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Diode-Pumped Mode-Locked Yb:KY$(WO_4)_2$ Laser Generating 46 fs Pulses

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Abstract

We report on sub-50 fs pulse generation from a diode-pumped mode-locked laser based on an ytterbium-doped monoclinic potassium yttrium double tungstate crystal operating in the 1 μm spectral region. Pumping by a low-power, spatially single-mode, fiber-coupled laser diode at 976 nm, a maximum continuous-wave output power of 433 mW at 1066.1 nm was obtained. Using a quartz-based intracavity Lyot filter, an exceptionally broad continuous-wavelength tuning range of 98 nm was achieved. In the mode-locked regime, the diode-pumped Yb:KY$(WO_4)_2$ laser delivered soliton pulses as short as 46 fs at a central wavelength of 1069.2 nm by employing a SEmiconductor Saturable Absorber Mirror. To the best of our knowledge, these results represent the broadest continuous-wave tuning range and the shortest pulse duration ever reported for lasers based on ytterbium-doped monoclinic double tungstate crystals.

Keywords: ultrafast laser; solid-state laser; ytterbium laser; mode-locking; diode-pumped

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1. Introduction

Ytterbium (Yb^{3+})-doped rare-earth (RE) potassium monoclinic double tungstates (MDTs) with the chemical formula Yb^{3+}:$KRE(WO_4)_2$, where RE^{3+} = Y^{3+}, Gd^{3+} or Lu^{3+} (abbreviated as Yb:KREW) [1–3], constitute a prominent family of gain media for medium-power but highly efficient continuous-wave (CW), Q-switched, and mode-locked (ML) lasers operating near 1 μm [4–11]. These ordered crystals are optically biaxial and crystallize in a monoclinic structure (space group $C_{2h}^6 - C2/c$; point group $2/m$). Yb^{3+} ions accommodate in a single type of site with C_2 symmetry and VIII-fold oxygen coordination. Owing to these structural features, monoclinic double tungstates exhibit pronounced polarization anisotropy, enabling pumping and emission in well-defined polarization eigenstates [1,3,12]. In addition, due to the exceptionally large dopant ion separation and weak

concentration quenching, Yb:KREW crystals can accommodate the highest possible Yb^{3+} concentration reaching the stoichiometric structure $KYb(WO_4)_2$ [13], which has stimulated the development of power-scalable thin-disk architectures [14–17]. The combination of high absorption and emission cross-sections with a spectrally broad gain makes these crystals particularly attractive for gigahertz-repetition-rate femtosecond ML oscillators [18–23] and femtosecond optical frequency comb generations [24–26], notwithstanding their moderate thermal conductivity of ~3 W/m K [27] and broadband gain cross-section spectra, which are suitable for developing high-power femtosecond mode-locked (ML) oscillators [9–11,28] and amplifiers [29–33] in the 1 μm spectral region.

Rapid progress in ultrashort pulse generation from ML Yb:KREW lasers began with the first sub-100 fs diode-pumped $Yb:KY(WO_4)_2$ laser based on soft-aperture Kerr-lens mode-locking (KLM), which produced 71 fs pulses at 1057 nm [34]. Pulses as short as 66 fs at 1029 nm and 65 fs at 1039 nm were obtained from a SEmiconductor Saturable Absorber Mirror (SESAM) ML $Yb:KY(WO_4)_2$ laser under Ti:sapphire and diode-laser pumping, respectively [35,36]. It was demonstrated that 83 fs pulses at 1049 nm were obtained from a single-walled carbon nanotube saturable absorber (SWCNT-SA) ML $Yb:KY(WO_4)_2$ laser pumped by a Ti:sapphire laser [37]. For the $Yb:KGd(WO_4)_2$ crystal, 67 fs pulses at 1032 nm were demonstrated using SESAM-assisted KLM [38], and a pulse duration of 56 fs at 1040 nm was later reported by the same group [39]. Using a 750 mW single-transverse-mode, fiber-coupled laser diode at 980 nm, a SESAM-assisted KLM $Yb:KGd(WO_4)_2$ laser delivered 59 fs pulses at 1036 nm [40]. During the first attempts to ML, the related $Yb:KLu(WO_4)_2$ laser with a SESAM produced 81 fs pulses at 1046 nm under Ti:sapphire laser pumping [41]. Under diode pumping, this laser generated 69 fs pulses at 1054 nm [42]. To date, the shortest pulses reported from an Yb:KREW ML laser amounts to 48 fs, achieved from a diode-pumped, hard-aperture KLM $Yb:KLu(WO_4)_2$ thin-disk laser at 1026 nm for an average output power of 425 mW at a pump power of 300 W [43].

Previously reported mode-locked Ytterbium monoclinic double tungstate lasers have operated on specific electronic transitions between Stark (crystal-field) sublevels of the $4f^n$ manifolds. Owing to the highly ordered nature of these crystals, in which RE^{3+} ions are regularly substituted by Yb^{3+} (which leads to rather low background absorption losses), the electronic gain bandwidth is intrinsically limited, although appropriate control of the polarization state can partially mitigate this constraint. Our recent advances in passively mode-locked Yb lasers delivering sub-50 fs pulses rely on operation in a regime where phonon-assisted gain at wavelengths extending beyond purely electronic transitions contributes significantly to the mode-locked bandwidth. This regime corresponds to low inversion levels in the gain medium, for which the nearly exponential Stokes multiphonon sideband flattens the overall spectral gain profile. Achieving this condition requires extremely low round-trip passive losses in the laser cavity, together with gain media exhibiting high effective gain (enabled by heavy doping and/or large stimulated-emission cross-sections), as well as strong electron–phonon coupling. This approach provides an efficient route toward further pulse shortening, albeit at the expense of a substantial red shift in the central wavelength of the mode-locked spectrum.

Here, we report new results on a diode-pumped SESAM ML $Yb:KY(WO_4)_2$ laser pumped by a spatially single-mode, fiber-coupled laser diode. By optimizing soliton-like pulse shaping via intracavity group-delay dispersion (GDD) management, we demonstrate pulses as short as 46 fs. To the best of our knowledge, this is the shortest pulse duration ever reported for any ML laser based on Yb-doped MDT crystals.

2. Experimental Setup

Laser operation was studied in an X-shaped, astigmatically compensated standing wave cavity, as shown in Figure 1. The pump source was a spatially single-mode, fiber-coupled InGaAs laser diode delivering unpolarized radiation at 976 nm with a maximum output power of 1.4 W. Its emission wavelength was stabilized by fiber Bragg grating (FBG), resulting in a spectral width of 0.2 nm (full width at half maximum, FWHM) well addressing the relatively narrow absorption zero phonon line of Yb^{3+} ions. The beam propagation factor (M^2) of the laser diode was measured to be 1.02 at the maximum output power.

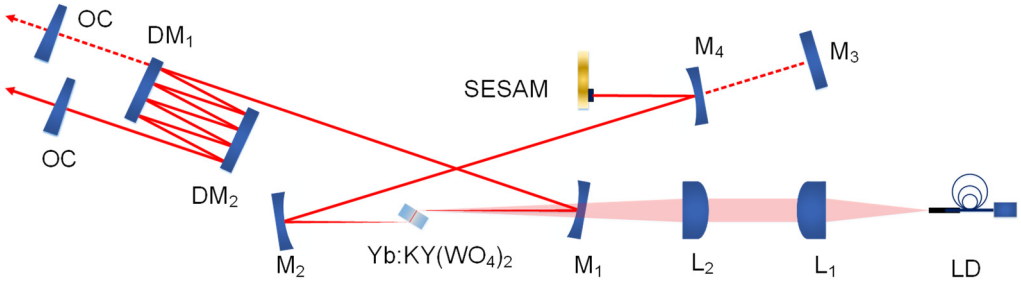


Figure 1. Experimental setup of the diode-pumped Yb:$KY(WO_4)_2$ laser. LD: fiber-coupled laser diode at 976 nm; L_1: aspherical collimating lens (f = 26 mm); L_2: spherical focusing lens (f = 75 mm); M_1, M_2 and M_4: plano-concave mirrors (RoC = −100 mm); M_3: flat rear mirror for CW laser operation; DM_1 and DM_2: flat dispersive mirrors; OC: output coupler; SESAM: SEmiconductor Saturable Absorber Mirror.

The gain medium was a 5 at.% Yb^{3+}-doped $KY(WO_4)_2$ crystal with dimensions of 3 mm × 3 mm × 3 mm (N_g-cut). The crystal was polished to laser-grade quality with high parallelism and left uncoated. It was mounted in a passively cooled copper holder and placed at Brewster's angle between two plano-concave mirrors (M_1 and M_2, radius of curvature, RoC = −100 mm). This configuration provided minimum loss for the laser polarization E ∥ N_m corresponding to the highest gain in this crystal. The pump beam was collimated by an aspherical lens (L_1, focal length, f = 26 mm) and focused into the crystal through the dichroic pump mirror (M_1) using a spherical focusing lens (L_2, f = 75 mm), yielding pump-waist radii ($1/e^2$) of 14.6 and 31.3 µm in the sagittal and tangential planes, respectively. Given the transmission losses of the pump imaging optics and the pump mirror (M_1), the maximum available incident pump power on the crystal was ~1.3 W.

3. Continuous-Wave Laser Operation

The CW performance of the diode-pumped Yb:$KY(WO_4)_2$ laser was investigated in a four-mirror cavity without implementing the SESAM and dispersive mirrors (DMs), cf. Figure 1. In this configuration, one cavity arm was terminated by a flat-end mirror (M_3), while the other arm was closed by a plane-wedged output coupler (OC) with transmission (T_{OC}) ranging from 0.4% to 7.5% at the laser wavelength. Using the ABCD-matrix formalism, the fundamental Gaussian-mode radii inside the Yb:$KY(WO_4)_2$ crystal were estimated to be 24 µm and 41 µm in the sagittal and tangential planes, respectively.

Figure 2a summarizes the CW output characteristics obtained with different OCs. A maximum output power of 433 mW at 1066.1 nm was achieved for an incident pump power of 1.297 W using a 0.8% OC. This corresponds to a slope efficiency (η) of 39.8% and a laser efficiency of 33.4%, with a laser threshold of 205 mW. The slope efficiency exhibits a characteristic dependence on the output coupling. It increases from 33.8% at T_{OC} = 0.4% to a maximum value of 42.3% at T_{OC} = 2.5%, and it then decreases to 37.7% at T_{OC} = 7.5%. This behavior reflects the trade-off between efficient power extraction and the increased

round-trip losses and hence higher laser threshold, associated with higher-output coupling. In quasi-three-level Yb lasers, reabsorption losses at the laser wavelength further contribute to this trend. Accordingly, the laser threshold increased monotonically with T_{OC}, from 149 mW at T_{OC} = 0.4% to 384 mW at T_{OC} = 7.5%.

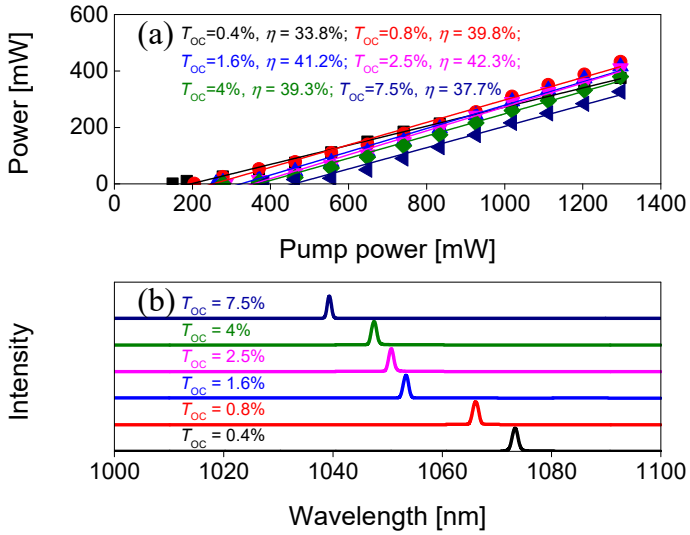


Figure 2. CW performance of the diode-pumped Yb:$KY(WO_4)_2$ laser for different OCs: (**a**) output power versus incident pump power for T_{OC} = 0.4%, 0.8%, 1.6%, 2.5%, 4%, and 7.5%; *solid lines* are linear fits used to determine the slope efficiency η; (**b**) representative CW laser spectra corresponding to the OCs in (**a**).

As illustrated in Figure 2b, the free-running laser wavelength exhibits a systematic blue shift with increasing output coupling, from 1073.3 nm at T_{OC} = 0.4% to 1039.3 nm at T_{OC} = 7.5%. This spectral behavior is typical for quasi-three-level Yb lasers, where increasing cavity losses shift the gain-loss balance toward shorter wavelengths with higher emission cross-sections, thereby enabling laser oscillation at elevated thresholds. The achieved laser wavelengths highlight operation in the small inversion regime.

The CW wavelength tuning characteristics were evaluated by inserting a 2 mm thick quartz-plate at Brewster's angle near the OC, forming an intracavity Lyot filter. As illustrated in Figure 3, continuous wavelength tuning from 1021.5 to 1119.5 nm was achieved, corresponding to a tuning span of 98 nm at zero power level, using a 0.2% OC at the maximum incident pump power of 1.297 W. To the best of our knowledge, this represents the broadest CW tuning range reported so far for any lasers based on the Yb^{3+}-doped MDT crystals.

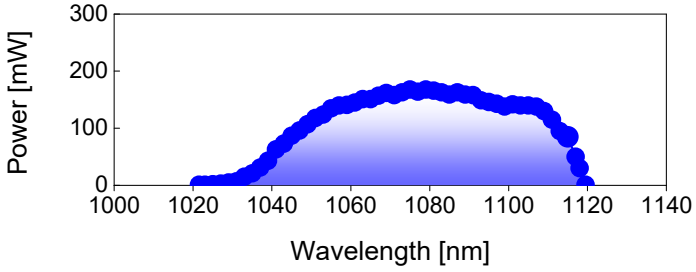


Figure 3. CW wavelength-tuning characteristics of the diode-pumped Yb:$KY(WO_4)_2$ laser obtained with a quartz-plate Lyot filter and a 0.2% OC.

Notably, the longest purely electronic $^2F_{5/2} \rightarrow {}^2F_{7/2}$ transition of Yb^{3+} ions in $KY(WO_4)_2$ occurs at ~1038 nm, underscoring the substantial contribution of phonon-assisted gain to the observed tuning curve. Monoclinic double tungstates rank among

the most efficient Raman-active media and are characterized by strong coupling of both internal and external phonon modes with the electronic states of rare-earth activator ions. This interaction gives rise to a quasi-continuous ensemble of vibronic levels, which can potentially support Yb^{3+} emission extending to wavelengths as long as 1.25 μm.

4. Mode-Locked Laser Operation

For passive ML operation, the flat-end mirror (M_3) was replaced by an additional plano-concave mirror (M_4, RoC = −100 mm) in order to create a secondary cavity beam waist on the SESAM. The beam radius on the SESAM was ~63 μm, ensuring efficient bleaching of the absorption. A commercial SESAM was used to initiate and stabilize the ML operation, featuring a modulation depth of 0.6% at 1040 nm, a saturation fluence of 70 μJ/cm^2, a non-saturable loss of 0.4%, and a recovery time constant of 1 ps. The round-trip material dispersion introduced by the 3 mm thick Yb:KY$(WO_4)_2$ crystal was estimated using the Sellmeier equation for N_m polarization [44] to be GDD ~ +1191 fs^2 at 1070 nm. Intracavity dispersion management was provided using two DMs with a GDD of −100 fs^2 per bounce. By applying four bounces on each DM, a total negative GDD of −1600 fs^2 was introduced, compensating the material dispersion and balancing the self-phase modulation accumulated in the laser crystal. The geometrical cavity length of the diode-pumped SESAM ML Yb:KY$(WO_4)_2$ laser was ~2.21 m, corresponding to a pulse repetition rate of ~67.8 MHz.

Stable ML operation was first achieved using a 1.6% OC after careful cavity alignment. The optical spectrum of the laser pulses, shown in Figure 4a, was centered at 1068.7 nm with a spectral width of 22.9 nm (FWHM), assuming a sech^2-shaped, spectral-shaped spectral profile. The corresponding second-harmonic generation (SHG)-based, background-free intensity autocorrelation trace, shown in Figure 4b, yielded a deconvolved pulse duration of 54 fs (FWHM) by assuming a sech^2-shaped temporal profile. This results in a time-bandwidth product (TBP) of 0.325, slightly above the Fourier-transform-limited of 0.315 for sech^2 pulses. At the maximum incident pump power, an average output power of 26 mW was obtained, corresponding to a peak power of 6.2 kW at a pulse repetition rate of 67.83 MHz. The inset in Figure 4b shows the SHG-based background-free intensity autocorrection trace recorded over a 50 ps time span, confirming single-pulse CW-ML operation without multiple-pulse instabilities.

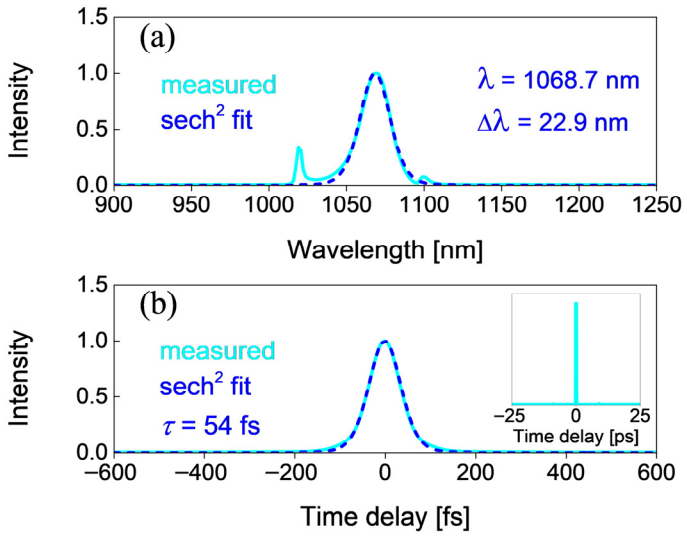


Figure 4. Diode-pumped SESAM ML Yb:KY$(WO_4)_2$ laser with T_{OC} = 1.6%. (**a**) Optical spectrum and (**b**) background-free SHG-based intensity autocorrelation trace. *Inset*: autocorrelation trace over a 50 ps time span.

The shortest pulses in a robust and stable regime were achieved using a 0.4% OC. The corresponding pulse characteristics are shown in Figure 5. The optical spectrum is centered at a central at a wavelength of 1069.2 nm with a spectral width of 26.6 nm (FWHM), assuming a sech^2-shaped spectral profile (see Figure 5a). The SHG-based, background-free intensity autocorrelation curve is well fitted with a sech^2-shaped temporal profile, resulting in a deconvolved pulse duration of 46 fs (FWHM) and a TBP of 0.321, which indicates near Fourier-transform-limited pulse generation. The 50 ps long-scale SHG-based intensity autocorrelation scan, shown in the inset of Figure 5b, confirms stable single-pulse CW-ML operation. The average output power with this OC was 7 mW, corresponding to a peak power of 2 kW and a pulse repetition rate of 67.81 MHz.

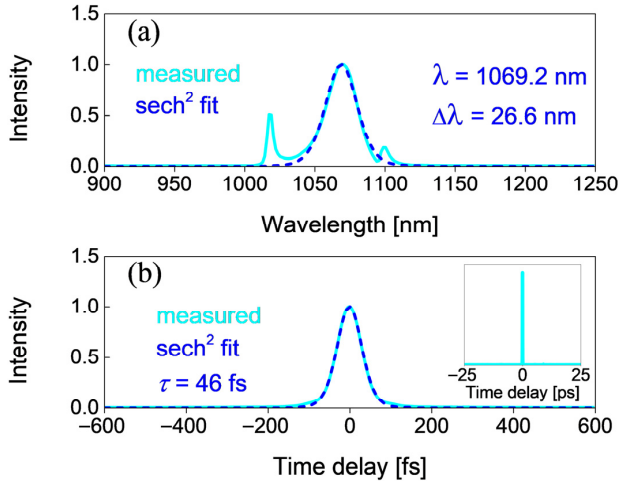


Figure 5. Diode-pumped SESAM ML Yb:KY$(WO_4)_2$ laser with T_{OC} = 0.4%. (**a**) Optical spectrum and (**b**) background-free SHG-based intensity autocorrelation trace. *Inset*: autocorrelation trace over a 50 ps time span.

The stability of the shortest pulses was further assessed using a radio frequency (RF) spectrum analyzer. Figure 6a shows the fundamental beat note at 67.81 MHz recorded with a resolution bandwidth (RBW) of 200 Hz. No spurious sidebands were observed, and the signal-to-noise ratio exceeded 80 dBc. In addition, the RF spectrum measured over a 1 GHz frequency span exhibits uniformly spaced harmonic peaks, providing clear evidence of stable CW-ML without any Q-switching or multiple-pulse instabilities, as illustrated in Figure 6b.

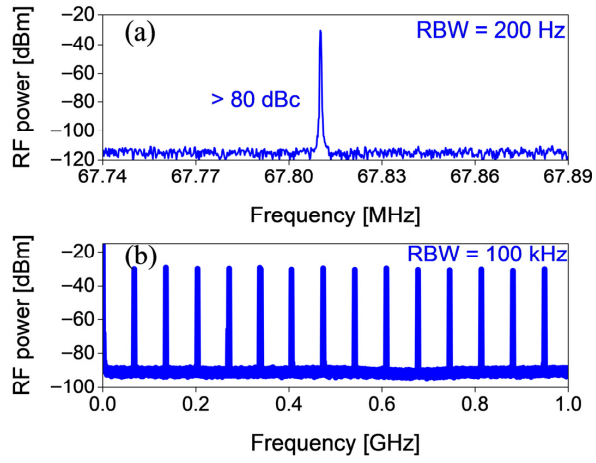


Figure 6. Radio frequency (RF) spectra of the diode-pumped SESAM ML Yb:KY$(WO_4)_2$ laser at T_{OC} = 0.4%: (**a**) Fundamental beat note at 67.81 MHz measured with a RBW = 200 Hz; (**b**) harmonics over a 1 GHz frequency span measured with a RBW = 100 kHz.

The relatively low average output powers for both OCs are attributed to increased cavity losses, which are likely associated with the SESAM and the DMs. Power scaling is expected with improved DM design providing higher GDD per bounce and reduced overall round-trip cavity losses.

5. Conclusions

In summary, we have demonstrated sub-50 fs pulse generation from a diode-pumped, passively mode-locked Yb:$KY(WO_4)_2$ laser. In the CW regime, continuous wavelength tuning over 98 nm was achieved using an intracavity quartz-based Lyot filter. In the mode-locked regime, a commercial SESAM enabled stable soliton pulse generation with a shortest pulse duration of 46 fs at a central wavelength of 1069.2 nm and a pulse repetition rate of 67.81 MHz. To the best of our knowledge, these results represent the broadest continuous-wave tuning span and the shortest pulse duration ever reported so far for lasers based on Yb^{3+}-doped potassium MDTs. In fact, this is true in a larger sense, i.e., including also the related lithium and sodium disordered tetragonal double tungstates [45] and double molybdates [46]. Given the relatively high nonlinear refractive index of Yb:$KY(WO_4)_2$ crystal ($n_2 = 19 \times 10^{-16}$ cm^2/W for N_m-polarized light [47]), further pulse shortening and power scaling are expected by increasing the pump power, e.g., using a high-power, single-transverse-mode fiber laser, and by leveraging soft-aperture Kerr-lens mode-locking.

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