Mode-locked Tm,Ho:YAP laser around 2.1 μm

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Abstract: A passively mode-locked Tm,Ho:YAP laser around 2.1 μm wavelength employing a semiconductor saturable absorber mirror is demonstrated. Stable continuous wave mode-locking operation was achieved at variable center wavelengths of 2036.5 nm, 2064.5 nm, 2095.5 nm, 2103.5 nm, and 2130 nm, respectively. Pulses as short as 40.4 ps were obtained at 2064.5 nm with a spectral FWHM of 0.5 nm at output powers of 132 mW and a repetition rate around 107 MHz. A maximum output power of 238 mW was obtained at 2130 nm with a pulse duration of 66 ps.

OCIS codes: (140.7090) Ultrafast lasers; (140.4050) Mode-locked lasers; (140.3070) Infrared and far-infrared lasers.

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1. Introduction

Apart from the applications in the fields of light detection and ranging (LIDAR), frequency metrology, time-resolved spectroscopy, laser microsurgery, plastics material processing, and free space optical communication [1, 2], ultrafast laser sources around 2 μm with high peak power are gaining more and more attention as potential pumping of solid state lasers such as Cr^{2+}:ZnSe [3] and optical parametric oscillators (OPOs) for the mid- and far-infrared spectral regions. Based on the above listed wide potential applications, wavelength tunable laser sources near 2 μm are potentially of high interest. Due to a strong absorption band around 800 nm covered by commercial AlGaAs diode lasers and a quantum efficiency up to two via cross relaxation, passively mode-locked Tm^{3+} or Tm^{3+}-Ho^{3+} doped lasers have become prevalent options to obtain 2 μm ultrashort pulses efficiently. To date passively mode-locked Tm^{3+}-doped or Tm^{3+}-Ho^{3+} co-doped garnet [4–6], tungstate [7], sesquioxide [8], and silicate [9] crystalline lasers at 2 μm have been successfully realized based on semiconductor saturable absorber mirrors (SESAMs) [7] or saturable absorption in carbon nanotubes (CNTs) [8], intersubband transitions (ISBTs) in quantum wells [4], graphene [5], as well as PbS quantum dots [6]. Meanwhile, on-going efforts explore novel ultrashort 2 μm laser systems combining different gain media and mode-locking methods.

The biaxial crystal yttrium aluminium oxide ($YAlO_3$), short YALO or YAP, has a natural birefringence that dominates thermally induced birefringence due to the anisotropic lattice structure. Thus thermally induced degradation is suppressed to a certain extent and the generation of linearly polarized emission becomes easy [10]. In comparison with YAG crystals, Tm^{3+} ions doped in a YAP host have a broader strong absorption peak with a FWHM of about 4 nm along the *b*-axis at around 795 nm [11], which makes YAP crystals a promising laser host for thulium or thulium-holmium doping. Very recently, we have demonstrated a maximum slope efficiency of nearly 46% and a quantum efficiency of above 1.4 from a Tm,Ho:YAP laser [10]. Although the continuous wave (CW) and Q-switched operations with Tm^{3+}-doped or Tm^{3+}-Ho^{3+} co-doped YAP crystals have been reported [10, 12–14], the mode-locking regimes were less explored. Only recently mode-locked Tm:YAP lasers with CNTs and graphene oxides were demonstrated in 2012 [15, 16]. However, there are no reports on the mode-locking operation of a Tm,Ho:YAP laser.

Here we report - for the first time to our best knowledge - a passively mode-locked Tm,Ho:YAP laser around 2 μm with a semiconductor saturable absorber mirror. Stable CW mode-locking was achieved at variable wavelengths of 2036.5 nm, 2064.5 nm, 2095.5 nm, 2103.5 nm, and 2130 nm with pulse durations of 48 ps, 66 ps, 48.8 ps, 40.4 ps and 43.6 ps, respectively. The shortest pulse with duration of 40.4 ps was obtained at 2064.5 nm with an output power of 132 mW and a repetition rate around 107 MHz.

2. Experimental setup and results

The employed schematic laser setup is shown in Fig. 1. A *b*-cut 5 at.% thulium and 0.3at.% holmium doped YAP crystal with size of 4 × 4 × 8 mm^3 was grown by the Czochralski technique (Shanghai Institute of Ceramics, China). Both faces of the crystal were antireflection coated from 750 to 850 nm (reflectivity < 2%) and 1930-2230 nm (reflectivity < 0.8%). The laser crystal was wrapped in indium foil and water-cooled to 12°C. A CW linearly polarized Ti:sapphire laser tunable from 726 nm to 859 nm was used as the pump source. Mirrors M_1 and M_2 had the same radii of curvature of 100 mm and reflectivity of 99.9% from 1820 to 2150 nm. The front surface of mirror M_1 was also anti-reflection coated at the wavelengths of 750-850 nm with a reflectivity less than 0.25%. Concave mirrors M_3, M_4, and M_5 with respective curvature radii of 30 mm, 50 mm and 100 mm were all high reflectivity

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coated from 1820 to 2150 nm (reflectivity >99.9%). All the cavity mirrors except the output couplers (OCs) were chirped with group delay dispersion (GDD) of ~-100 fs^2 in the 1820 nm to 2150 nm spectral region. OCs with transmissions of 1% (1820nm - 2150 nm, ± 0.2%) and 2% (1950 nm-2150 nm, ± 0.3%) were employed for comparison. A commercial InGaAs-SESAM (Batop Inc.) with a saturation fluence of 70 μJ/cm^2 and a modulation depth of about 0.6% at 2100 nm was employed to start and stabilize the mode-locking. The total cavity length was 1.4 m. This length was maintained whether a silicon prism pair was inserted into the cavity or not. The corresponding repetition rate was about 107 MHz. To compensate the astigmatism, the folding angles of the mirrors were about 5°. With ABCD matrix propagation theory, the laser mode waist radii in the laser crystal were calculated to be 43 μm and 41 μm in sagittal and tangential planes, respectively, and the beam waist radii on the SESAM was about 82 μm in the sagittal plane and 84 μm in the tangential planes.

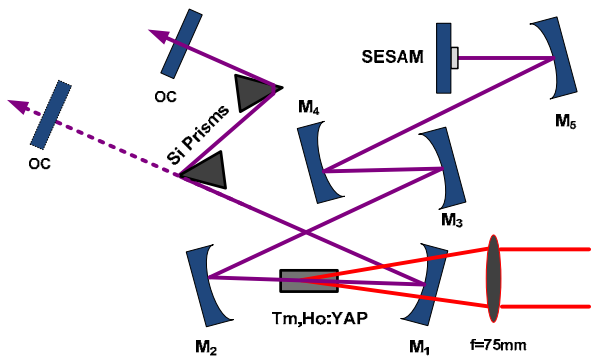

Fig. 1. Schematic setup of mode-locked Tm,Ho:YAP laser. OC: output coupler

With the Ti:Sapphire laser tuned to 791.7 nm, the Tm,Ho:YAP laser was first investigated without the silicon prisms in the cavity. A 1 GHz bandwidth digital oscilloscope (DPO 5104, Tektronix Inc.) and a 60 MHz bandwidth extended-InGaAs PIN photodiode (G8423, Hamamatsu Inc.) were used to monitor the pulse train leaking from mirror M_3 to optimize the stability of CW mode-locking. With careful alignment of the cavity, passive mode-locking operation was achieved. The output spectra were recorded by a laser spectrometer with a resolution of 0.4 nm (APE WaveScan, APE Inc.), and a collinear autocorrelation setup using second harmonic generation with a PPLN crystal was employed to measure the pulse durations. Figures 2(a)–2(f) summarize the output characteristics including average output powers, optical spectra, and autocorrelations of the mode-locked Tm,Ho:YAP lasers with 1% and 2% OCs. With 1% OC used, CW mode-locking was achieved at 2103.5 nm and 2130 nm, respectively by aligning the OC carefully, with the threshold absorbed pump powers of 680 mW and 413 mW. At the threshold pump powers for CW mode-locking, the output powers at 2103.5 nm and 2130 nm were 17.4 mW and 33.1 mW, respectively corresponding to the fluences of 75 μJ/cm^2 and 143 μJ/cm^2 on the SESAM. However, when the laser ran in the CW mode-locking regime, the slope efficiencies decreased to 6.9% and 6.5%, respectively, as shown in Figs. 2(a) and 2(d). The maximum output powers of 164 mW at 2103.5 nm and 184 mW at 2130 nm were obtained with a repetition rate of about 107 MHz. During the experiment, we observed double pulse mode-locking at both 2103.5 nm and 2130 nm under the maximum pump power when a 1% OC was used, which were attributed to the much higher intracavity fluences of 708 μJ/cm^2 and 795 μJ/cm^2 on the SESAM than the saturation fluence of 70 μJ/cm^2.

However, when a 2% OC was employed, CW mode-locking could only be achieved at 2130 nm. From Fig. 2(d), we can see that the threshold absorbed pump power for CW mode-locking was increased to be 1.55 W, corresponding to an output power of about 155 mW, which generated a fluence of 335 μJ/cm^2 on the SESAM and was much higher than the case

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with 1% OC. A slope efficiency of 11.5% and a maximum output power of 238 mW with respect to an absorbed pump power of 2.31 W were obtained, which is shown in red in Fig. 2(d). The maximum fluence on the SESAM was about 514 μJ/cm^2, and we did not observe double pulse formation. Figure 2(e) shows the optical spectrum centered at 2130 nm with a spectral bandwidth of 0.4 nm. A pulse duration of 66 ps was obtained by assuming a sech^2 pulse shape as shown in Fig. 2(f). Due to the spectrometers low resolution, we omit to give a time-bandwidth product (TBP) here.

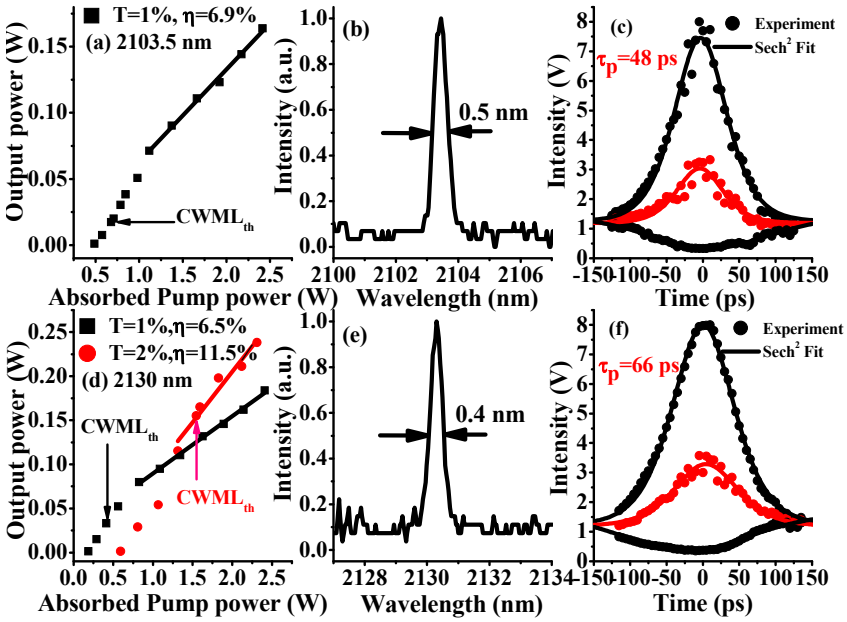

Fig. 2. Average output powers, optical spectra and autocorrelations (from left to right) of mode-locked Tm,Ho:YAP laser with 1% and 2% OCs.

To investigate the influences of the intracavity dispersions on the pulse duration, a pair of silicon prisms with tip to tip separation of 55 mm was inserted into the cavity. Considering the GDD introduced by the cavity mirrors and Tm,Ho:YAP crystal as well as the silicon prism pair, the maximum compensated dispersion was ~-10000 fs^2, which increased by 1600 fs^2/mm with the insertion length of silicon prism into the cavity. However, the Tm,Ho:YAP laser could not oscillate either at 2103.5 nm or at 2130 nm any more after the insertion of the silicon prisms with 1% or 2% OCs, while the CW mode-locking operations at 2036.5 nm, 2064.5 nm and 2095.5 nm were achieved by aligning the OCs carefully. By using 1% OC the Tm,Ho:YAP laser could only oscillate in CW regime at 2036.5 nm. However, the mode-locking operation could be realized at 2036.5 nm with a threshold absorbed pump power of 1.88 W, corresponding to an output power of 64.8 mW and a fluence of 140 μJ/cm^2 on the SESAM when 2% OC used. The output power characteristics are shown in Fig. 3(a), from which we can see that a maximum output power of 80 mW with respect to an absorbed pump power of 2.36 W was obtained, corresponding to a slope efficiency of 7.5%. Under CW mode-locking, Fig. 3(b) shows the spectral bandwidth of 0.6 nm centered at 2036.5 nm with the corresponding pulse duration of 48.8 ps as shown in Fig. 3(c).

With the OCs aligned carefully, CW mode-locking operations at the other wavelengths of 2064.5 nm and 2095.5 nm could be realized both for 1% and 2% OCs. When the laser ran at 2064.5 nm, the threshold absorbed pump powers for CW mode-locking were 1.43 W and 1.52 W, corresponding to the output powers of 36.3 mW and 58.9 mW as well as the fluences of 157 μJ/cm^2 and 127 μJ/cm^2 on the SESAM, respectively, for the 1% and 2% OCs. The slope efficiencies of 5.3% for 1% OC and 10% for 2% OC were obtained, with the maximum

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output powers of 85 mW and 132 mW as shown in Fig. 3(d), respectively. The spectrum centered at 2064.5 nm with a spectral FWHM of about 0.5 nm is shown in Fig. 3(e), corresponding to a pulse duration of 40.4 ps as demonstrated in Fig. 3(f). This was the shortest pulse obtained from the mode-locked Tm,Ho:YAP laser in the experiment.

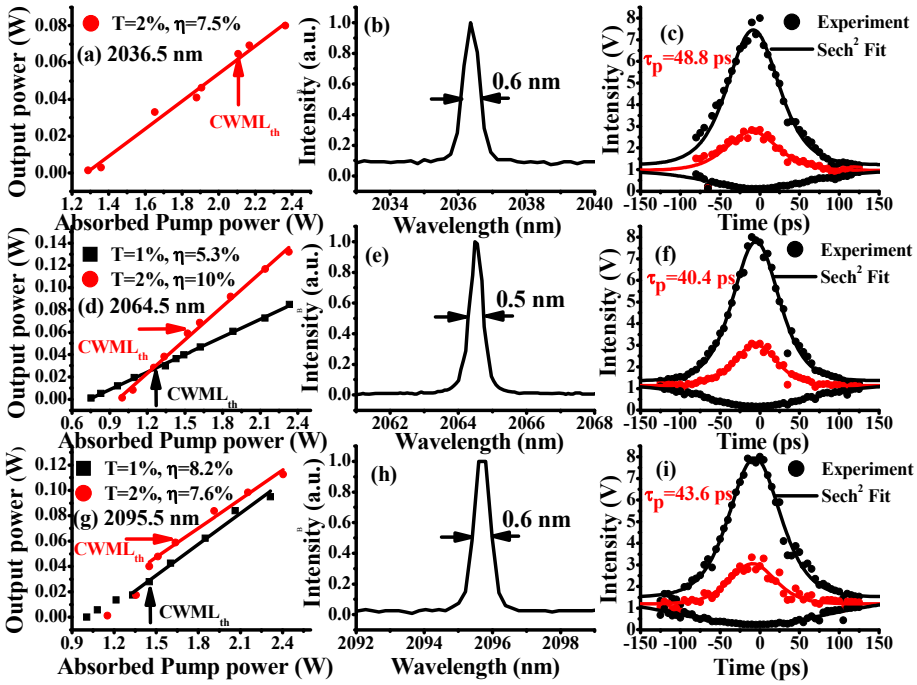

Fig. 3. Average output powers, optical spectra and autocorrelations (from left to right) of mode-locked Tm,Ho:YAP laser with dispersion compensated by silicon prisms for 1% and 2% OCs.

Figure 4 shows the first beat note of the radio frequency (RF) spectrum of the stable CW mode-locking at 2064.5 nm at the maximum pump power when the OC of T = 2% was employed, which was recorded by a spectrum analyzer with a bandwidth of 13.2 GHz and a resolution bandwidth of 1 KHz (E4405B, Agilent Inc.). The RF spectrum obtained under a span of 50 kHz shows a clean peak at the repetition rate of about 107 MHz without side peaks, which exactly agrees with the roundtrip time of the cavity and reveals stable CW mode-locking operation of the laser as well as the absence of Q-switching instabilities. In addition, the wide-span RF measurement indicated the single pulse operation of the mode-locked Tm,Ho:YAP laser, as shown inset of Fig. 4.

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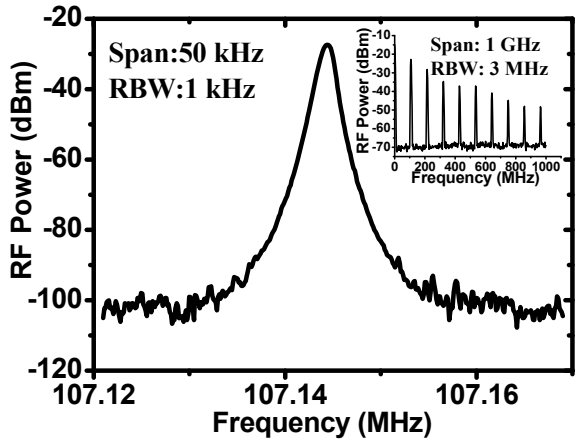

Fig. 4. RF spectrum of continuous wave mode-locked Tm,Ho:YAP laser at 2095.5 nm. RBW: resolution bandwidth.

The CW mode-locked Tm,Ho:YAP laser could run at 2095.5 nm with the threshold absorbed pump powers of 1.45 W and 1.64 W, corresponding to the output power of 28 mW and 58.8 mW as well as the fluences of on 121 μJ/cm^2 and 127 μJ/cm^2 on SESAM, respectively for 1% and 2% OCs. As shown in Fig. 3(g), the obtained maximum output powers were 95 mW and 113 mW, corresponding to the slope efficiencies of 8.2% and 7.6% for 1% and 2% OCs, respectively. Under CW mode-locking, the spectrum centered at 2095.5 nm was recorded with a spectral FWHM of 0.6 nm as shown in Fig. 3(h). A recorded autocorrelation signal for pulse with duration of 43.6 ps is shown in Fig. 3(i). In the experiment, we did not observe obvious variation of the pulse duration when changing the introduced dispersion from about ~-10000 fs^2 to about –200 fs^2 by aligning the silicon prisms in the cavity. According to the measured emission spectra of a *c*-cut Tm,Ho:YAP crystal [17], the narrow peaks of the emission spectra in our previous experimental spectral range may be the reason for the rather long pulse durations here.

Table 1. Output characteristics of mode-locked Tm,Ho:YAP laser at variable wavelengths

Wavelength (nm)	2036.5	2064.5		2095.5		2103.5	2130	
OCs Transmission	2%	1%	2%	1%	2%	1%	1%	2%
Threshold Absorbed Pump Power (W)	2.11	1.43	1.52	1.45	1.64	0.68	0.41	1.55
Threshold Output Power (mW)	64.8	36.3	58.9	28	58.8	17.4	33.1	155
Threshold Fluence on SESAM (μJ/cm^2)	140	157	127	121	127	75	143	335
Maximum Output Power (mW)	80	85	132	95	113	164	184	238
Slope Efficiency (%)	7.5	5.3	10	8.2	7.6	6.9	6.5	11.5
Pulse Duration (ps)	48.8	40.4		43.6		48	66	
FWHM (nm)	0.6	0.5		0.6		0.5	0.4	

Table 1 summarizes the output characteristics of the mode-locked Tm,Ho:YAP laser with SESAM at variable wavelengths for 1% and 2% OCs. From the Table, we can see that when the fluence on the SESAM was increased to about twice the saturation fluence, CW mode-locking could be obtained except at 2130 nm with 2% OC. It should be also noted that when the fluence on the SESAM reaches ten times the saturation fluence, double pulse mode-locking occurs, i.e., the case at 2103.5 nm and 2130 nm with 1% OC under maximum pump

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power. In other words, a fluence on the SESAM ranging from twice to ten times of the saturation fluence can allow for stable single pulse mode-locking of the Tm,Ho:YAP laser.

3. Conclusion

In conclusion, a passively mode-locked Tm,Ho:YAP laser around 2 μm with a semiconductor saturable absorber mirror is reported to the best of our knowledge for the first time. Stable continuous wave mode-locking was achieved at variable wavelengths of 2036.5 nm, 2064.5 nm, 2095.5 nm, 2103.5 nm, and 2130 nm, respectively. Pulses as short as 40.4 ps were obtained at 2064.5 nm with a spectral FWHM of 0.5 nm.The coresponding output power was 132 mW and the repetition rate was around 107 MHz. A maximum output power of 238 mW was obtained at 2130 nm with pulse duration of 66 ps.

Acknowledgments

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