Diode-pumped femtosecond Yb:KGd(WO$_4$)$_2$ laser with 1.1-W average power

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We demonstrate what is to our knowledge the first mode-locked Yb:KGd(WO$_4$)$_2$ laser. Using a semiconductor saturable-absorber mirror for passive mode locking, we obtain pulses of 176-fs duration with an average power of 1.1 W and a peak power of 64 kW at a center wavelength of 1037 nm. We achieve pulses as short as 112 fs at a lower output power. The laser is based on a standard delta cavity and pumped by two high-brightness laser diodes, making the whole system very simple and compact. Tuning the laser by means of a knife-edge results in mode-locked pulses within a wavelength range from 1032 to 1054 nm. In cw operation, we achieve output powers as high as 1.3 W. © 2000 Optical Society of America

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In the past few years there has been growing interest in simple and robust diode-pumped femtosecond laser systems with average powers in the watt regime. Numerous applications benefit from the multikilowatt peak powers of such systems. Examples are three-photon microscopy and Z-scan measurements in the field of nonlinear spectroscopy, synchronous pumping of optical parametrical oscillators for femtosecond tunable IR sources, and efficient and simple UV generation by cascaded external single-pass wavelength converters.

Passively mode-locked femtosecond high-power lasers require a gain medium with a broad amplification bandwidth, relatively large laser cross sections for suppression of Q-switched mode-locking instabilities,[1] and good thermal conductivity so that they can handle the heat load. So far, the absence of laser materials with this combination of properties has limited the average output power of diode-pumped femtosecond lasers to a few hundred milliwatts. Femtosecond pulses with multiwatt average power have been obtained only from Ti:sapphire lasers,[2,3] which, however, rely on bulky, inefficient argon-ion lasers or on expensive frequency-doubled diode-pumped pump lasers. Only very recently, two approaches for obtaining femtosecond diode-pumped lasers with average powers of more than 1 W were presented. Aus der Au *et al.* presented a passively mode-locked Nd:glass laser with an average output power of 1 W and a pulse duration of 175 fs,[4] pumped by a 20-W diode bar. However, that laser relies on a highly elliptical pump mode approach because of the poor thermal conductivity and the low stress-fracture limit of glass, making the whole system complex and rather inefficient. For somewhat longer pulses, we recently presented a passively mode-locked thin-disk Yb:YAG laser that yielded 16.2 W with a pulse duration of 0.73 ps.[5]

In this Letter we report on what is believed to be the first passively mode-locked Yb:KGd(WO$_4$)$_2$ (Yb:KGW) laser. We obtain 1.1-W average power in 176-fs pulses from a simple delta cavity pumped by two high-brightness laser diodes. These results have become possible because of the beneficial properties of this new laser material.[6,7] The Yb^{3+}-doped crystal has a broad amplification bandwidth, comparable to that of Yb-doped glasses. A wide tuning range has been demonstrated,[8] confirming the potential of this material for sub-100-fs pulse generation. In addition, the crystal has a thermal conductivity roughly four times that of Yb-doped phosphate glass. Also, the laser emission cross section is larger than that of Yb:YAG (and therefore significantly larger than that of Yb:glass), leading to a smaller saturation energy, which is beneficial for suppression of Q-switched mode locking.[1] With its absorption peak at 981 nm and its laser wavelength at 1026 nm, Yb:KGW exhibits an extremely low quantum defect ($\lambda_{\mathrm{pump}}/\lambda_{\mathrm{laser}} = 0.96$). The pump saturation intensity of Yb:KGW is ≈10 times smaller than that of Yb:YAG, allowing for good laser efficiency even when the material is pumped by low-brightness sources.

We design the laser cavity (Fig. 1) to operate in the middle of stability zone I (Ref. 9) to obtain good alignment stability. As the gain material, we use a 3-mm-thick 5-at. % Yb^{3+}-doped $KGd(WO_4)_2$ crystal at Brewster incidence. The material is mounted on a heat sink kept at 10 °C. The crystal is longitudinally pumped by two high-brightness, single-emitter InGaAs–GaAs laser diodes (maximum 3 W each) with a 100-μm ridge width, operated at ≈980 nm, with a spectral bandwidth of 6 nm. The absorption length of the crystal at this pump spectrum is ≈1.6 mm. The M^2 value on the slow axis of the diodes is measured to be 25. In the fast axis the emission of the diodes is nearly diffraction limited, with $M^2_{\text{fast}} = 1.4$. Efficient pumping through the spherically curved cavity mirrors, M1 and M2 (Fig. 1), would require a special dichroic coating because of the closeness of the pump and the laser wavelengths. However, we use standard $\lambda/4$ coatings optimized for high reflectivity at wavelengths of >1030 nm. As a consequence, the mirrors have transmission of 94% (M2) and only 63% (M1) at 980 nm, reducing the maximum pump power that is incident on the crystal to 4 W. The transmission at 1026 nm is 0.23% for M2 and 0.14% for M1, increasing to 0.4% and 0.25%, respectively, at 1020 nm. Effectively, mirrors M1 and M2 induce round-trip losses of more than 1%, which are significant considering the output coupling of 4.3%. Therefore, laser operation occurs at 1037 nm rather than at the gain maximum of Yb:KGW. The pump light is focused to a beam radius of 160 μm × 70 μm inside the crystal, resulting in a confocal parameter of ≈2.9 mm for the slow axis of the diodes. The laser mode radius inside the gain medium is calculated to be 120 μm × 60 μm.

For passive mode locking we use a SESAM.[10,11] The SESAM, which is used as an end mirror, consists of a 25-nm-thick InGaAs–GaAs quantum well in a low-finesse structure, as described in Ref. 11. Growing the SESAM by low-temperature molecular beam epitaxy reduces the absorber recovery time and the stress in the quantum well. The device has a modulation depth of ≈1.3% and a saturation fluence of ≈350 $\mu J/cm^2$. At full pump power, the energy fluence on the SESAM is ≈10 times the saturation fluence of the absorber. In this regime we do not observe any signs of damage, which typically occurs at ~100 times the saturation fluence.

A main challenge in passive mode locking of a solid-state laser is to suppress the strong tendency toward Q-switched mode locking[1] that is introduced by the saturable absorber. This problem is particularly severe for gain media with low-emission cross sections and therefore high saturation fluences. Compared with other Yb-doped materials (particularly glasses), Yb:KGW has large cross sections. In addition, the use of high-brightness laser diodes allows us to choose a relatively small laser mode size inside the gain medium, reducing the saturation energy. Together with the stabilizing effect resulting from soliton mode locking,[1] this reduced saturation energy leads to stable cw mode locking. Soliton mode locking[12] is obtained by the interplay of self-phase modulation in the gain material and the negative group-delay dispersion from a prism pair (Fig. 1). In contrast with Kerr-lens mode locking, no critical cavity length adjustments are required, and the mode-locking process is decoupled from the transverse cavity mode.

With the cavity shown in Fig. 1 and an output transmission of 4.3%, we obtain 1.1-W average power in transform-limited soliton pulses (time–bandwidth product, 0.32) with 176-fs duration at a center wavelength of 1037 nm (Fig. 2). This is to our knowledge the first demonstration of a mode-locked Yb:KGW laser. At a pulse repetition rate of 86.4 MHz, the peak power is as high as 64 kW. The M^2 values are measured to be 1.7 in the tangential direction and 1.0 in the sagittal direction. We attribute the deviation from the ideal M^2 value in the tangential direction to the fact that the pump beam radius in the crystal is slightly larger than the laser mode. The shortest pulse duration that we have achieved with an output

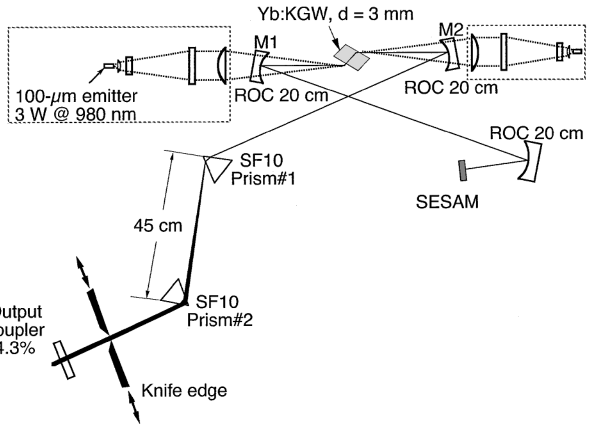

Fig. 1. Setup of the 1.1-W laser pumped by two high-brightness laser diodes. ROC, radius of the spherically curved mirrors; SESAM, semiconductor saturable-absorber mirror, SF10.

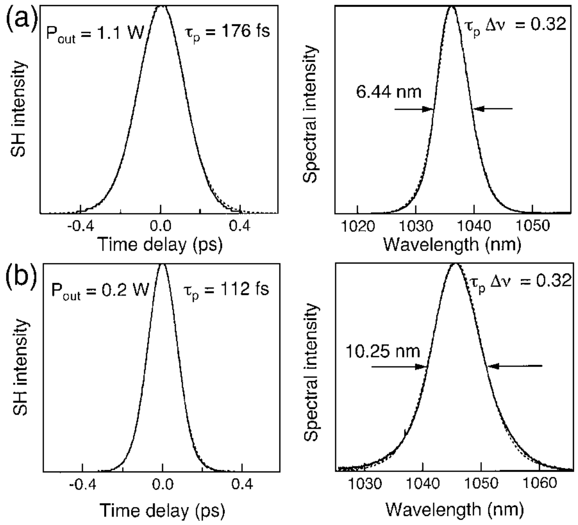

Fig. 2. (left) Intensity autocorrelation and (right) optical spectrum of the Yb:KGW laser: (a) maximum average power $P_{\text{out}} = 1.1$ W, with 176-fs pulse duration; (b) minimum pulse duration $\tau_p = 112$ fs, with 0.2-W average power. The dotted curves represent fits assuming a soliton (sech^2) pulse shape. The time–bandwidth product is 0.32 in both cases. SH, second harmonic.

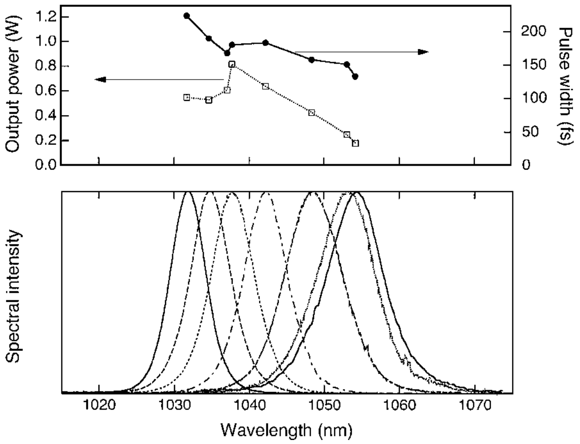

Fig. 3. Tunability of the mode-locked Yb:KGW laser within a wavelength range of 22 nm. Bottom, measured pulse spectra; top, corresponding output powers and pulse widths.

coupler with 3% transmission is 112 fs at a center wavelength of 1046 nm with 200-mW output power (Fig. 2).

The wavelength of the Yb:KGW laser can be tuned by insertion of a knife-edge into the spatially dispersed beam between the second prism and the output coupler. In mode-locked operation, we obtain a tuning range of 22 nm, from 1032 to 1054 nm (Fig. 3). The output power varies from 180 to 820 mW, and the pulse duration varies from 133 to 224 fs. Within this tuning range, the transmission of the output coupler is (4.2 ± 0.4)%. By using an output coupler with a lower transmission, we can extend the tuning range to slightly longer wavelengths at somewhat lower output powers. At shorter wavelengths, we are limited by the rapidly increasing transmission of dichroic cavity mirrors M1 and M2.

$KGd(WO_4)_2$ has a large coefficient for stimulated Raman scattering.[13] In spite of the high peak intensity in the crystal ($\approx 6.6\ \mathrm{GW/cm^2}$), Raman lasing is suppressed by large intracavity losses at the SESAM. Also note that the pulse bandwidth is significantly larger than the bandwidth of the vibrational mode of $KGd(WO_4)_2$ with a phonon energy of $901\ \mathrm{cm}^{-1}$ ($\Delta\tilde{\nu} = 5.7\ \mathrm{cm}^{-1}$).

In cw configuration, i.e., with a high reflector substituted for the SESAM and no prisms inside the cavity, we obtain a maximum output power of 1.3 W at 1038 nm. To our knowledge this is the highest cw output power reported from an Yb:KGW laser. The pump power that is incident on the crystal is 4 W, resulting in an optical-to-optical efficiency of 33%. The slope efficiency is 57% with respect to the absorbed pump power. No roll-off is observed at high pump powers. This implies that so far thermal problems are no limitation to the output power, which is limited only by the available pump power. The output coupling is 3%.

In conclusion, we have demonstrated what we believe is the first mode-locked Yb:KGW laser. This gain material combines a relatively broad emission bandwidth (similar to that of Yb-doped glasses) with the good thermal properties of crystals, making it very suitable for application in high-power femtosecond lasers. Using a SESAM for passive mode locking, we obtain 1.1-W average power in transform-limited soliton pulses with 176-fs duration and peak powers as high as 64 kW. The beam quality is close to diffraction limited. Tunability of the wavelength within a range of 22 nm is demonstrated. cw operation yields 1.3-W output power and a slope efficiency of 57%. In comparison with previous approaches with similar performance, our system is considerably simpler, as it relies on a standard delta cavity and high-brightness laser diodes. The output power of our laser is limited only by the available pump power and not by thermal problems. This suggests that Yb:KGW applied in a suitable high-power setup (thin disk[14] or elliptical pump geometry[15]) can lead to multiwatt femtosecond lasers.

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