	[16, 17]

*estimated from the optical spectrum, no autocorrelation was provided

In this paper, we report on the highest repetition rate ever obtained with a femtosecond DPSSL. We present a SESAM modelocked Yb:KGW laser with a repetition rate of 4.8 GHz, a pulse duration of 396 fs and an average output power of 1.9 W. This corresponds to a pulse energy of 0.4 nJ and a peak power of 0.9 kW. This result is based on fundamental modelocking in contrast to harmonic modelocking [18, 19] which always introduces additional noise.

2. Experimental setup

In a previous publication, we reported on a fundamentally modelocked femtosecond Yb:KGW laser with a repetition rate of 1 GHz [17]. The corresponding optical cavity length is 14.8 cm. Furthermore, we demonstrated harmonic modelocking up to a repetition rate of 4 GHz with the same cavity but with a decreased mode size on the SESAM which resulted in an increased SESAM saturation [17]. For the results presented here, a similar saturation level as in [16] was maintained, by decreasing the optical cavity length to 3.1 cm and the mode size on the SESAM. A schematic and a photo of the fundamentally modelocked 4.8-GHz Yb:KGW laser is shown in Fig. 1(a) respectively Fig. 1(b).

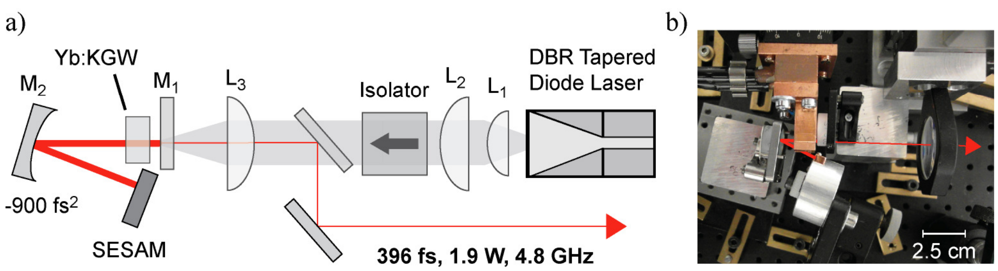

Fig. 1. Layout of the 4.8-GHz Yb:KGW laser: a) schematic of the laser setup with L_1, L_2, L_3: pump optics; M_1: flat mirror transparent for the pump wavelength and output coupler for the lasing wavelength, transmission 2.8%, M_2: curved highly reflective Gires-Tournois interferometer type mirror with a group delay dispersion of –900 fs^2, radius of curvature: 15 mm; SESAM: semiconductor saturable absorber mirror and b) photo of the cavity.

The pump laser was a distributed Bragg reflector (DBR) tapered diode laser [20]. Owing to its high brightness, this is a promising pump laser source for high repetition rate femtosecond DPSSLs. The used DBR tapered diode laser delivered a pump power of up to 5.3-W at the wavelength of 980 nm with a nearly diffraction limited beam with an M^2(1/e^2) of 1.3, where more than 85% of the power was in the central lobe. An isolator was used to

#160525 - $15.00 USD Received 23 Dec 2011; revised 30 Jan 2012; accepted 2 Feb 2012; published 6 Feb 2012

protect the pump laser from back reflections. The gain medium was a passively water-cooled 2-mm-thick, anti-reflection coated Yb:KGW crystal with a doping concentration of 5 at.%. One end mirror of the cavity (M_1) exhibited a high transmission for the pump wavelength and was used as an output coupler with a transmission of 2.8% for the lasing wavelength of 1043 nm. A dichroic mirror in front of the cavity separated the laser and the pump light. The other end mirror of the cavity was a SESAM [21]. It was a standard quantum-well based, antiresonant SESAM with a modulation depth of 0.7%, nonsaturable losses less than 0.1% and a saturation fluence of 81 μJ/cm^2 (measured with the setup presented in [22]). A Gires-Tournois interferometer (GTI)-mirror (M_2) provided a group delay dispersion of –900 fs^2. This cavity design allowed small spot sizes both on the gain and on the SESAM which is favorable for to achieve stable continuous wave modelocking [23]. According to ABCD-matrix calculations, the radius of the laser mode was around 38 μm on both the gain medium and the SESAM.

3. Results

With the above described setup, we achieved stable fundamental SESAM-soliton-modelocking [24] at the repetition rate of 4.8 GHz (Fig. 2). The average output power was 1.9 W at a pump power of 5.3 W. The microwave frequency spectrum confirms clean continuous wave (cw) modelocking without disturbances or side peaks.

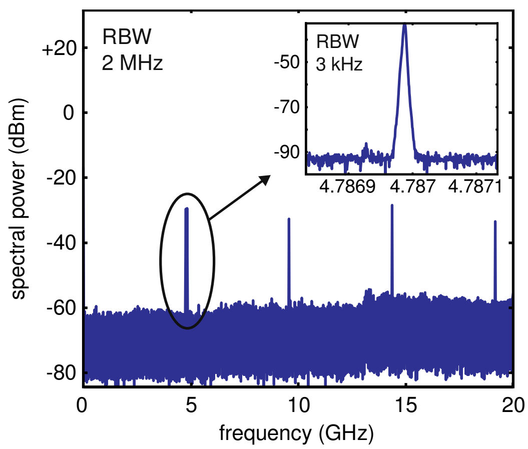

Fig. 2. The microwave spectrum of the output power (monitored with a photodetector and a microwave spectrum analyzer) with a spectral span of 20 GHz and a resolution bandwidth (RBW) of 2 MHz shows a repetition rate of 4.8 GHz. The inset shows the spectrum on a small span of 300 kHz with a RBW of 3 kHz.

The pulse duration τ_p was 396 fs (Fig. 3(a)) and the optical spectrum (Fig. 3(b)) had a full width at half maximum (FWHM) $\Delta\lambda$ of 4.1 nm and was centered around 1043 nm. Both the optical spectrum and the autocorrelation trace were well fitted assuming ideal sech^2-pulses. The time bandwidth product (TBP) of 0.446 was 1.4 times the theoretical value for sech^2-pulses of 0.315. The peak power was 0.9 kW and the pulse energy was 0.4 nJ.

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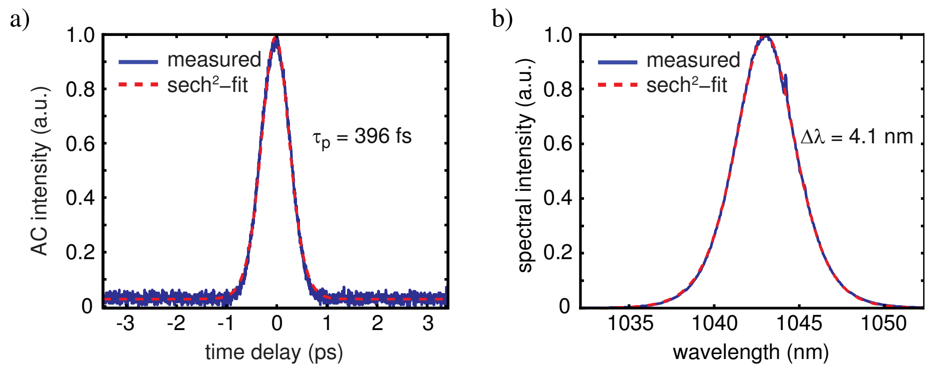

Fig. 3. SESAM soliton-modelocked 4.8-GHz Yb:KGW laser: a) normalized autocorrelation (AC) and b) optical spectrum with the fits for $sech^2$-pulses. The pulse duration was 396 fs and the spectral bandwidth was 4.1 nm centered around 1043 nm.

In modelocked operation, the optical-to-optical efficiency was 36%, the slope efficiency was 33% (Fig. 4) and the electrical power consumption was less than 25 W. The beam was close to the diffraction limit with a measured $M^2_x = 1.2$ and $M^2_y = 1.0$. Single pulse operation has been verified with scanning the autocorrelator for cross correlations (scanning range 180 ps).

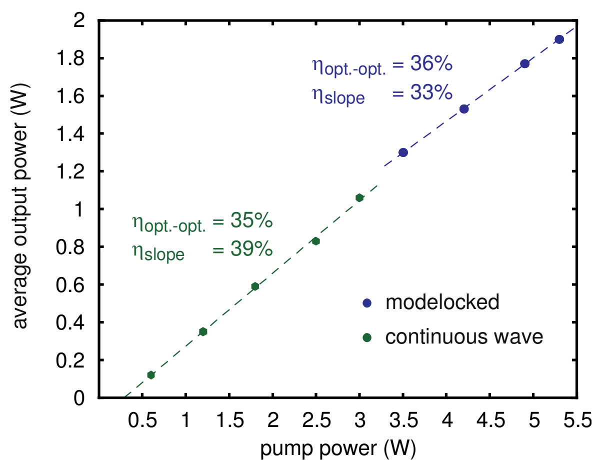

Fig. 4. Yb:KGW laser efficiency at continuous wave (cw) and cw modelocked operation: average output power as a function of the pump power. We applied a linear fit (dashed lines) to determine the slope efficiencies both in cw and cw modelocked operation. At lower pump power only cw operation was achieved with a 3-W pump power threshold for the onset of stable SESAM modelocking. When cw modelocking starts the averaged SESAM loss becomes reduced which increases the average output power and we therefore quote a different slope and optical-to-optical efficiency for this regime.

4. Conclusion and outlook

In conclusion, we have presented an efficient and compact femtosecond Yb:KGW laser oscillator with a repetition rate of 4.8 GHz. To our knowledge, this is the highest repetition rate ever reported for a femtosecond DPSSL. Stable, fundamental modelocked operation was achieved with a SESAM. The laser delivered an average output power of 1.9 W in 396-fs pulses at the wavelength of 1043 nm. The corresponding peak power was 0.9 kW. The combination of a high repetition rate, femtosecond pulses and a high power level makes the presented laser a promising source for multi-GHz self-referenced frequency combs. In the present configuration, the time-bandwidth product is 1.4 times the ideal value. Therefore,

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shorter pulse durations could be achieved by an optimized dispersion compensation. This was not possible in the current setup with the given dispersion from a single GTI-mirror. In addition, the minimal achievable pulse duration can be limited by the available self-phase modulation (SPM) [25]. Therefore, further investigations on the required amount of SPM are planned. Furthermore, materials with a broader gain bandwidth, as for instance Yb-doped Borates [26], might enable shorter pulse durations. Even higher repetition rates in fundamental, cw modelocked operation seem feasible, especially as a consequence of the fact that no Q-switched modelocking was observed at any pump power.

Acknowledgments

This work was supported by the Swiss Innovation Promotion Agency with the KTI contract Nr. 10497.2 PFNM-NM.