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Compact passively Q-switched diode-pumped $Tm:KY(WO_4)_2$ laser with 8 ns/30 μJ pulses

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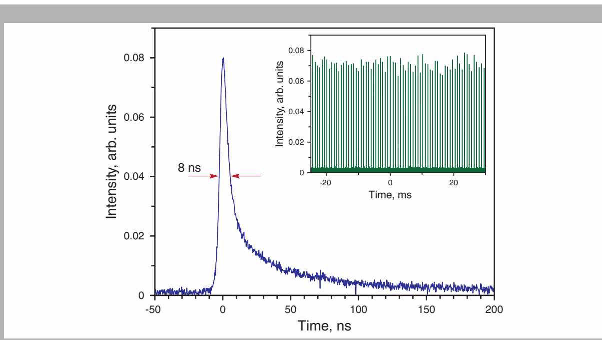
Abstract: A compact diode-pumped solid-state $Tm:KY(WO_4)_2$ laser with cavity length of 1 cm passively Q-switched with a PbS-quantum-dot-based saturable absorber is presented. The laser operates at the wavelength of 1.94 μm and produces pulses with duration of 8 ns and energy of 30 μJ at the repetition rate up to 4.2 kHz. The maximum output power of 120 mW is achieved at incident pump power of 1.15 W.



Oscilloscope trace of a single Q-switched laser pulse. The inset represents a pulse train

Compact passively Q-switched diode-pumped $Tm:KY(WO_4)_2$ laser with 8 ns/30 μJ pulses

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1. Introduction

Potassium double tungstate crystals ($K\mathit{Re}(WO_4)_2$, where *Re* stands for Y, Gd, or Lu) are attractive hosts for lanthanide ions, such as Yb, Nd, or Tm, in order to create solid-state lasers emitting in the near IR spectral range [1–17]. Efficient continuous-wave, Q-switched and semiconductor saturable absorber mirror (SESAM) mode-locked operation of such lasers were demonstrated [2–15]. Diode-pumped SESAM mode-locked $Yb:KGd(WO_4)_2$ [6,7] and $Yb:KY(WO_4)_2$ [8] lasers emitting 100-fs pulses were reported. 240-fs pulses with average output power of 22 W from a mode-locked thin-disk $Yb:KY(WO_4)_2$ laser were achieved [9]. The nonlinearity of refractive index allowed to develop femtosecond $Yb:KY(WO_4)_2$ lasers with 100-fs pulses utilizing soft aperture Kerr-lens mode locking [10,11]. Moreover, double tungstate crystals are efficient Raman media, which made possible development of lasers with intracavity frequency self-conversion [12–15]. Furthermore, high refractive indexes of double tungstate crystals make these materials potentially suitable for applications that require high integration density of components. The demonstration of waveguide lasers and their integration with other optical structures on a chip was presented [16,17].

Being doped with Tm ions, double tungstate crystals are suitable for 2-μm lasers. Their emission is based on the $^3F_4 \rightarrow {}^3H_6$ transition of the Tm ions. The strong absorption bands around 800 nm corresponded to $^3H_6 \rightarrow {}^3H_4$ transition provide possibility to use commercially available diode lasers for pumping. The cross-relaxation energy transfer process $^3H_4 \rightarrow {}^3F_4 - {}^3H_6 \rightarrow {}^3F_4$ in adjacent Tm ions leads (in ideal case) to creation of two upper

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laser level $^3F_4$ states following the absorption of one photon of 800-nm radiation, thus making such a pumping scheme very efficient. Tm-doped double tungstates combine high absorption and emission cross sections with broad linewidths [13,18–20], and satisfactory thermo-optic properties [21], and attract attention as a gain media for efficient and tunable lasers emitting in the spectral range of 2 μm. Efficient diode-pumped continuous-wave Tm:KY(WO_4) [20,22], Tm:KGd(WO_4) [23], and Tm:KLu(WO_4) [24] bulk lasers were reported. More recently, Tm:KY(WO_4) laser based on a planar waveguide architecture was reported [25]; thin disk laser based on a highly doped Tm:KLu$(WO_4)_2$/KLu$(WO_4)_2$ epitaxial active element was presented [26]; widely-tunable (1830–2110 nm) continuous-wave and femtosecond SESAM mode-locked bulk Tm:KY$(WO_4)_2$ lasers pumped by Ti:Sapphire laser were demonstrated [27].

Passive Q-switching of lasers with saturable absorbers (SAs) provides a compact and easy-to-use solution to obtain nanosecond pulsed radiation. In the recent years, the advances in the implementation of such an approach for solid-state diode-pumped, planar waveguide and fiber lasers based on Tm^{3+}- and Ho^{3+}-doped materials with emission wavelength in spectral range of 2-μm were demonstrated. Different kinds of SAs for these lasers were reported. Crystalline Cr:ZnS SA was used in diode-pumped solid-state Tm:KY$(WO_4)_2$ [13] and Tm,Ho:LiYF_4 [28,29] lasers, which emitted pulses with duration of 30 ns and ~ 1 μs at the wavelength of 1.93 μm and 2.05 μs, respectively, with the corresponding pulse energies of 2 and 4 μJ. The use of Cr:ZnSe SA in the Tm:KY$(WO_4)_2$ laser allowed generation of pulses with energy of 4 μJ and duration of 57 ns [13]. Tm-doped KY$(WO_4)_2$ planar waveguide laser passively Q-switched with Cr:ZnSe SA operated at the wavelength of 1.84 μm and produced pulses with energy of 120 nJ and duration of 1.8 μs [25]. Another type of the SA proposed is based on semiconductor quantum well structures. An InGaSb SA mirror was used for the Q-switching of a Tm,Ho-doped silica fiber laser operated at 1.97 μm [30]. Pulses with energy of 15 μJ and duration of 20 ns were demonstrated. Diode-pumped solid-state Tm:YAlO_3 laser was passively Q-switched with an InGaAs/GaAs-based SA [31]. The laser operated at two wavelengths (1.94 and 1.99 μm) and emitted pulses with energy of 28 μJ and duration of 447 ns.

In our recent publications, we have presented glass doped with PbS semiconductor quantum dots as a SA for solid-state lasers operating in the 2-μm spectral range [32–34]. Tm:KY$(WO_4)_2$ laser passively Q-switched with this SA produced pulses with energy of 40 μJ and duration of 60 ns [32]. It was shown that efficient laser operation can be obtained with the similar intracavity mode size in the SA used and the gain medium [32]. Thus, the realization of a thulium laser with a short-length cavity passively Q-switched with this SA should be possible. In the present work, we report the diode-pumped solid-state Tm:KY$(WO_4)_2$ mini-laser with 1-cm cavity length passively Q-switched with PbS-quantum-dot SA, which produces pulses with energy of 30 μJ and duration of 8 ns.

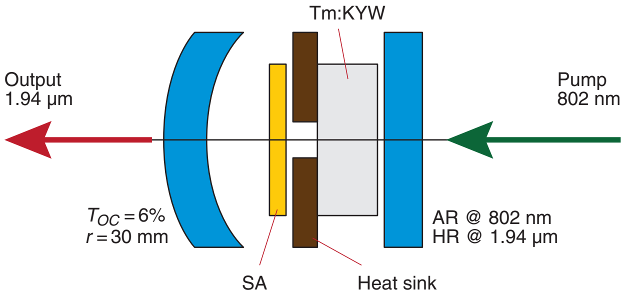

Figure 1 (online color at www.lphys.org) Schematics of the passively Q-switched laser

2. Experiment and results

Schematics of the laser cavity is presented in the Fig. 1. In order to increase the cavity stability against thermal lens instabilities, the output coupler ($T_{OC} = 6\%$) with a 30-mm radius of curvature was used (Fig. 1). The intracavity mode radius in the gain medium and SA was calculated to be 91 and 95 μm, respectively. The Tm(5 at.%): KY$(WO_4)_2$ crystal with a thickness of 2.5 mm cut along the Ng axis had antireflection coatings and was placed on a temperature-controlled copper heat-sink. The temperature was set to 18°C. The cavity length was 1 cm. A fiber-coupled laser diode with unpolarized output at 802 nm ($M^2 = 16$) was used as a pump source. The focusing system provided a pump spot inside the Tm:KY$(WO_4)_2$ crystal with radius of ~ 110 μm. The maximum incident pump power on the gain medium was 1.15 W. The laser produces 220 mW of an output power in a free-running mode with the corresponding threshold of 480 mW of incident pump power, which corresponded to the optical-to-optical efficiency of 19%. About 80% of pump radiation was absorbed in the Tm:KY$(WO_4)_2$ crystal during the laser operation. A sample of glass with PbS quantum dots was prepared according to the technique described in [35]. Maximum of the absorption band corresponding to the first exciton resonance was located at the wavelength of 1.9 μm. The initial sample was polished to a thickness of ~ 300 μm and anti-reflection coated at the laser wavelength. The SA produced had an internal transmission of 94% and was placed between the gain medium and the output coupler (Fig. 1).

Stable Q-switching operation was achieved with the threshold of 820 mW of incident pump power. The maximum laser output power was 120 mW, which corresponds to optical-to-optical efficiency of 11% (Fig. 2a). Maximum pulse repetition rate was 4.2 kHz (Fig. 2b). Q-switched pulse energy was estimated to be 30 μJ (Fig. 2c). The pulse

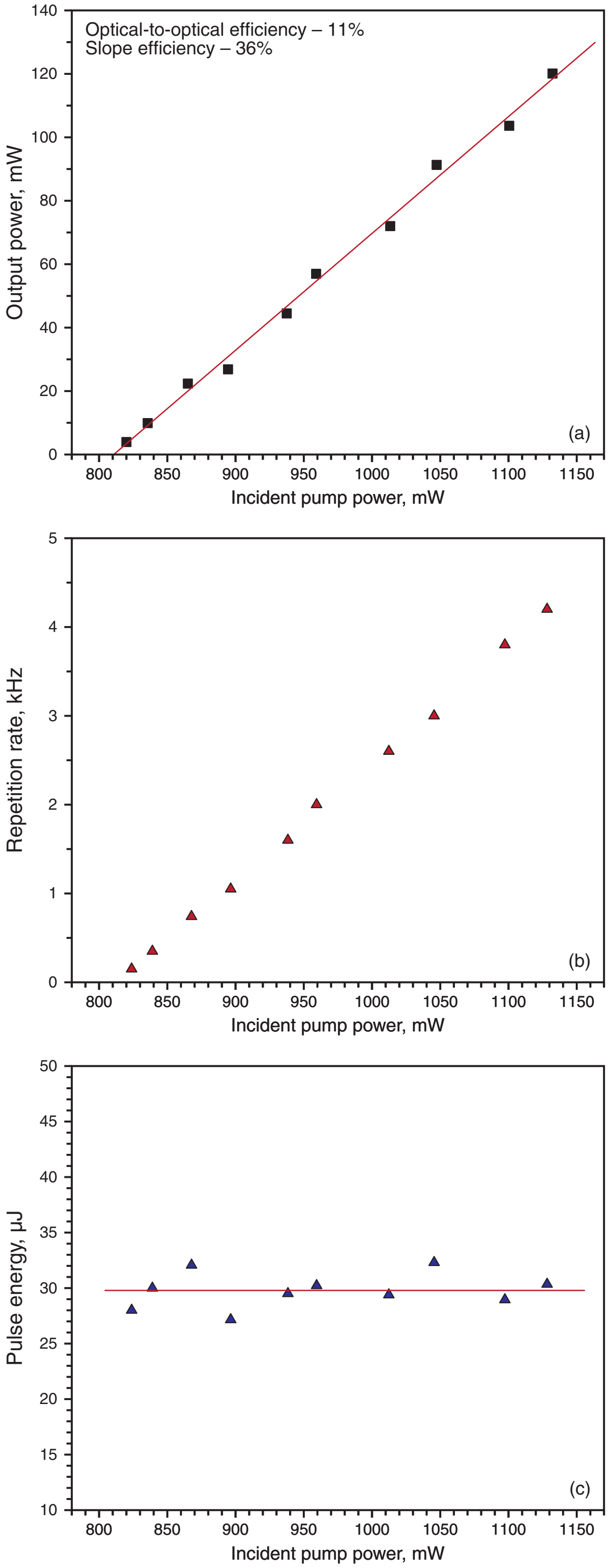

Figure 2 (online color at www.lphys.org) Output characteristics of the Q-switched laser versus incident pump power: average output power (a), pulse repetition rate (b), and pulse energy (c)

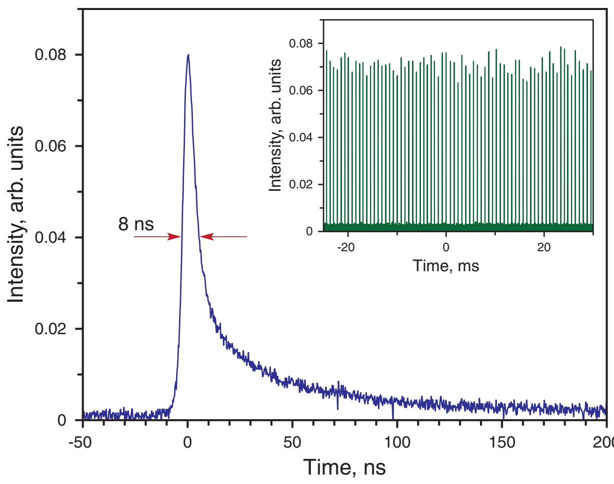

Figure 3 (online color at www.lphys.org) Oscilloscope trace of a single Q-switched laser pulse. The inset represents a pulse train

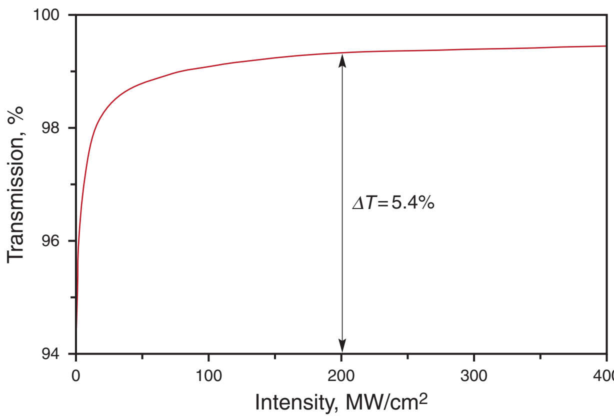

Figure 4 (online color at www.lphys.org) Calculated nonlinear transmission curve of the SA

duration was measured to be 8 ns. Oscilloscope traces of a single Q-switched laser pulse and a pulse train are presented in Fig. 3. The laser operation wavelength was 1936 nm. The laser beam propagation factor at the maximum pump power was estimated to be $M^2 = 1.14$.

The intracavity radiation intensity in the SA was estimated to be ~ 200 MW/cm^2 (corresponding energy fluence is ~ 3 J/cm^2). This value is two orders of magnitude higher than typical values of absorption saturation intensity under nanosecond excitation reported in literature [32,34]. According to our calculations, under these conditions the SA operates with modulation depth $\Delta T = 5.4\%$ and fully bleaches (Fig. 4). The optical damage threshold of the SA under illumination by 50 ns laser pulses was measured to be 15 J/cm^2, which leaves some room for augment of output pulse energy with the cavity design used. The further decrease of laser pulse duration and increase of its energy can be achieved by optimization of the SA initial transmission and output coupler reflectivity.

3. Conclusion

In conclusion, we demonstrated a diode-pumped passively Q-switched Tm:KY$(WO_4)_2$ mini-laser. The laser produces pulses with energy of 30 μJ and duration of 8 ns at the wavelength of 1.94 μm, the maximum output power being 120 mW.

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