# 240-fs pulses with 22-W average power from a mode-locked thin-disk Yb:KY($WO_4$)$_2$ laser

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We demonstrate what is to our knowledge the first passively mode-locked thin-disk Yb:KY($WO_4$)$_2$ laser. The laser produces pulses of 240-fs duration with an average power of 22 W at a center wavelength of 1028 nm. At a pulse repetition rate of 25 MHz, the pulse energy is 0.9 $\mu$J, and the peak power is as high as 3.3 MW. The beam quality is very close to the diffraction limit, with $M^2 = 1.1$.

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Femtosecond lasers with high average output power have attracted great interest over the past few years. The high peak power of such lasers is particularly attractive for applications involving nonlinear effects, e.g., wavelength conversion for laser projection displays and multiphoton spectroscopy. For reasons of simplicity and compactness, it is advantageous to obtain such performance directly from a diode-pumped laser oscillator without the use of additional amplifier stages. One can realize such a laser by combining a diode-pumped thin-disk laser head[1] with a semiconductor saturable-absorber mirror[2,3] (SESAM) for passive mode locking. This concept has the crucial advantage of power scalability, which arises from the nearly one-dimensional longitudinal heat flow both in the laser material and in the saturable absorber.[4] As a first demonstration of a laser based on this concept we produced an Yb:YAG laser that generated 16 W of average power in 700-fs pulses.[4] Also, the successful application of this laser as a pump source in an optical parametric generator[5] and a fiber-feedback optical parametric oscillator[6] has been demonstrated.

In this Letter we report on what we believe to be the first passively mode-locked thin-disk laser that is based on the novel gain medium Yb:KY($WO_4$)$_2$ (Yb:KYW).[7–9] This laser crystal has a larger amplification bandwidth than Yb:YAG and is therefore suitable for the generation of significantly shorter pulses. Previous mode-locked lasers based on Yb-doped tungstate crystals such as Yb:KYW and Yb:KGd($WO_4$)$_2$ (Yb:KGW) have demonstrated the potential of these gain media for generation of femtosecond pulses. Pulse durations of 71 fs for Kerr-lens mode locking[10] and of 112 fs for mode locking with a SESAM[11] have been reported, whereas mode-locked average output powers were limited to 1.5 W.[12]

Yb:KYW is particularly attractive in a thin-disk laser setup because of its low quantum defect ($\lambda_{\mathrm{pump}}/\lambda_{\mathrm{laser}} \approx 0.96$) and thus a reduced thermal load in the gain medium. Its thermal conductivity (3.3 W $m^{-1}$ $K^{-1}$) is $\approx$2 times lower than that of 10-at.%-doped Yb:YAG. A remarkable feature of both Yb:KYW and Yb:KGW is that, despite the large bandwidth, the emission cross sections are even slightly larger than those of Yb:YAG. These large cross sections lead to smaller gain saturation fluence, which helps to suppress $Q$-switching instabilities.[13] This is one of the crucial challenges in passive mode locking of a solid-state laser. This $Q$-switching tendency is strong for gain media with the low laser cross sections that are typical for Yb-doped materials, in particular for many of those with large amplification bandwidths. We chose the laser polarization to be parallel to the $a$ axis of the $b$-cut Yb:KYW crystal to utilize the largest emission cross section ($\approx 3 \times 10^{-20}$ $cm^2$). In addition, we use a cavity with a low repetition rate and exploit the stabilizing effect from soliton mode locking to successfully suppress $Q$-switching instabilities.[13]

With the setup shown in Fig. 1, we obtain self-starting mode locking with pulses of 240-fs duration and an average output power of 22 W at a center wavelength of 1028 nm (Fig. 2). The pulse repetition rate is 24.6 MHz, resulting in a pulse energy of 0.9 $\mu$J and a peak power as high as 3.3 MW. The time–bandwidth product is 0.47, i.e., $\approx$1.5 times the ideal time-bandwidth product for soliton pulses (0.315). The

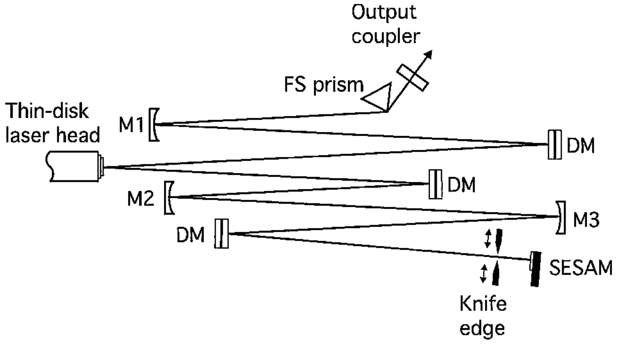

Fig. 1. Setup of the Yb:KYW thin-disk laser: M1–M3, spherically curved mirrors with radii of curvature of 1 m (M1) and 0.75 m (M2, M3); DM's flat dispersive mirrors, each with a group-delay dispersion of $\approx -400$ fs$^2$ per bounce; FS, fused silica.

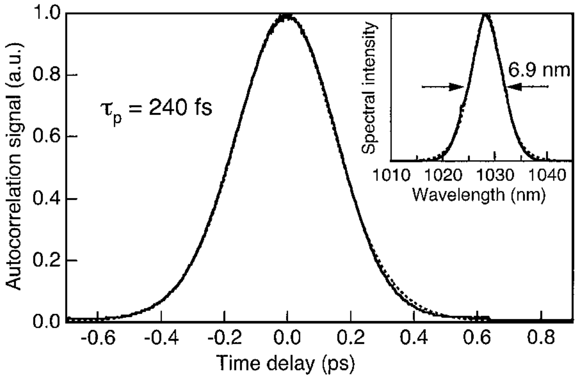

Fig. 2. Autocorrelation trace and optical spectrum (inset) of the 240-fs pulses obtained from the thin-disk Yb:KYW laser at 22-W average output power. Dashed curves, sech$^2$ fits.

beam quality is very close to the diffraction limit, with an $M^2$ value measured to be 1.1. Focusing the beam to a spot diameter of 2 $\mu$m would result in a peak intensity of $2 \times 10^{14}$ W cm$^{-2}$ on the beam axis.

The thin-disk laser head contains a 160-$\mu$m thin 5-at.%-doped Yb:KYW disk as the gain material. One face of the disk is coated for high reflectivity for both pump and laser wavelengths, and the other side has an antireflection coating for both wavelengths. To eliminate the effects of residual reflections from the AR coating, the disk is slightly wedged. The reflecting face is directly attached to a cooling finger. The Yb:KYW disk is pumped by up to 100 W of power at 981 nm from fiber-coupled diode bars. These diode bars can deliver more power but only at longer wavelengths, which are not efficiently absorbed because of the narrow absorption peak of Yb:KYW (effective bandwidth, $\approx$7.5 nm FWHM). The pump radiation at 981 nm is effectively absorbed in 24 passes through the disk. The pump diameter ($\approx$1.5 mm) is considerably larger than the disk thickness (160 $\mu$m), resulting in a nearly one-dimensional heat flow along the optical axis of the laser beam and therefore in only weak thermal lensing. In the present setup the focusing power of the thermal lens in the disk is estimated to be of the order of $-0.3$ m$^{-1}$ at full pump power. We use the Yb:KYW disk as a folding mirror in the laser cavity shown in Fig. 1. The cavity is designed to operate near the middle of stability zone I (Ref. 14) to provide good stability against misalignment and changes of the thermal lens in the Yb:KYW disk. The transmission of the output coupler is 5.5%. For passive mode locking we use a SESAM as an end mirror. The calculated laser mode radii are $\approx$630 $\mu$m in the Yb:KYW disk and $\approx$610 $\mu$m on the SESAM. The SESAM is grown by low-temperature molecular-beam epitaxy and consists of a single 8-nm-thick $\mathrm{In_{0.3}Ga_{0.7}As}$ quantum well in a low-finesse structure as described in Ref. 3. Growing the SESAM by low-temperature molecular beam epitaxy reduces the recovery time of the absorber and the stress in the quantum well. The SESAM exhibits a bitemporal impulse response, with a fast recovery time constant of $\approx$600 fs and a slower one of $\approx$9 ps. The modulation depth of the device is $\approx$0.5% and the saturation fluence $\approx$100 $\mu$J/cm$^2$. The SESAM is mounted upon a heat sink kept at $\approx$20 °C. Negative group-delay dispersion for soliton mode locking is obtained from three dispersive mirrors, each of which contributes a group-delay dispersion of $\approx -400$ fs$^2$ per bounce.

Initial experiments were carried out with a laser cavity that did not contain a prism. In this case the laser always operated at the wavelength of maximum gain, $\approx$1025 nm. We then achieved a minimum pulse duration of $\approx$400 fs, i.e., significantly longer than would be expected from the broad gain spectrum. We attribute this long pulse duration to the strong curvature of the gain spectrum at the peak, as it occurs for polarization along the *a* axis at high inversion levels. Note that previous mode-locked lasers based on Yb-doped tungstate crystals did not suffer from this problem because they used a much thicker gain medium (to achieve sufficient pump absorption without a multipass arrangement) and thus operated at lower inversion levels, where the gain spectrum is smoother.

Significantly longer pulse durations than 400 fs were not possible because of spatial hole burning in the Yb:KYW disk, as was studied in detail[15] with a numerical model. This model is not quantitatively applicable here because it assumes a Gaussian-shaped gain spectrum, but it suggests that operation with significantly longer pulse durations than 400 fs should indeed be unstable.

To obtain a smoother gain spectrum we inserted the fused-silica prism as shown in Fig. 1, such that the different wavelength components were spatially dispersed and we could tune the laser to longer wavelengths by inserting a knife-edge. (The cavity was designed such that the spatial dispersion is negligible at the Yb:KYW disk.) Indeed, we observed that the shortest pulses, with 240-fs duration, can be obtained for somewhat longer center wavelengths near 1028 nm (Fig. 2), although the use of the knife-edge slightly reduced the obtainable average output power by a few watts.

We used a single prism instead of a prism pair to minimize the number of additional path lengths in the prism material and thus additional thermal lensing effects (with a focusing power that is not well known) as well as excessive Kerr nonlinearity. Our laser already operates with a nonlinear phase shift of the order of a few hundred milliradians per cavity round trip, and numerical simulations show that a further increase of the nonlinear phase shift could destabilize the mode-locking process.[16] Note that the prism also introduces an additional group-delay dispersion of $\approx + 500\ \mathrm{fs}^2$ per round trip, which is overcompensated for by the dispersive mirrors.

It should also be possible to achieve a smoother gain spectrum by utilizing polarization along the *b* axis in Yb:KGW and possibly in Yb:KYW. Such a configuration is expected to work well in a thin-disk laser if a *c*-cut crystal is used, so the pump can be polarized along the *a* and *b* axes. (Note that the use of a *c*-cut crystal with *b* polarization appears to be less suitable for a laser with a Brewster–Brewster cut gain medium because of the much weaker pump absorption for *b* polarization.)

In conclusion, we have demonstrated what is to our knowledge the first passively mode-locked thin-disk Yb:KYW laser. This novel gain medium has a larger amplification bandwidth than Yb:YAG and is therefore suitable for considerably shorter pulses. We obtained 22 W of average output power in pulses of 240-fs duration at a center wavelength of 1028 nm. At a pulse repetition rate of 24.6 MHz, the pulse energy is 0.9 $\mu$J and the peak power is as high as 3.3 MW. The beam quality is close to the diffraction limit, with $M^2 = 1.1$. Laser polarization along a different axis from that used in this experiment might allow for shorter pulse durations. In addition, the concept of combining a thin-disk laser head with a SESAM for passive mode locking is power scalable. Therefore, further improvements both of pulse duration and average power appear possible.

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