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A single-longitudinal-mode continuous-wave Ho^{3+}:YVO_4 laser at 2.05 μm pumped by a Tm-fibre laser*

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We present a single-longitudinal-mode continuous-wave Ho^{3+}:YVO_4 laser at 2.05 μm pumped by a Tm-doped fibre laser. Use of a cavity etalon enables spectral selectivity for single-mode operation. The highest power achieved in the single longitudinal mode at 2052.5 nm is 282 mW at a slope efficiency of 6.9%, corresponding to an optical conversion efficiency of 3.0%. These features demonstrate that this single-longitudinal-mode Ho:YVO_4 laser is suitable for use as a seed laser in some Lidar systems (e.g., coherent Lidar or differential absorption Lidar). To the best of our knowledge, this is the first report on such a single-longitudinal-mode Ho:YVO_4 laser at 2.05 μm.

Keywords: Ho:YVO_4 laser, intracavity etalons, single longitudinal mode, Tm-doped fibre laser

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1. Introduction

Single-longitudinal-mode (SLM) solid-state lasers near 2 μm have been widely used as seed lasers for Lidar systems owing to their eye safety at low power and good transparency in the atmosphere.[1,2] They also have important applications for remote sensing, range finding, optical communication,[3,4] and so on. Among the ordinary techniques for achieving SLM operation of a solid state laser, including use of microchips,[5] coupled cavities,[6] twisted-mode cavities,[7,8] and intracavity etalons, the intracavity etalon is the simplest one with which the laser wavelength can be continuously tuned. In 2004, Scholle *et al.* reported an SLM Tm,Ho:LuAG laser that produces a maximum output power of 51 mW.[9] In 2011, Yao *et al.* demonstrated a Tm,Ho:YAP laser composed of double Fabry–Perot (F–P) etalons that has an output power of 72.6 mW at 2102.5 nm.[10] In 2014, Zhang *et al.* constructed a tunable single-frequency Tm,Ho:LLF laser operating at 2064.4 nm, from which the highest power obtained is 221 mW, corresponding to a slope efficiency of 15.4%.[11]

Previous ∼2 μm SLM lasers have employed mainly Tm, Ho-codoped crystals, such as Tm, Ho:YAG, Tm, Ho:YLF, and Tm, Ho:YVO_4.[12–15] However, these lasers suffer from the drawbacks of high lasing threshold and low conversion efficiency owing to the severe upconversion losses.[16] Instead, use of a holmium-doped crystal pumped by a 1.9-μm Tm-doped laser can avoid these problems. Meanwhile, YVO_4 crystals have been attracting significant attention because of their stabilised chemical properties, better mechanical properties, and high thermal conductivity. Compared to YAG and YLF analogues, YVO_4 crystals doped by Ho^{3+} ions have similar upper state lifetime, wider pump bandwidth, and larger emission cross section, all of which enable higher efficiency of laser operation.[17,18] Over the past few years, both *Q*-switched and continuous-wave (CW) Ho:YVO_4 lasers have been reported, yet the output characteristics of such SLM lasers have not been investigated. In 2013, Duan *et al.* reported a CW Ho:YVO_4 laser at 2067 nm operating at room temperature with a maximum output power of 0.54 W and a slope efficiency of 20.0%.[17] In 2014, Han *et al.* built a CW and *Q*-switched dual-mode Ho:YVO_4 laser with a maximum CW power at 2052 nm of 3.9 W and a maximum pulse energy at the *Q*-switched mode of 0.38 mJ.[19] In 2015, Ding *et al.* constructed a *Q*-switched Ho:YVO_4 laser that achieves its highest averaged power of 11.4 W at 10 kHz.[18] In 2015, Dai *et al.* demonstrated an Ho:YVO_4 laser at 114.6 kHz in which Cr^{2+}:ZnS is used as a saturable absorber for *Q*-switching and whose maximum pulse energy is 70.3 μJ.[20]

To date, an SLM Ho:YVO_4 laser pumped by a 1.94-μm Tm-doped fibre laser has not been reported in the literature. Here we introduce an SLM Ho:YVO_4 laser in which intracavity etalons are inserted for improving the spectral selectivity of the cavity. A highest SLM power of 282 mW at 2052.5 nm is observed when the pump power is set at 9.45 W, and its slope efficiency reaches 6.9%.

2. Experimental setup

The experimental layout is depicted in Fig. 1. The pump source used is a 1.94-μm Tm-doped fibre laser that has a max-

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imum CW power of ∼25 W. The pump beam is focused down to 200 μm in diameter onto an Ho:YVO_4 crystal by a collimator lens ($f = 160$ mm). A half-wave plate is used to control the polarization of the pump and to optimise the absorption of the Ho:YVO_4 crystal to the pump. Namely, the interference effect induced by the retro-reflection on the Tm-doped fibre laser can be greatly depressed. The a-cut Ho:YVO_4 crystal has a size of $3 \times 3 \times 20$ mm^3 and a dopant concentration of 0.6 at.%. The coated ends of crystal ensure high transmittance at both 2.05 μm ($T > 99.9\%$) and 1.94 μm ($T > 95\%$). The Ho:YVO_4 crystal wrapped by indium foil is held in a water-cooled copper heat sink in which the temperature is precisely controlled by a TEC cooler at 14 °C. The total length of the L-shaped plane-concave laser cavity is ∼100 mm. Two 45° planar mirrors M1 and M2 are coated with antireflection coatings at 1.94 μm and high reflection coatings at 2.05 μm ($R > 99.8\%$). The plane-concave mirror M3 ($r = 150$ mm) has a transmissivity of 30% at 2.05 μm. The finesse of the cavity (defined by the inverse of the number of longitudinal modes that can operate within the transmission band of a cavity) is estimated to be 17.5. To achieve SLM operation of the Ho:YVO_4 laser, two F–P etalons (1 and 6 mm in thickness, respectively) with a reflectivity of 20% are inserted into the cavity. The SLM operation can be engaged while the transmission peak of double etalons coincides with the maximum value of the gain curve of the Ho:YVO_4 crystal. By employing a 45° planar mirror M4 (50% transmissivity at 2.05 μm), the output wavelength and longitudinal mode can be simultaneously monitored.

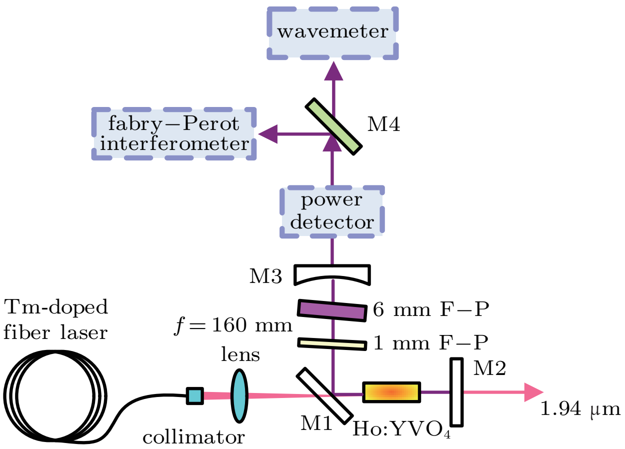

Fig. 1. (color online) Experimental setup of the SLM Ho:YVO_4 laser.

3. Experimental results and discussion

The absorbed pump power by the Ho:YVO_4 crystal and the corresponding absorption efficiency versus the incident pump power are plotted in Fig. 2. As can be seen, the absorption efficiency ranges from 55% to 27% with increasing incident pump power, whereas the maximum absorbed pump power is 6.0 W. Along with increasing incident pump power, the pump saturation effect emerges owing to the ground-state loss. This effect usually leads to a reduction of the absorbed pump power by the crystal. Especially, at higher incident pump power, the Ho:YVO_4 crystal will be completely saturated and the absorption efficiency should be approximately constant.

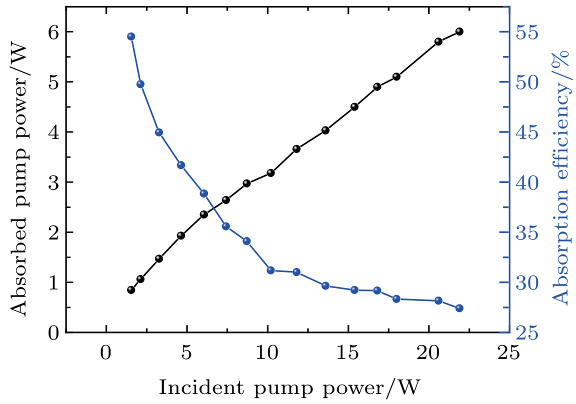

Fig. 2. (color online) Absorbed pump power and absorption efficiency of the Ho:YVO_4 crystal.

The output power of the Ho:YVO_4 laser (without F–P etalons) as a function of the incident pump power is displayed in Fig. 3. The maximum output power for operation in this multimode is 4.09 W at an incident pump power of 21.9 W, corresponding to an optical conversion efficiency of 18.6% and a slope efficiency of 26%.

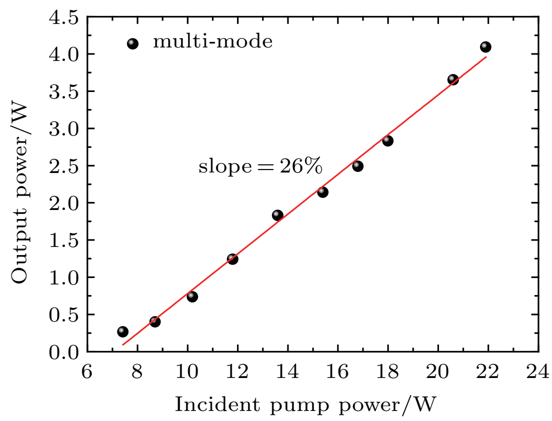

Fig. 3. (color online) Output power of the Ho:YVO_4 laser.

The output F–P spectrum of this multimode Ho:YVO_4 laser is measured by a Fabry–Perot scanning interferometer (Thorlabs SA200-18B, with a free spectral range of 1.5 GHz) in which a sinusoidal waveform is applied to the piezo actuator (see Fig. 4). The blue line indicates the driving voltage of the piezo actuator and the red line represents the longitudinal modes of the laser. As can be seen in Fig. 4, the competition between modes is quite intense. The output spectra of this Ho:YVO_4 laser (without F–P etalons) recorded by a wavemeter (Bristol, with 0.7-pm resolution) is shown in Fig. 5; it is clear that the laser emits multiple wavelengths under this condition.

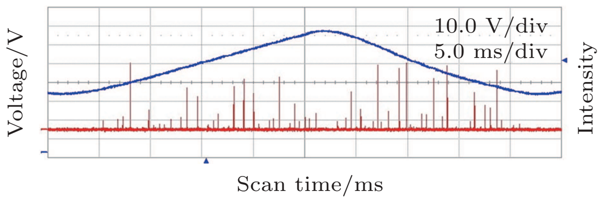

Fig. 4. (color online) F–P spectrum of the Ho:YVO_4 laser.

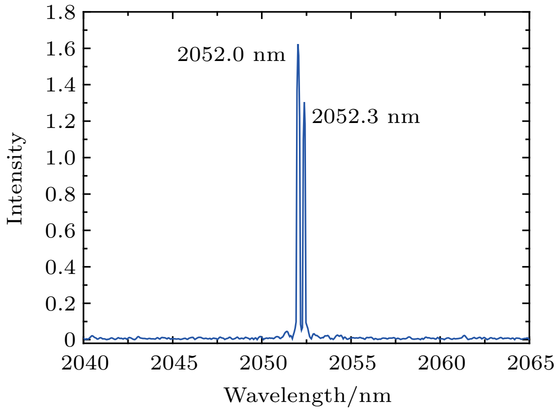

Fig. 5. (color online) Output wavelength of the Ho:YVO_4 laser.

As mentioned previously, to accomplish SLM operation of this Ho:YVO_4 laser, two F–P etalons (of 1 and 6 mm in thickness) with 20% reflectivity are inserted into the resonator. Figure 6 shows the transmission band of the SLM F–P cavity, resulting from a theoretical analysis of the cavity selectivity. The transmission curve of the F–P etalon is the cumulative effect of its refractivity, thickness, and angle of the etalon. Greater refractivity and thicker etalons result in narrower transmission curves but also bring a larger cavity loss. Thus, the parameter settings for the F–P etalons are particularly crucial when balancing narrow-band operation and high output power. The reference frequency (zero point in Fig. 6) is set at 146.16 THz (2052.5 nm). Figure 6(a) shows the transmission curves of the two etalons, with the 1-mm etalon plotted as a red solid line and the 6-mm etalon plotted as a green solid line. The transmission curve of the 6-mm etalon is much narrower than that of the 1-mm etalon. Combining the transmission curves of the two etalons gives a resulting frequency difference between the two transmission peaks of ~82.5 GHz. The blue solid line in Fig. 6(b) represents the final transmission curve (which is a combination of the 1-mm etalon curve (red dashed line) and the 6-mm etalon curve (green dashed line)). The black solid line represents the longitudinal modes that fit the transmission band of the free-running cavity, the frequency difference being ~1.17 GHz. Hence, the gain difference between the adjacent longitudinal modes is enlarged by using two etalons. As seen in Fig. 6(b), only one mode achieves the highest gain, with other modes being suppressed by precise matching of the angles of the two F–P etalons. Thus, SLM operation of the Ho:YVO_4 laser can be achieved with this F–P cavity structure.

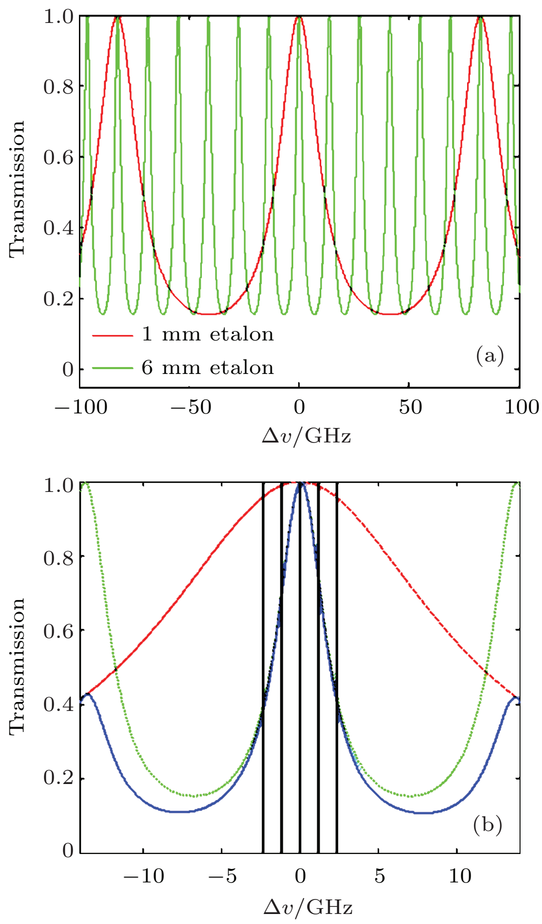

Fig. 6. (color online) Transmission band of the SLM F–P cavity. (a) Transmittance curves of the 1-mm and 6-mm etalons. (b) Transmittance curves for two etalons and adjacent laser modes.

In our experiment, by carefully regulating the angle of the F–P etalons, possible SLM operation can be monitored by a Fabry–Perot scanning interferometer. Figure 7 shows the typical time behaviour of the laser spectrum spanning 50 ms, as monitored with an oscilloscope (LeCory, WaveSurfer, 64Xs). It is clearly seen in Fig. 7 that the extreme peaks located on opposite sides of the maximum voltage arise between the 1.5-GHz free spectra range (the free spectra range voltage being ~11 V) and the Ho:YVO_4 laser is operating in an SLM.

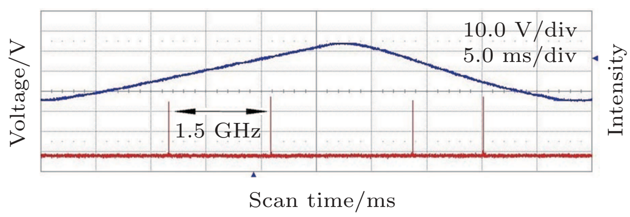

Fig. 7. (color online) F–P spectrum of the SLM Ho:YVO_4 laser.

As shown in Fig. 8, the output power of the Ho:YVO_4 laser containing the 1-mm etalon and an SLM were investigated. With the 1-mm etalon and in an SLM, the output power is 600 and 282 mW, respectively, with the same incident pump power of 9.45 W, corresponding to slope efficiency values of 14.1% and 6.9%. The high threshold and low efficiency of the SLM Ho:YVO_4 laser may be due to the large loss caused by the two F–P etalons with 20% reflectivity. When the pump power was > 9.45 W, mode-hopping occurred and several (at least two) longitudinal modes were generated (as observed in the oscilloscope) simultaneously, which were caused by the effect of spatial hole burning in the standing-wave cavity. Figure 9 depicts the single-wavelength output spectrum of the SLM Ho:YVO_4 laser, whose centre wavelength is 2052.5 nm (0.7 nm spectral bandwidth).

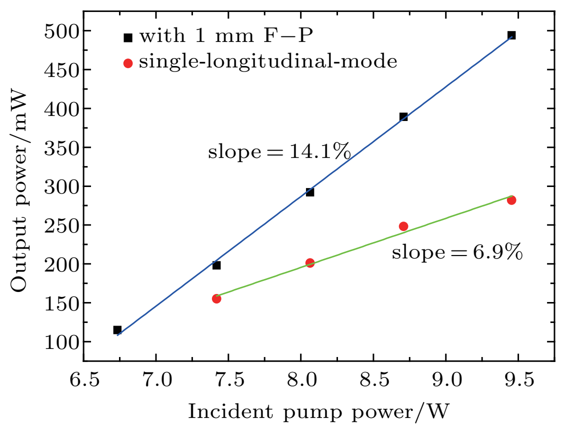

Fig. 8. (color online) Output power versus incident pump power of the Ho:YVO_4 laser with a 1-mm etalon and in an SLM.

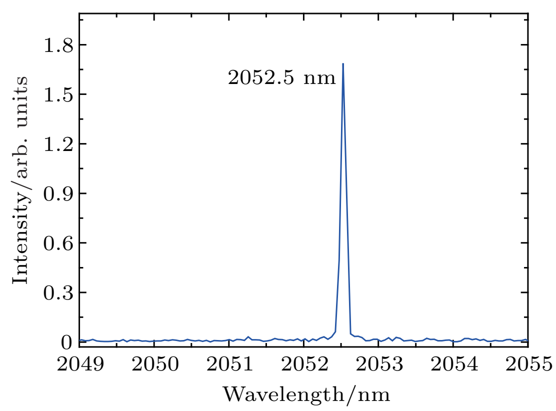

Fig. 9. (color online) Output wavelength of the SLM Ho:YVO_4 laser.

4. Conclusion

In summary, we constructed an SLM Ho:YVO_4 laser pumped by a 1.94-μm Tm-doped fibre laser by employing a double F–P etalon technique. A maximum SLM power of 282 mW at 2052.5 nm was obtained with an incident pump power of 9.45 W. Optical conversion efficiency and slope efficiency reached 3% and 6.9%, respectively. The SLM Ho:YVO_4 laser at 2.05 μm has potential applications to coherent Lidar, differential absorption Lidar, optical remote sensing, and other research areas.

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