Femtosecond $Yb:KGd(WO_4)_2$ laser oscillator pumped by a high power fiber-coupled diode laser module

Arkady Major, Richard Cisek and Virginijus Barzda

Department of Physics and Institute for Optical Sciences, University of Toronto, 3359 Mississauga Rd. N., Mississauga, ON, L5L 1C6, Canada
a.major@utoronto.ca

Abstract: The development and characterization of a diode-pumped ultrashort pulse $Yb:KGd(WO_4)_2$ laser oscillator is reported. The laser was pumped by a 25W fiber-coupled diode laser module operating at 980 nm wavelength. In the mode-locked regime, 296 fs duration pulses centered around 1031 nm were generated at a repetition rate of 61 MHz with a total average output power of up to 3.7W, corresponding to 205 kW of peak power and 60 nJ of energy per pulse. Compensation of positive intracavity dispersion was realized using a single chirped dielectric mirror.

OCIS Codes: (140.3580) Lasers, solid-state; (140.3480) Lasers, diode-pumped; (140.7090) Ultrafast lasers; (140.4050) Mode-locked lasers

References and links

1. W. F. Krupke, "Ytterbium solid-state lasers - the first decade," IEEE J. Sel. Top. Quantum Electron. **6**, 1287-1296 (2000).
2. A. Brenier, "A new evaluation of Yb^{3+}-doped crystals for laser applications," J. Luminesc. **92**, 199-2004 (2001).
3. N. V. Kuleshov, A. A. Lagatsky, A. V. Podlipensky, V. P. Mikhailov, G. Huber, "Pulsed laser operation of Yb-doped $KY(WO_4)_2$ and $KGd(WO_4)_2$," Opt. Lett. **22**, 1317-1319 (1997).
4. F. Brunner, G. J. Spühler, J. Aus der Au, L. Krainer, F. Morier-Genoud, R. Paschotta, N. Lichtenstein, S. Weiss, C. Harder, A. A. Lagatsky, A. Abdolvand, N. V. Kuleshov, and U. Keller, "Diode-pumped femtosecond $Yb:KGd(WO_4)_2$ laser with 1.1W average output," Opt. Lett. **25**, 1119-1121 (2000).
5. A. Courjaud, N. Deguil, F. Salin, "High power diode-pumped Yb:KGW ultrafast laser," in OSA *Trends in Optics and Photonics (TOPS) Vol. **73**, Conference on Lasers and Electro-Optics,* OSA Technical Digest (Optical Society of America, Washington DC, 2002), paper CThO 3, pp. 501-502.
6. F. Brunner, T. Südmeyer, E. Innerhofer, F. Morier-Genoud, R. Paschotta, V. E. Kisel, V. G. Shcherbitsky, N. V. Kuleshov, J. Gao, K. Contag, A. Giesen, U. Keller, "240-fs pulses with 22-W average power from a mode-locked thin-disk $Yb:KY(WO_4)_2$ laser," Opt. Lett. **27**, 1162-1164 (2002).
7. G. R. Holtom, "Mode-locked Yb:KGW laser longitudinally pumped by polarization-coupled diode bars," Opt. Lett. **31**, 2719-2721 (2006).
8. A. Major, P. Piunno, S. Musikhin, U. Krull and V. Barzda, "An extended cavity diode-pumped femtosecond Yb:KGW laser for applications in optical DNA sensor technology based on fluorescence lifetime measurements," Opt. Express **14**, 5285-5294 (2006).
9. A. A. Lagatsky, E. U. Rafailov, C. G. Leburn, C. T. A. Brown, N. Xiang, O. G. Okhotnikov, and W. Sibbett, "Highly efficient femtosecond Yb:KYW laser pumped by single narrow-stripe laser diode," Electron. Lett. **39**, 1108-1110 (2003).
10. A. Major, R. Cisek, and V. Barzda, "Diode-pumped high power continuous-wave Yb:KGW laser," in *Conference on Lasers and Electro-Optics / Quantum Electronics and Laser Science Conference and Photonic Applications, Systems and Technologies 2006 Technical Digest* (Optical Society of America, Washington, DC, 2006), paper CThF6.
11. A. Lucca, G. Debourg, M. Jacquemet, F. Druon, F. Balembois, P. Georges, P. Camy, J. L. Doualan, and R. Moncorgé, "High-power diode-pumped $Yb^{3+}:CaF_2$ femtosecond laser," Opt. Lett. **29**, 2767-2769 (2004).
12. F. Thibault, D. Pelenc, F. Druon, Y. Zaouter, M. Jacquemet, and P. Georges, "Efficient diode-pumped $Yb^{3+}:Y_2SiO_5$ and $Yb^{3+}:Lu_2SiO_5$ high-power femtosecond laser operation," Opt. Lett. **31**, 1555-1557 (2006).

#75252 - $15.00 USD Received 19 September 2006; revised 21 November 2006; accepted 26 November 2006

1. Introduction

Directly diode-pumped Yb^{3+}-ion doped solid-state lasers form ideal platforms for the development of efficient mode-locked femtosecond oscillators and amplifiers [1-12]. Among a variety of the Yb-doped crystalline laser materials, the crystals of Yb-doped double tungstates Yb:KGd$(WO_4)_2$ and Yb:KY$(WO_4)_2$ (Yb:KGW and Yb:KYW, respectively) are known to have broad amplification bandwidths, high laser emission and pump absorption cross sections, and small quantum defects [2,3]. These properties make them particularly suitable for ultrashort pulse generation with efficient diode pumping using commercially available InGaAs laser diodes in the 930-980 nm region [4-6].

Previously, output powers on the order of 1W were demonstrated from longitudinally-pumped Yb:KGW lasers both in continuous wave (CW) as well as in mode-locked regimes [4,5]. Power scaling of such laser systems is very attractive for applications in, for example, nonlinear microscopy, spectroscopy, and frequency conversion. Unfortunately, higher output powers usually come at the expense of simplicity and cost. In one case, the use of a more sophisticated and bulky thin-disk geometry produced more than 22W of average power in 240 fs duration pulses [6]. In another experiment, 10W of average power was generated with slightly longer pulses by the use of two polarization-coupled diode bars [7]. The Brewster's angle incidence of pump radiation on the dichroic mirrors makes the construction and service of this setup quite complicated.

On the other hand, power scaling of laser systems based on classical delta-cavity designs and fiber-coupled diode pump modules presents a promising alternative in terms of simplicity and cost-effectiveness [8]. In this paper we demonstrate a simple design of a high power femtosecond Yb:KGW laser and show that its output power can be scaled to reach multi-Watt levels.

2. Experimental setup and results

Initially, a high-power CW diode-pumped Yb:KGW laser was developed and characterized. Since optical pumping at 980 nm provides a smaller quantum defect than pumping at 930-940 nm, and results in lower heat deposition inside the crystal, a laser diode operating near this wavelength was used.

2.1 Continuous-wave operation

An experimental setup of the CW Yb:KGW laser is presented in Fig. 1. A 25W diode module (Apollo Instruments Inc.) coupled into a 200 μm core diameter (0.22 NA) optical fiber was employed for optical pumping. The output of the laser diode was imaged by two antireflection (AR) coated spherical lenses (40 and 50 mm focal lengths) onto a 4-mm-long and 2-mm-thick AR-coated plane/plane Yb:KGW crystal (Eksma) with 5% Yb-doping. The crystal had a slab design to facilitate efficient heat removal and was cut along the N_p-axis to access the high-gain polarization parallel to the crystallographic N_m-axis [9]. The pump beam passed through a dichroic mirror M1, coated for high transmission (>95%) at the pump wavelength and high reflection (>99.9%) in the 1020-1080 nm region (Laseroptik GmbH). The pump spot inside the crystal was ~250 μm in diameter, corresponding to a confocal parameter of ~2.9 mm. The crystal was wrapped in indium foil and held between thermoelectric coolers which kept it at a constant temperature of about 10 °C.

The laser cavity was formed by the dichroic mirror M1, a highly reflective concave mirror M2 (radius of curvature r = 200 mm) and a plane output coupler (OC) with transmission in the range between 1.5 and 6.0%. The cavity was configured to provide a mode size diameter of 240 μm inside the crystal. The folding angle of the cavity was kept as small as possible (~4°) in order to minimize introduced beam astigmatism.

#75252 - $15.00 USD Received 19 September 2006; revised 21 November 2006; accepted 26 November 2006

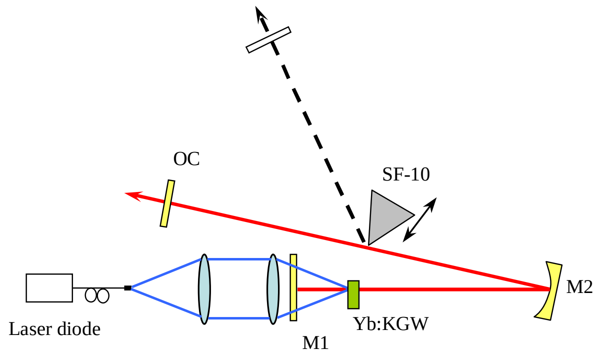

Fig. 1. Layout of a CW Yb:KGW laser.

The performance of the laser in the CW regime is shown in Fig. 2. The highest output power was achieved with 1.5% OC. At the maximum incident pump power of 23W the laser delivered up to 6.0W of CW radiation (polarized along the N_m-axis), corresponding to a laser slope efficiency of 41% with respect to the incident pump power. For comparison, laser power achieved using a 4.5% OC is also shown in Fig. 2. The pump absorption in the crystal was measured to be 70-80% under non-lasing conditions depending on the pump power level. The laser always operated in the fundamental transverse mode.

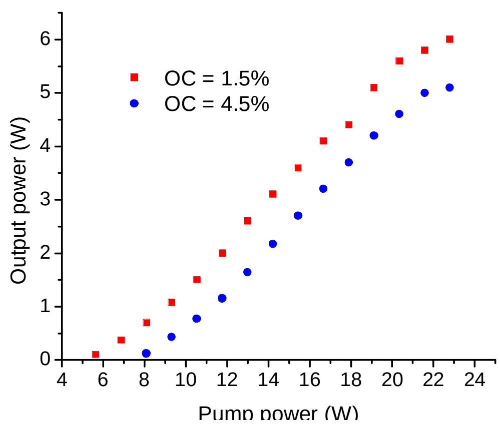

Fig. 2. Output power versus incident pump power in the CW regime.

To tune the laser wavelength, an SF10 dispersive prism was introduced between the folding mirror M2 and the OC (Fig. 1). In this configuration, the laser could be continuously tuned over 41 nm, between 1035 and 1076 nm, providing between 1.3 and 4.5W of output power [10], as shown in Fig. 3. When the OC was replaced with a highly reflective mirror, the tunability range became 1030-1090 nm, which should be expected owing to the lower cavity losses.

2.2 Mode-locked operation

To obtain femtosecond pulse generation, the continuous-wave cavity was changed to the cavity configuration illustrated in Fig. 4. The pump focusing arrangement, the dichroic mirror, as well as the laser crystal were kept the same. The concave mirrors M2 and M4 had radii of curvature of 500 mm, and the mirror M1 was flat. All the mirrors had highly reflective coatings in the 1020-1080 nm wavelength range. The cavity mode spot size inside the crystal

#75252 - $15.00 USD Received 19 September 2006; revised 21 November 2006; accepted 26 November 2006

was also kept the same.

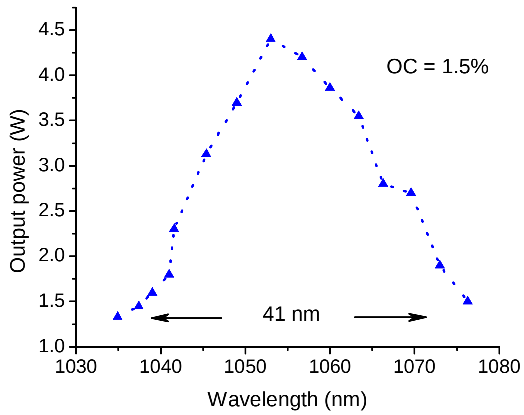

Fig. 3. Wavelength tuning in the CW regime.

A single Gires-Tournois interferometer (GTI) mirror (Layertec GmbH) was used to compensate for the positive dispersion introduced by the cavity elements. With the help of mirror M1, up to three reflections off the GTI mirror could be accommodated in the laser setup. The mirror was designed to have a dispersion of -1300 ± 50 fs^2 per reflection. As a mode locking element, a semiconductor saturable absorber mirror (SESAM, Batop GmbH) designed for 1040 nm wavelength with a specified modulation depth of 1% was inserted at one end of the cavity. The cavity focusing mirror M4 provided a beam spot size on the SESAM of approximately ~350 µm in diameter. The round-trip cavity length was ~4.9 m, giving a pulse repetition frequency of 61 MHz.

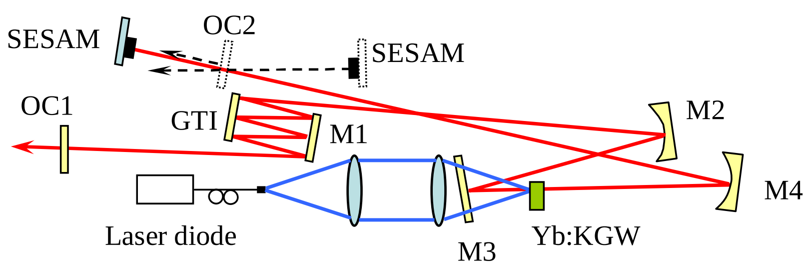

Fig. 4. Cavity layout of the high-power femtosecond Yb:KGW laser.

At first, the optimum performance in the mode-locked regime was obtained with a 6.0% output coupler (OC1 in Fig. 4) and three reflections on the GTI mirror. The lower number of bounces on the GTI mirror resulted only in multiple pulse mode locking. Above the mode locking threshold, corresponding to ~550 mW of average output power (or 11.2W of pump power), operation of the laser changed from the Q-switched regime to a mode-locked one to produce stable trains of femtosecond pulses. With 18.5W of pump power the laser generated as high as 2.4W of average output power, which corresponded to an optical-to-optical efficiency of 13%.

Further increase in pump power resulted in pulse splitting. The spacing between the pulses in the cavity depended on the pump power, laser alignment and ranged from 2-3 ps to half the cavity round-trip time. The pulse splitting was most likely caused by the uncompensated excess self-phase modulation. Special care was taken to verify single pulse operation using a time-correlated single photon counting technique with temporal resolution of ~30 ps.

The duration of the generated laser pulses was characterized with a second order autocorrelator based on two-photon absorption in a red light-emitting diode. The corresponding pulse spectrum, centered at 1038 nm, and an autocorrelation trace of 230 fs pulses measured at 2.4W of average output power are presented in Fig. 5. The peak-to-background ratio of the autocorrelation was checked to be 3:1, confirming proper mode locking (not shown in Fig. 5). The time-bandwidth product was calculated to be 0.35, indicating that the pulses were almost transform-limited (0.32 assuming a $sech^2$ temporal profile). This discrepancy could in part be caused by the limited resolution of our spectrometer, which is on the order of 1 nm, uncompensated self-phase modulation and higher-order dispersion. The pulse duration did not appreciably change with the output power. Taking into account the pulse repetition rate of 61 MHz, the laser generated approximately 39 nJ of energy per pulse. Therefore, the peak power delivered by the pulses can be estimated to be 170 kW.

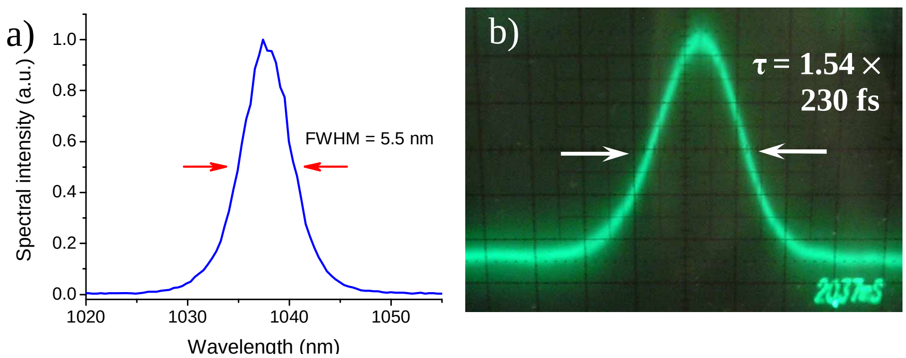

Fig. 5. Measured spectrum (a) and autocorrelation trace (b) of the 230 fs pulses.

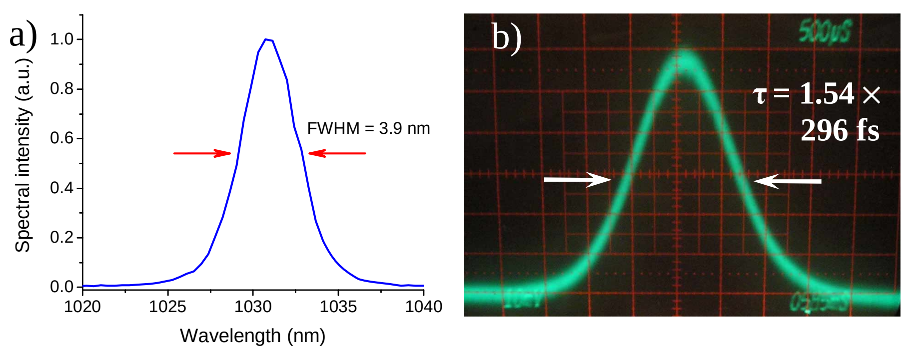

Fig. 6. Measured spectrum (a) and autocorrelation trace (b) of the 296 fs pulses.

To avoid pulse splitting due to excess self-phase modulation, the amount of intracavity power was lowered by increasing the output coupling of the laser. Since an OC with transmission higher than 6.0% was not available at the time of experiments, a second OC was introduced in the cavity, which acted as a folding mirror and resulted in two additional output beams (OC2 in Fig. 4). Optimum performance was achieved with a 4.5% transmission OC2, corresponding to a net useful loss of 15.0%. At 22.8W of pump power the laser generated a total of 3.7W of average output power, with a higher optical-to-optical efficiency of 16%. The mode locking threshold and pulse duration increased to 1.1W of output power and 296 fs

#75252 - $15.00 USD Received 19 September 2006; revised 21 November 2006; accepted 26 November 2006

respectively. The pulse width measurements and monitoring were done in the same way as before, with corresponding spectral and temporal profile traces shown in Fig. 6. In this case the time-bandwidth product of the pulses was found to be 0.33, within 5% of the transform-limit. The maximum effective generated pulse energy can be estimated to be 60 nJ, which translates into 205 kW of peak power. A single beam output with similar performance can be readily produced if a proper output coupler with 15.0% of transmission would be available. Depending on laser alignment, pulse break up into two pulses could also be observed.

In both cases passive mode locking was not completely self-starting and often required a slight tap on any mirror mount to start. Once initiated, it could be sustained for hours of operation. The maximum energy fluence on the SESAM for 6.0 and 15.0% OC was calculated to be 660 and 415 μJ/cm^2, respectively, and no damage of the device was observed. Including the pump module, the laser setup had a 90×20 cm footprint.

3. Conclusion

In conclusion, we demonstrated a simple design of a high power ultrashort pulse Yb:KGW laser which was pumped by a high-brightness fiber-coupled diode module. The laser provided up to 2.4W in 230 fs pulses or up to 3.7W (combined) in 296 fs pulses at a repetition rate of 61 MHz. The output power in our case was limited by the available pump power and therefore can be scaled to higher values. Our results compare favorably with the recently demonstrated performance of CaF_2, Yb:LSO and Yb:YSO based laser systems [11,12], which operated in the 2W regime of output power.

Acknowledgments

This research was funded by Canada Foundation of Innovation, Ontario Innovation Trust and the Natural Sciences and Engineering Research Council of Canada.

#75252 - $15.00 USD Received 19 September 2006; revised 21 November 2006; accepted 26 November 2006