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Efficient continuous wave and passively mode-locked Tm-doped crystalline silicate laser

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Abstract: An efficient continuous wave and passively mode-locked thulium-doped oxyorthosilicate Tm:LuYSiO$_5$ laser is demonstrated. A maximum slope efficiency of 56.3% is obtained at 2057.4 nm in continuous wave operation regime. With an InGaAs quantum well SESAM, self-starting passively mode-locked Tm:LuYSiO$_5$ laser is realized in the 1929 nm to 2065 nm spectral region. A maximum average output power of 130.2 mW with a pulse duration of 33.1 ps and a repetition rate of about 100 MHz is generated at 1984.1 nm. Pulses as short as 24.2 ps with an average output power of 100 mW are obtained with silicon prisms where used to manage the intracavity dispersion. The shortest pulse duration of about 19.6 ps is obtained with an average output power of 64.5 mW at 1944.3 nm.

OCIS codes: (140.7090) Ultrafast lasers; (140.4050) Mode-locked lasers; (140.3070) Infrared and far-infrared lasers; (140.3600) Lasers, tunable.

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1. Introduction

In recent years ultrashort laser sources at 2 µm have attracted much attention because of their important applications in light detection and ranging (LIDAR), frequency metrology, time-resolved spectroscopy, laser microsurgery, optical communication, and efficient attainment of laser pulses farther in mid-infrared (MIR) range [1, 2]. Tm^{3+}-doped and Tm^{3+}-Ho^{3+} co-doped crystalline hosts or fibres operating in the range of 1800-2100 nm have been one of the most prevalent options, because Tm^{3+}- ions exhibits a strong absorption band around 800 nm and hence can be directly pumped by low-cost and high-power AlGaAs diode lasers. To date, based on Tm^{3+} or Tm^{3+}-Ho^{3+} co-doped active materials, a variety of mode-locking mechanisms have been employed to produce ultrashort pulses in the picosecond or femtosecond regimes, such as active mode-locking [3], additive-pulse mode-locking [4], and saturable absorption mode-locking [5, 6]. Among the methods available, saturable absorption mode-locking has gained precedence due to the compactness and capability to generate ultrashort pulses. Therefore several feasible materials for mode-locking, i.e. semiconductor saturable absorber mirrors (SESAMs) [7], single-walled carbon nanotubes (SWCNTs) [8], intersubband transitions (ISBTs) in quantum wells [9] as well as PbS quantum dots [10] have been successfully employed to generate ultrashort pulses at around 2 µm. Very recently, pulses as short as 191 fs and 175 fs were generated from a Tm,Ho:$NaY(WO_4)_2$ laser with an InGaAsSb quantum well SESAM [7] and a Tm:Lu_2O_3 laser with SWCNTs [8], respectively, which demonstrated the feasibility ultrafast 2 µm lasers.

On the other hand, due to the quasi-three-level scheme of both Tm^{3+} and Ho^{3+} ions operating at 2 µm, a long-standing and on-going effort is the investigation of novel gain hosts with large splitting of the ground state laser level reducing the reabsorption and with a high thermal conductivity. Besides Tm doped fibers, the passively mode-locked crystalline lasers at 2 µm are mainly concentrated on the Tm^{3+}-doped or Tm^{3+}-Ho^{3+} co-doped YAG, tungstate, sesquioxide and fluoride crystals. Recently Tm-doped Lu_2SiO_5 (LSO) and Y_2SiO_5 (YSO) oxyorthosilicate crystals, both belonging to the monoclinic biaxial system with a C2/c space group, have attracted much attention due to their good physical, chemical and thermal properties, such as the large ground state splitting of 1094 cm^{-1} for Tm:LSO [11] and 1021 cm^{-1} for Tm:YSO [12], which are much larger than 610 cm^{-1} for Tm:YAG [13], 419 cm^{-1} for Tm:YLF [14], and 530 cm^{-1} for Tm:$KLu(WO_4)_2$ [15], and comparable with 863 cm^{-1} for Tm:Y_2O_3 [13] and 1035 cm^{-1} for Tm:Sc_2O_3 [13]. This is helpful to improve the laser

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efficiency and to reduce the reabsorption loss. Broad emission spectra due to the abundant Stark levels in the $^3H_6$ ground and $^3F_4$ excited manifolds which are induced by the low site symmetry. A high thermal conductivity (5.3 $Wm^{-1}K^{-1}$ for un-doped LSO host and 4.4 $Wm^{-1}K^{-1}$ for un-doped YSO host) [11] is also beneficial. With the alloy of LSO and YSO crystals, i.e., $LuYSiO_5$ (LYSO), Yb and Nd doped LYSO crystals have been successfully demonstrated in CW and mode-locked lasers [16–19]. Especially, the Yb:LYSO crystal exhibited a continuous wave (CW) tunability over a spectral range 77 nm from 1014 nm to 1091 nm and thermal conductivity of 5 $Wm^{-1}K^{-1}$ [16], which predestines it as promising gain medium for femtosecond lasers [17]. However, to our best knowledge, there is no report either on CW or mode-locking operation of Tm-doped LYSO lasers so far.

Here a CW and passively mode-locked Tm:LYSO laser with InGaAs quantum well SESAM pumped by a tunable CW Ti:Sapphire laser was presented. In CW operation regime, a maximum slope efficiency of 56.3% related to the absorbed pump power at a wavelength of 2057.4 nm and a maximum output power of 1.019 W at 2058.9 nm with an absorbed pump power of 2.3 W at 777 nm were obtained. With a 2 mm thick quartz plate acting as lyot filter, the Tm:LYSO laser exhibited wavelength tunability over a broad spectral range from 1922 nm to 2061 nm. By using an InGaAs quantum well SESAM (BATOP Inc.) and a quartz plate, passive mode-locking operation was realized in the 1929 nm to 2065 nm spectral region. A maximum average output power of 130.2 mW with a pulse duration of 33.1 ps and a repetition rate of about 100 MHz was obtained at 1984.1 nm, where pulses as short as 24.2 ps with an average output power of 100 mW was generated when silicon prisms were e used to manage the intracavity dispersion. The shortest pulse duration of 19.6 ps was obtained with an average output power of 64.5 mW at 1944.3 nm.

2. Experimental setup and results

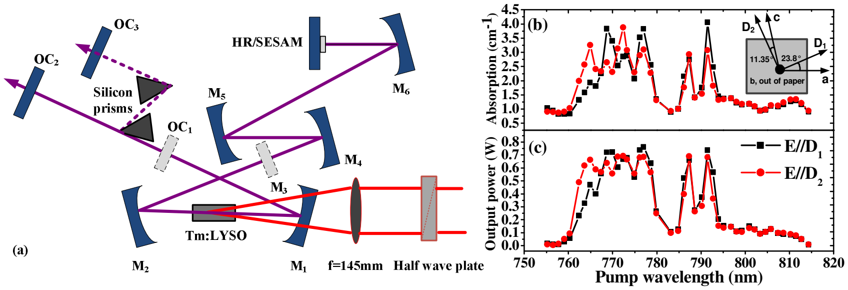

Fig. 1. (a) CW and passively mode-locked Tm:LYSO laser setup, (b) Polarized absorption spectrum and (c) laser emission power of Tm:LYSO crystal under lasing operation: Square, (**E**) ǁ **D₁**; Circle, (**E**) ǁ **D₂**. The inset in Fig. 1 (b) is the crystalline orientation of Tm:YSO crystal [9].

The schematic laser setup is shown in Fig. 1(a). The pump source is a wavelength tunable continuous wave Ti:sapphire laser emitting from 726 nm to 859 nm. A half wave plate with antireflection coating at 780 nm was used to vary the pump light polarization. A lens with a focal length of 145 mm was used to focus the pump light into a ***b***-cut 3 × 3 × 5 mm^3 Tm:LYSO crystal, which was anti-reflection coated on both flat-polished parallel facets from 750 - 850 nm (reflectivity < 2%) and 1930 - 2230 nm (reflectivity < 0.8%). The Tm:LYSO crystal was wrapped in indium foil and water cooled to 12° C. 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%. Flat mirror M_3 and concave mirrors M_4, M_5 and M_6 with respective curvature radii of 30 mm, 50 mm and 100 mm were all high reflectivity coated from 1820 to 2150 nm (reflectivity >99.9%). All the cavity mirrors except the output couplers had group delay dispersion (GDD) of ~-100 fs^2 in the 1820 nm to 2150 nm spectral region.

The CW operation of the Tm:LYSO laser was studied first in a X-type cavity consisting of mirrors M_1, M_2, M_3 and OC_1. Considering the monoclinic structure and crystalline orientation of the ***b***-cut Tm:LYSO similar to that of Tm:YSO [20] as shown in the inset of Fig. 1(b), we investigated the absorption and emission characteristics of Tm:LYSO crystal under lasing operation by employing $\mathbf{E} \parallel \mathbf{D_1}$ and $\mathbf{E} \parallel \mathbf{D_2}$ polarized pump light and an output coupler of T = 3% first. Here E represents the polarization direction of pump light, and D_1 and D_2 represent two optical axes of the Tm:LYSO crystal, respectively. As shown in Fig. 1(b), in the pump spectral range of 760-780 nm the absorption peaks were located at 768 nm with absorption coefficient of 3.83 cm^{-1}, 773 nm with 2.88 cm^{-1} and 777 nm with 3.82 cm^{-1} for $\mathbf{E} \parallel \mathbf{D_1}$ and 765 nm with absorption coefficient of 3.25 cm^{-1}, 772 nm with 3.88 cm^{-1} and 777 nm with 3.09 cm^{-1} for $\mathbf{E} \parallel \mathbf{D_2}$, respectively. However, the absorption was the same for $\mathbf{E} \parallel \mathbf{D_1}$ and $\mathbf{E} \parallel \mathbf{D_2}$ in the spectral range of 780-800 nm. With $\mathbf{E} \parallel \mathbf{D_1}$ pumped, a maximum absorption coefficient of 4.06 cm^{-1} was obtained at 791.5 nm, while it was only 3.07 cm^{-1} in the case of $\mathbf{E} \parallel \mathbf{D_2}$. Figure 1(c) shows the average output powers versus different pump wavelengths. With an absorbed pump power of 2.24 W at 777 nm, a maximum output power of 780 mW for $\mathbf{E} \parallel \mathbf{D_1}$ and a maximum output power of 684 mW for $\mathbf{E} \parallel \mathbf{D_2}$ were both obtained. Therefore, we employed the pump light of 777 nm in the following experiments. In addition, the output emission spectra of the Tm:LYSO laser was located in the spectral range of 1982 nm - 1986 nm both for $\mathbf{E} \parallel \mathbf{D_1}$ and $\mathbf{E} \parallel \mathbf{D_2}$, demonstrating little sensitivity to the pump wavelength.

Using the 777 nm pump light with polarization orientation of $\mathbf{E} \parallel \mathbf{D_1}$, we investigated the dependences of average output powers of the Tm:LYSO laser on the absorbed pump powers with different output couplers. All the output couplers used here were partial reflection coated over a broad spectral region around 2μm. The average output powers and the fitted slope efficiencies are shown in Fig. 2(a). By using the output couplers of T = 0.5%, 2% and 3%, the output center wavelength was located at around 2060 nm. A maximum output power of 1.019 W was obtained at 2058.9 nm with an absorbed pump power of 2.3 W at 777 nm and an output coupler of T = 2%, which corresponds to an optical conversion efficiency of 44.4%. With an output coupler of T = 3%, a maximum slope efficiency of 56.3% related to the absorbed pump power was achieved at 2057.4 nm. According to the measured slope efficiency η shown in Fig. 2(a) and the formula $\eta = \eta_q(\nu_L/\nu_p)T/(T + L)$ [21], where η_q is the pump quantum efficiency, T is the transmission of the output coupler, L is the intrinsic intracavity loss and ν_L and ν_p are the laser and pump frequencies, respectively, we estimated pump quantum efficiency $\eta_q = 1.52$ and the intrinsic loss L = 0.24% for the emission around 2060 nm. A slope efficiency of 55.8% was obtained at 1984 nm when an output coupler of T = 5% was used. We observed that the recorded output spectra of the Tm:LYSO laser could be varied by aligning the output coupler which indicates a potential wavelength tunability of Tm:LYSO crystals.

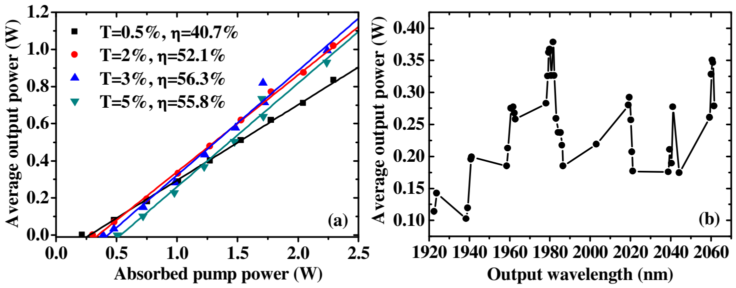

Fig. 2. (a) Average output powers versus absorbed pump power, Symbols: experimental data, line: linearly fit; (b) Tunable curve of the Tm:LYSO laser at 777 nm with 3% output coupling.

With a 2 mm thick quartz plate inserted before the output coupler OC_1 at Brewster's angle, a wavelength tunable continuous wave Tm:LYSO laser was realized. The pump light wavelength was fixed at 777 nm with **E** || $\mathbf{D_1}$ polarization and the transition of output coupler was T = 3%. By rotating the quartz plate, the output wavelengths were tuned in the spectral region of 1922.6 nm to 2061.6 nm. The average output powers versus output wavelengths were recorded and shown in Fig. 2(b), which shows again that the Tm:LYSO laser has considerable efficiency not only near 1980 nm but also at 2060 nm.

By employing an InGaAs SESAM (BATOP Inc.) with a saturation fluence of 70 μJ/cm^2 and modulation depth of about 1% at around 1980 nm, passive mode-locking operation of Tm:LYSO laser was achieved in a cavity formed by mirrors M_1, M_2, M_4, M_5, M_6, SESAM and OC_2. The SESAM was characterized by a reflectivity of 98.2-98.6% in the range of 1900 nm to 2100 nm, which incorporated the absorbance of the quantum wells inside. In order not to limit the lasing spectrum, an output coupler OC_2 with transition of T = 1% over a broad spectral range of 1850-2150 nm was used. The **E** || $\mathbf{D_1}$ polarized pump light was used to pump the Tm:LYSO crystal. By carefully adjusting the cavity and positions of SESAM, CW mode-locking could be achieved. A 1 GHz bandwidth digital oscilloscope (DPO, Tektronix Inc.) and a 60 MHz bandwidth extended-InGaAs PIN photodiode (G8423, Hamamatsu Inc.) were used to monitor the mode-locked pulse train leaking from mirror M_4 to optimize the stability of continuous wave mode-locking. A maximum output power of about 150 mW under CW mode-locking was obtained at 1984.1 nm. However, stable CW mode-locking could only run for several minutes, probably due to the thermal timescales problem.

To explore the factors influencing the CW mode-locking stability, two silicon prisms with tip to tip separation of 55 mm were tried in a cavity consisting of mirrors M_1, M_2, M_4, M_5, M_6, SESAM, silicon prism pair and OC_3 with the same transmission of T = 1%. The silicon prisms were used not only to suppress the mode competition but to manage the intracavity dispersion. With the silicon prisms used, the mode-locking stability was improved much and its sensitivity to the cavity alignment was obviously decreased. Under stable CW mode-locking regime, a maximum output power of about 100 mW at 1984.1 nm was obtained at the repetition rate of about 100 MHz. To measure the mode-locked pulse duration, a collinear autocorrelation setup using second harmonic generation with a PPLN crystal was employed. Pulse duration as short as 24.2 ps was obtained by assuming a sech^2 pulse shape as shown in Fig. 3(a). The optical spectrum with FWHM of 1.06 nm was measured by a laser spectrometer with a resolution bandwidth of 0.4 nm (APE WaveScan, APE Inc.), which is shown in Fig. 3(b). Due to the spectrometers low resolution, we omit to give a time-bandwidth product (TBP) here. Figure 3(c) shows the first beat note of radio frequency (RF) spectrum obtained by measuring the leaked power from high reflectivity mirror M_4, in which a clean peak at the repetition rate of 100.05 MHz is observed under a span of 100 kHz. The absence of side peaks indicated the absence of Q-switching instability. However, we did not find obvious variation of the pulse duration when changing the dispersion by moving the silicon prism into the cavity.

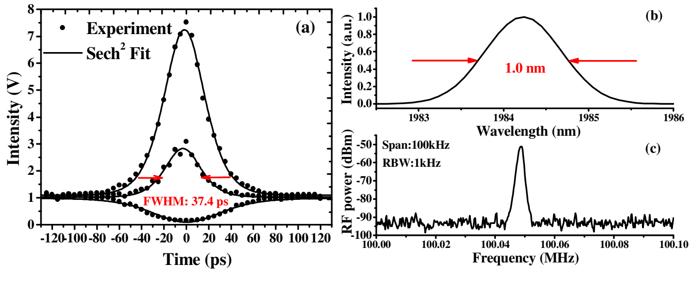

Fig. 3. (a) Autocorrelation intensity trace, (b) optical spectrum and (c) RF spectrum of continuous wave mode-locked Tm:LYSO laser.

With the silicon prisms used, the mode-locked Tm:LYSO laser wavelength could be tuned in a small spectral range of 1982-1986 nm by aligning the output coupler OC_3 carefully. To investigate the wavelength tunability of the mode-locked Tm:LYSO laser, we moved the

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silicon prism pair out of cavity and placed the 2mm quartz plate in front of OC_2, then stable and self-starting mode-locking was obtained in the spectral range of 1929-2065nm. Figures 4(a) and (b) show the dependence of pulse durations and average output power with respect on the output wavelengths. The pulse durations ranged from 22.7 ps at 1929.7 nm with output power of 45.7 mW to 37.5 ps at 2065nm with output power of 116 mW. However, the pulse durations and output powers do not show any disciplinary dependence on the output wavelength. A maximum output power of 130.3 mW was obtained at 1984.1 nm with the corresponding pulse duration of 33.1 ps, which is somehow longer than that of 24.2 ps with silicon prisms in the cavity. Assuming a sech^2 pulse shape the shortest pulse duration of 19.6 ps was obtained at 1944.3 nm with an output power of 64.5 mW. The corresponding intensity autocorrelation trace with a FWHM of 30.3 ps and the optical spectrum with a FWHM of 0.6 nm are shown in Figs. 4(c) and (d). Although a shorter pulse duration was obtained at 1944.3 nm, the spectrums FWHM of only 0.6 nm was much narrower than that of 1.06 nm at 1984.1 nm, which was the maximum FWHM of the spectrum in the mode-locked spectral region of 1929-2065nm. In addition, we tried to place the silicon prisms in the cavity together with the quartz plate, however, the low lasing efficiency did not allow the pulse duration measurement.

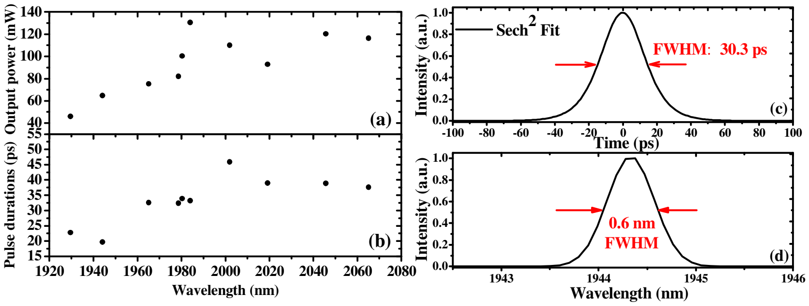

Fig. 4. (a) and (b) tunability of the mode-locked Tm:LYSO laser, (c) intensity autocorrelation of the mode-locked pulse at 1944.3 nm, (d) the corresponding optical spectrum at 1944.3 nm.

3. Conclusion

We have demonstrated an efficient CW and passively mode-locked Tm:LYSO laser pumped with a CW Ti:Sapphire laser. In CW operation regime, a maximum slope efficiency of 56.3% at 2057.4 nm and a maximum output power of 1.019 W at 2058.9 nm with an absorbed pump power of 2.3 W at 777 nm were obtained, corresponding to an optical conversion efficiency of 44.4%. With a 2 mm quartz plate as lyot filter, the Tm:LYSO laser exhibited a wavelength tunability over a wide spectral range from 1922 to 2061 nm. Using an InGaAs quantum well SESAM, passive mode-locking operation was realized in the spectral region of 1929-2065 nm. A maximum average output power of 130.2 mW with a pulse duration of 33.1 ps and a repetition rate of about 100 MHz was produced at 1984.1 nm. Pulses as short as 24.2 ps with an average output power of 100 mW were generated when silicon prisms were used to manage the intracavity dispersion. The shortest pulse duration of about 19.6 ps was obtained with an average output power of 64.5mW at 1944.3 nm.

Acknowledgments

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