Passively mode-locked Tm,Ho:YVO_4 laser based on a semiconductor saturable absorber mirror

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We report the demonstration of passively continuous-wave mode-locking (CWML) of diode-pumped Tm,Ho:YVO_4 laser using an InGaAs/GaAs multiple quantum-well (MQW) structure semiconductor as the saturable absorber. Stable mode-locking pulses at the central wavelength of 2 041 nm are obtained. The maximum output power is 151 mW. The pulse duration is 10.5 ps at the repetition rate of 64.3 MHz.

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Solid-state lasers near the range of 2 μm have drawn much attention in recent years due to their significant applications in wind lidar, laser ranging, and the generation of mid-infrared (MIR) lasers via nonlinear processes such as optical parametric oscillator (OPO). Ultrafast lasers emitted in this wavelength range are promising light sources in these usages, as well as in other aspects, such as time-resolved spectrum or frequency metrology, because they generate pulses with shorter duration and higher energy. Both Tm^{3+} and Tm^{3+} Ho^{3+} co-doped bulk crystals can be employed as gain media to generate picosecond or femtosacond pulses in this range. Actively mode-locked lasers have been successfully demonstrated since 1 990s in bulk crystals such as Tm:YAG[1], Cr,Tm:YAG[2], Tm,Ho:BaY_2F_8[3], and Tm,Ho:$LiYF_4$[4]. Passively mode-locked (PML) bulk lasers, which had the advantages of simplicity and compactness, were obtained in Tm:$KLu(WO_4)_2$[5] and Tm:YLF[6] based on single-wall carbon nanotube. Meanwhile, InGaAs multiple-quantum wells (MQWs) and Sb-based semiconductor saturable absorber mirrors (SESAMs) were also proven to be valid mode lockers in Tm,Ho:YAG[7], Tm:GLF[8], Tm,Ho:KYW[9,10], Tm,Ho:NaYW[11], Tm:KYW[12], and Tm:Glass[13] lasers.

Most of these previous works studied tungstate and YAG host media. Aside from these crystals, the tetragonal uniaxial yttrium vanadate YVO_4 crystal has attracted a lot of interest in recent years for doping with Tm and Ho ions. The spectra of Ho:YVO_4 have been reported in detail by Golab *et al.*[14] and, more recently, by our group for Tm,Ho:YVO_4[15]. The large-emission cross-section (2.4×10^{-20} cm^2 at 2 052 nm and 2.7×10^{-20} cm^2 at 2 040 nm for π-polarization, 0.7×10^{-20} cm^2 at 2 066 nm and 1.3×10^{-20} cm^2 at 2 008 nm for σ-polarization, respectively[15]) makes this crystal a promising host medium for the generation of 2 μm radiation. For Ho^{3+} single-doped YVO_4 crystal, Newburgh *et al.* firstly reported[16] a resonantly pumped Ho:YVO_4 laser at 77 K and obtained 1.6-W laser output at 2 054 nm[16] Most recently, our group demonstrated an efficient room-temperature Ho:YVO_4 laser resonantly pumped by 1.94-μm Tm:YAP laser and obtained up to 8-W laser output at 2 053 nm[17]. Tm,Ho:YVO_4 has a large absorption coefficient and absorption bandwidth of approximately 796 nm, which allows it directly diode-pumped and has a large tolerance of laser diode (LD) temperature variation[15]. With two Tm,Ho:YVO_4 rods (cooled by liquid-N_2) connected in series in a laser resonator, up to 20-W laser output in continuous wave (CW) and Q-switched performance was obtained in Ref. [18]. Additionally, Tm,Ho:YVO_4 is also a good candidate for ultrafast laser operation. Firstly, the large emission cross-section will lower the threshold of CW mode-locking (CWML) according to the theory of PML lasers[19]. This characteristic is similar to that of Nd:YVO_4, which has been widely researched for mode-locking operation[20,21]. Secondly, shorter pulses are expected to be acquired due to broad gain bandwidth of Tm,Ho:YVO_4[20,21]. Relative works had been conducted, and Q-switched mode-locking laser was achieved[22].

In this letter, we report the demonstration of a CWML diode-pumped Tm,Ho:YVO_4 laser, by use of SESAM as the saturable absorber. A maximum output power of 151 mW was obtained at the repetition rate of 64.3 MHz. The shortest pulse was measured to be 10.5 ps.

The schematic setup is shown in Fig. 1. The pump source was a fiber-coupled LD operating at the wavelength of 789 nm. The fiber diameter was 100 μm, and the numerical aperture was 0.22. We should mention that, limited by our experimental condition, this wavelength is not the absorption peak of Tm,Ho:YVO_4, which is at 796 nm[15]. The maximum output power was 21 W. The pump laser was focused into the laser crystal via two lenses that had focal lengths of 50 and 75

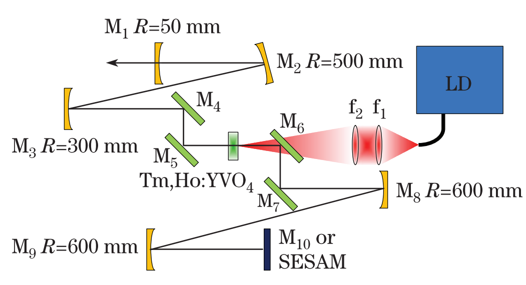

Fig. 1. Experimental setup of the Tm,Ho:YVO_4 laser.

mm, respectively. A 2-mm-long 4 at.-% Tm^{3+}, 0.4 at.-% Ho^{3+}: YVO_4 crystal was employed as the gain medium. Both sides of the crystal were anti-reflection (AR)-coated by 800 nm and near 2 μm. The crystal used here was an a-cut one, and the emission laser polarization was along c-axis (π polarization). The sample was wrapped with indium foil, set in a liquid-nitrogen-cooled copper heat sink, and placed on the focus center of M_3 and M_8. M_4, M_5, M_6, and M_7 were flat mirrors and highly reflective at 2 μm, whereas M_5 and M_6 also had high transmission around 800 nm and were used for coupling the pump light into the crystal. M_{10} was a high reflective mirror at 2 μm. When it was substituted for SESAM, a pulsed laser would be generated. The whole cavity length was designed to be 2.325 m. The radii of curvature for all the concave mirrors are shown in Fig. 1. According to the ABCD propagation matrix, the laser mode waist radii at the crystal and the SESAM were 75 and 100 μm, respectively. M_1 was the output coupler with the transmission of 1.5%. M_4, M_5, M_6, and M_7 were flat mirrors designed to couple the pump laser into the crystal. The folding angle was set as less than 5° to compensate the astigmatism. The distances between M_1, M_2, M_3, M_8, M_9, M_{10} were, respectively, 27.5, 50, 45, 70, and 40 cm, comprising the whole cavity of 2.325 m.

The SESAM provided by Batop GmbH was SAM-2000-5-x, the substrate of which was semi-insulating GaAs. The absorber layer consisted of $In_xGa_{1-x}As$ with GaAs barriers. The front surface of the saturable absorber (SA) was AR-coated by 2 μm. SA had high reflection band (R>85%) between 1 920 and 2 045 nm, whereas the actual reflectivity at laser wavelength (2.041 μm) was experimentally measured to be 88% at low intensity. SA had a cross-section measuring 4×4 (mm). The thickness of the chip was 400 μm. The modulation depth of the SA device was 3% and the absorbance was 5%,

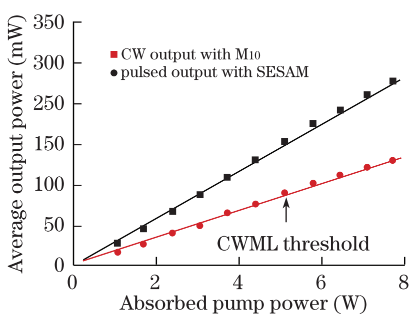

Fig. 2. CW and pulsed average output power versus absorbed pump power.

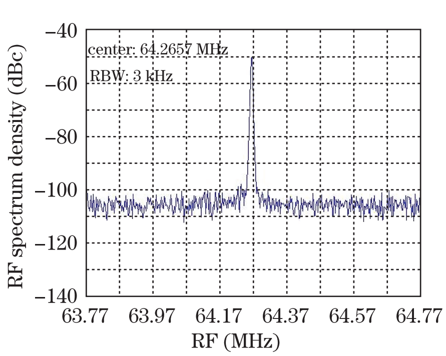

Fig. 3. RF spectrum of CWML Tm,Ho:YVO_4 laser.

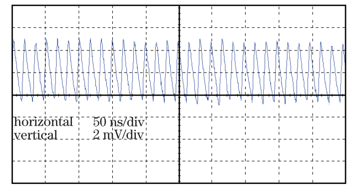

Fig. 4. Temporal behaviors of the laser output at CWML operation.

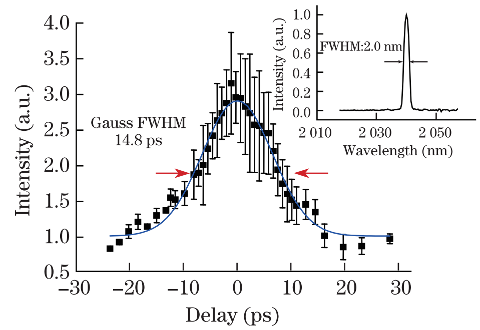

Fig. 5 Envelop of the intensity autocorrelation trace. The Gauss FWHM is 14.8 ps, which indicates that the pulse width is 10.5 ps.

indicating that the nonsaturable loss of the SA was approximately 2%. The saturation fluence was 60 $\mu J/cm^2$. SA was glued on a glided Cu-cylinder sink, which was cooled by water.

When the high-reflectance M_{10} was used, CW laser output was obtained. Figure 2 shows the average output power at different pump powers with the output mirror transmission of 1.5%. The maximum output power was 265 mW at the absorbed pump power of 7.73 W, corresponding to a slope efficiency of ~3.6%. We did not increase the pump power furthermore in consideration of material damage. The low efficiency could be attributed to two points. Firstly, the laser cavity was extremely long and the total laser gain volume was small (beam radius at the gain medium was 75 μm and the length was 2 mm). Therefore the diffraction loss was high compared to the low gain of the laser. Secondly, in the experiment, we found laser output after 45° dichroic mirrors M_5 and M_6 due to the imperfect coatings, which increased the cavity loss. Through optimized cavity design and better mirrors, higher efficiency can be expected in our next work. When SESAM was employed, the Q-switching pulses emerged with a repetition rate of tens of kilohertz. Carefully adjusting the cavity mirror and the saturable absorber, we acquired the Q-switched mode-locking and CWML pulses successively. The threshold of CWML was 106 mW, and a maximum output power of 151 mW was obtained, which was less than the CW one because the saturable absorber was not completely reflective. In this range, the intracavity energy fluence on the SESAM increased from 357 to 508 $\mu J/cm^2$, approximately equivalent to 6–8.5 times of the saturation fluence. Considering the repetition rate of 64.3 MHz, the maximum single pulse energy was calculated to be 2.3 nJ. The CWML was self-starting and could be maintained stably for over 2 h.

The radio frequency (RF) of the CWML laser under pump power of 6.45 W is shown in Fig. 3, as recorded by a spectrum analyzer with a PIN photodiode. The RF spectrum under a span of 1 MHz shows a clean peak at the repetition of 64.2657 MHz without any side peaks. This result is constant with the cavity round-trip time of 15.5 ns, which verifies that the laser was operating in CWML mode without Q-switching instabilities. This point could be further proven by the temporal behaviors of the output laser shown in Fig. 4 (recorded by a Tektronix digital oscilloscope DPO 7104, 10 Gs/s 1 GHz bandwidth).

We measured the pulse duration by second harmonic autocorrelation, employing a periodically poled lithium niobate (PPLN) as the nonlinear crystal. Figure 5 shows the intensity autocorrelation result at the maximum absorbed pump power of 7.73 W, where shortest pulses are achieved when Gaussian shape fit is assumed. Full-width at half-maximum (FWHM) of the autocorrelation trace was 14.8 ps, corresponding to the pulse width of 10.5 ps. Meanwhile, the spectrum of the CWML laser was also measured, as shown in the inset of Fig. 5. Wavelength division multiplexing (WDM) 1–3 monochromator with a 600 line/mm grating blazed at 2.0 μm was used to scan across the laser emission spectrum (0.05-nm resolution). The spectral bandwidth was 2.0 nm and the time bandwidth product (TBP) was approximately 1.5, which is higher than the transform-limited value 0.441 of Gaussian shape (approximately 3.4 times). This result meant that the laser was highly chirped, which contributed to our taking no consideration in the intracavity dispersion. If measures are taken to compensate for the intracavity dispersion, such as inserting a pair of prisms, shorter and transform-limited pulses are expected to be obtained[10].

In addition, the beam quality of CWML laser was also measured by travelling 90/10 knife-edge method at the maximum output power (Fig. 6). By fitting Gaussian beam standard expression to these data, we estimated the beam quality to be M^2=2.13. The poor beam quality was mainly credited to the astigmatism induced by the folding mirrors. Theoretically, the laser cavity was designed with only occasional astigmatism. Nevertheless, the laser mode was sensitive to the cavity parameters. The difference between the tangential and sagittal plane increased obviously, even when the distance between two mirrors changed several millimeters. In fact, all the elements were discretely placed on the optical platform, and the cavity parameters could not be set exactly. A promising solution to this problem is to carefully design and fabricate an integrated scheme.

In conclusion, we demonstrate a CWML Tm,Ho:YVO_4 laser by use of a semiconductor saturable absorber. Mode-locked laser pulse with a maximum output power of 151 mW is obtained at the central wavelength of 2 041 nm. The laser pulse width is measured to be 10.5 ps at the repetition of 64.3 MHz.

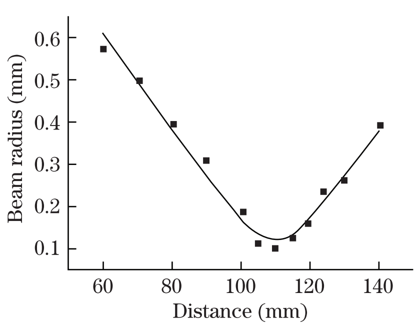

Fig. 6. Beam radius as a function of the distance from the focusing lens. The experimental data fit a curve of a standard Gaussian beam propagation expression.

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