Diode-pumped tunable single-longitudinal-mode Tm, Ho:YAG twisted-mode laser

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A diode-end-pumped tunable twisted-mode cavity Tm, Ho:YAG laser with single-longitudinal-mode (SLM) operation is demonstrated in this Letter. The maximal SLM output power is 106 mW with a slope efficiency of 4.86%. The wavelength can be changed from 2090.38 to 2097.32 nm by tuning the angle of an etalon.

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Solid-state lasers operating in the eye-safe 2 μm spectral region present significant interests for a number of advanced applications, such as gas sensing, coherent Doppler lidar, differential absorption lidar, medicine, and pumping sources for optical parametric oscillators[1–6]. Single frequency and remarkable power are both required by the coherent Doppler lidar and the differential absorption lidar. As the emission source of lidar, the 2 μm continuous wave single-longitudinal-mode (SLM) laser is an essential component.

The SLM laser can be obtained through some methods, such as microchip lasers, double-cavity lasers, nonplanar ring oscillators (NPROs), and lasers inserted with etalons and twisted-mode cavity (TMC) lasers. However, the output power is generally low by using the microchip laser or the double-cavity laser[7,8]. The system of the NPRO laser is complex and expensive for achieving a laser with a SLM output[9–11]. Laser-inserted etalons in the cavity is an ordinary method used to obtain SLM operation[12,13]. Stable SLM operation will be achieved by precisely choosing the angle, thickness, and refractive index of the etalon. However, multimode oscillation will occur under a high pump power. TMC technology is a useful way to obtain SLM laser output. Its implementation is simple, and is still SLM operation when there is a high power output[14]. The TMC was introduced by Evtuhov and Siegman in 1965[15]. It can eliminate the spatial hole burning by the standing wave in a cavity with axially uniform energy density through the laser crystal. The TMC technology takes its name from the electric field mode pattern in the gain medium, which has the shape of a twisted ribbon with a spatial period of one optical wavelength[15]. This can be realized easily through a polarizer and two quarter-wave plates. Inserting the polarizer leads to linear-polarization oscillation in the cavity. The output laser with SLM operation could be achieved when the pair of quarter-wave plates are inserted into a cavity and rotated to a suitable fast axis angle with the polarization direction.

Tm-Ho co-doped crystals are attractive gain mediums used to generate a 2 μm laser; their significant performance involve an intensive energy storage linked to a long upper-level lifetime and a quantum efficiency of up to 2 because of cross relaxation.

The Ho^{3+} appears to have a larger emission cross section than Tm^{3+} in the energy level transition of the laser crystal, but the absorption of Ho^{3+} around 785 nm is very weak. Tm^{3+} shows a strong absorption at 785 nm, so it could be co-doped in the crystal as sensitization ions to be pumped efficiently by an AlGaAs laser diode[16]. For Tm ion concentrations exceeding ~2%, with 785 nm pumping, the Tm ions are excited to $^3H_4$ and the cross-relaxation process $^3H_4 + {}^3H_6 - 2{}^3F_4$ leads to an overall pump quantum efficiency of 2[17]. There is a rapid energy migration among the thulium ions, resonant energy transfer to the Ho $^5I_7$ level, and finally the laser action on the $^5I_7 - {}^5I_8$ transition[18,19]. The schematic energy level of Tm, Ho:YAG is shown in Fig. 1[18].

In this Letter, we reported a diode-pumped tunable SLM Tm, Ho:YAG laser employing a TMC. The maximal SLM output power was 106 mW with the central wavelength of 2090.38 nm. The output laser is linear polarized, and the wavelength can be changed from 2089 to 2097 nm.

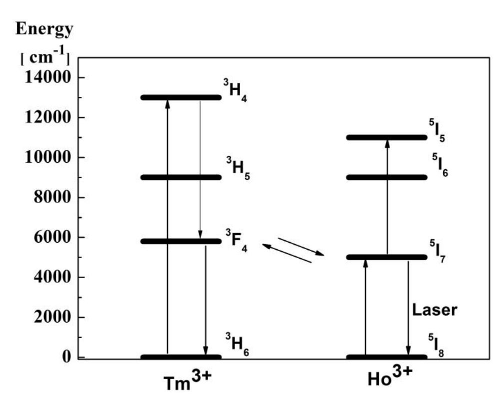

Fig. 1. Energy-level diagrams for Tm, Ho:YAG[18].

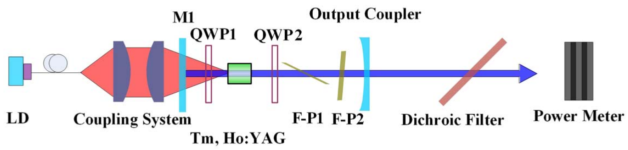

Fig. 2. Schematic of the experimental setup.

To our knowledge, this was the first time for using TMC technology to obtain a SLM Tm, Ho:YAG laser.

The schematic layout of a Tm, Ho:YAG TMC laser is shown in Fig. 2. We have measured the thermal focal length of a Tm, Ho:YAG crystal under different pump powers and the thermal focal length has been considered in the design of laser cavity. First we made a Tm, Ho:YAG laser with a short cavity length, then measured the output beam quality of the laser with free-running operation by measuring the beam radius with a knife-edge technique at several positions through a waist formed by a lens. The data were fitted by least-squares analysis to standard mix-mode Gaussian beam propagation equations to determine the beam quality. Then, we could deduced the thermal focal length.

Although the measurement of the thermal focal length is rough, it was helpful to make the Tm, Ho:YAG laser with a longer cavity to insert more components that the twisted-mode technology need. In view of the thermal focal length, the laser employed a plano-concave resonator with a cavity length of 67 mm. We selected a curvature radius of 100 mm and a transmission of 2% at 2 μm as the output coupler. The laser cavity is comprised of an input mirror, a pair of quarter-wave plates at 2.09 μm, two YAG etalons and an output coupler mirror. M1 is the input mirror coating with a high transmission at 785 nm and a high reflection at 2 μm. QWP1 and QWP2 are the pair of uncoated quarter-wave plates that are set on each side of the laser crystal. F-P1 and F-P2 are both uncoated YAG etalons with thicknesses of 0.05 and 0.1 mm, respectively. F-P1 is set at the Brewster angle to achieve a linear-polarization output laser. Different wavelengths of output laser could be achieved by changing the angle of F-P2. The dichroic filter is covered with a high-transmission coating at 2 μm and a high-reflection coating at 785 nm. The pump source is a 10 W fiber-coupled diode laser with a central wavelength of 785 nm. The wavelength could be tuned to match the absorption peak of Tm, Ho:YAG by changing the laser diode temperature. The fiber has an inner core diameter of 200 μm. The pump laser is focused into a Tm, Ho:YAG crystal with a beam diameter of 320 μm by a coupling system. The Tm, Ho:YAG crystal has dimensions of $\Phi 3 \times 3\,(\mathrm{mm})$, and the nominal dopant concentration is 6 at.% Tm^{3+} and 0.3 at.% Ho^{3+}. Both surfaces of the crystal are antireflection-coated at 785 nm and 2 μm. The temperature of the crystal is measured on the surface of the copper mount in which the crystal is set, and the copper heat-sink maintains the temperature at 10°C with a thermoelectric cooler (TEC).

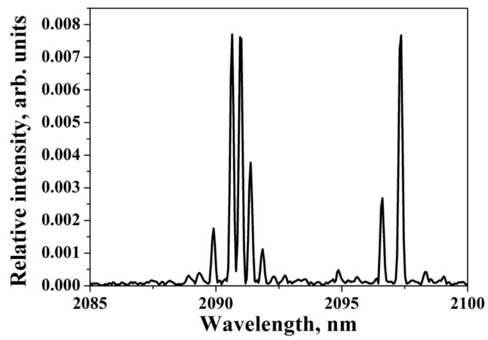

Fig. 3. Spectrum of Tm, Ho:YAG laser under free running.

The wavelength of the output laser was recorded by the Bristol 721 A IR spectrum analyzer. From Fig. 3, we can see that the output spectrum of the free-running Tm, Ho:YAG twisted-mode laser is centered around 2090 and 2097 nm. There were many wavelengths while the quarter-wave plates and etalons were not inserted in the cavity. Meanwhile, the longitude modes of the Tm, Ho: YAG twisted-mode laser were measured by the Fabry–Perot (F–P) interferometer with a free spectral range of 1.5 GHz. Figure 4 shows that the laser is free running with a multimode oscillation.

Then we inserted the laser with F-P1. The etalon was set at the Brewster angle in order to achieve a linear polarization output. As seen from Figs. 5 and 6, the Tm, Ho:YAG laser has less wavelengths and longitudinal modes but still has a multimode oscillation.

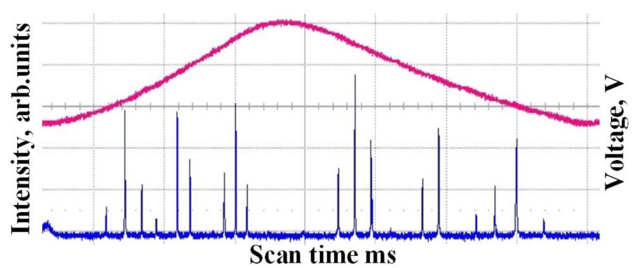

Fig. 4. F-P spectrum of the free Tm, Ho:YAG laser.

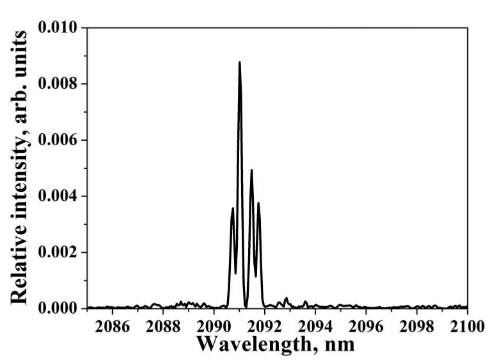

Fig. 5. Spectrum of the Tm, Ho:YAG laser with a 0.05 mm etalon.

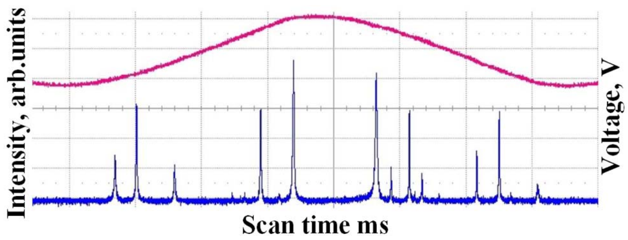

Fig. 6. F–P spectrum of the Tm, Ho:YAG laser with a 0.05 mm etalon.

The SLM Tm, Ho:YAG twisted-mode laser operating at 2090.38 nm was achieved when the pair of quarter-wave plates were inserted into the cavity and rotated to a suitable angle so that the fast axis of the quarter-wave plates were orthogonal and separately oriented at an angle of 45° to the polarization. The output spectrum of the SLM laser is shown in Fig. 7. As can be seen from Fig. 8, there were no more transmission modes to be observed through the F–P interferometer. The Tm, Ho:YAG laser is running on SLM operation.

The wavelength stability of the SLM Tm, Ho:YAG laser is shown in Fig. 9. The Bristol 721A spectrum analyzer has an accuracy of 0.2 ppm and a resolution of 2 GHz. The average wavelength is 2090.38 nm. The standard deviation of the wavelength measured is 3.1 pm.

Figure 10 plots the output power of the Tm, Ho:YAG TMC laser with free and SLM operation as a function of pump power. The coherent PM30 was used to measure the pump power, and the output power of the laser was measured by LPE-1A (resolution limited to 0.1 mW with a maximum power of 2 W). We used a dichroic filter to block the pump light before measuring the output power. The maximum output power and slope efficiency for free running were 391 mW and 9.91% by the pump power of 5.9 W. When the Tm, Ho:YAG TMC laser ran on SLM operation, the maximum SLM output power was up to 106 mW at 2090.3 nm under the pump power of 5.45 W, corresponding to a slope efficiency of 4.86%.

To obtain the tunable wavelength, we inserted the F-P2 in the cavity. The wavelength could be tuned over a range from 2089.13 to 2097.32 nm by changing the angle of F-P2. From Table 1, we can see that output power with different wavelengths under the same pump power. The output power variation of different wavelengths

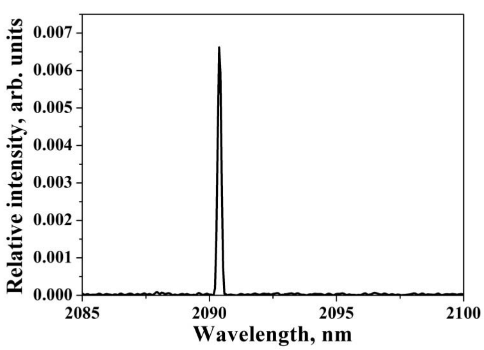

Fig. 7. Spectrum of the Tm, Ho:YAG laser with SLM operation.

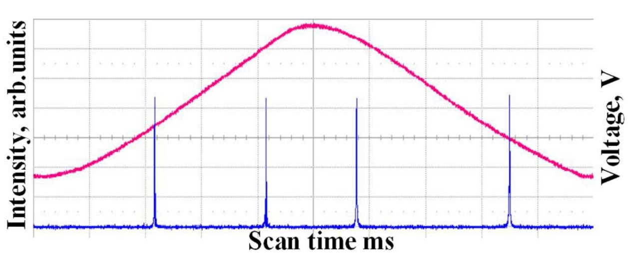

Fig. 8. F-P spectrum of the SLM Tm, Ho:YAG laser.

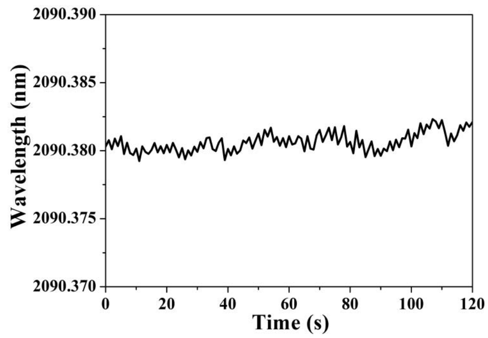

Fig. 9. Wavelength stability of the SLM Tm, Ho:YAG laser.

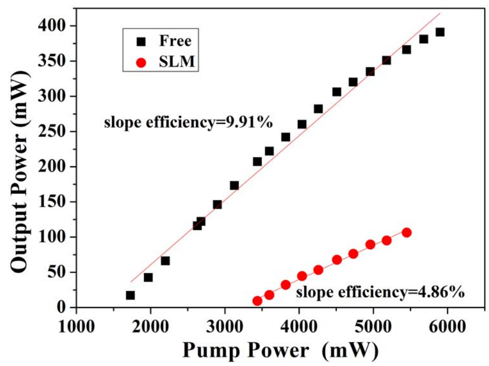

Fig. 10. Output power as a function of pump power.

Table 1. Output Power with Wavelength

Output Wavelength (nm)	Output Power of SLM (mW)
2089.13	82.5
2090.38	106
2091.34	92.3
2093.17	79.7
2095.16	52.7
2096.12	61.5
2097.32	70.3

is according to the different losses and gains of the modes oscillating in laser cavity.

In conclusion, we report a tunable SLM Tm, Ho:YAG with a TMC laser. The maximum SLM output power of 106 mW at 2090.38 nm is achieved under the pump power of 5.9 W, corresponding to a slope efficiency of 4.86%. The output wavelength of the SLM laser can be tuned from 2089 to 2097 nm by adjusting the etalon. The SLM Tm, Ho:YAG laser can be used as a seed laser in coherent Doppler lidarand differential absorption lidar.

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