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A tunable and single-longitudinal-mode Ho:YLF laser

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HIGHLIGHTS

- A 345 mW Ho:YLF laser operating on single-longitudinal-mode is reported.
- The intracavity etalon method is used to achieve tunable operation.
- The output wavelength can be tuned from 2051.6 nm to 2063.3 nm.
- A 1.94 μm Tm-doped fiber laser is used as pump source.

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ABSTRACT

A 1.94 μm Tm-doped fiber laser pumped tunable single-longitudinal-mode Ho:YLF laser with double etalons was reported for the first time. The maximum single-longitudinal-mode output power of 345 mW at 2051.6 nm was achieved at the absorbed pump power of 11.9 W, corresponding to a slope efficiency of 5.5% and an optical conversion efficiency of 2.9%. By regulating the angle of the F–P etalons, the output wavelength of the laser can be tuned from 2051.6 nm to 2063.3 nm. The single-longitude-mode Ho:YLF laser operating at 2 μm can be used as the seed laser source of coherent Doppler lidar, differential absorption lidar and so on.

1. Introduction

Single-longitudinal-mode solid state lasers around 2 μm have the advantages of eye-safe and good transparency in the atmosphere [1,2]. Therefore, 2 μm single-longitudinal-mode lasers can be as seed sources of Lidars, such as coherent lidar systems for wind measurements, differential absorption lidar for concentration measurement of H_2O and CO_2 in the atmosphere [3,4]. Moreover, 2 μm single-longitudinal-mode lasers also widely used in remote sensing, range finding and optical communication [5,6]. Various methods to obtain the single-longitudinal-mode lasers, such as microchip laser [7], twisted-mode cavity [8], coupled cavity [9], and intra-cavity Fabry–Perot (F–P) etalons. Intra-cavity F–P etalons is the most simplest way to achieve tunable single-longitudinal-mode operation. In 1990, Henderson et al. demonstrated single-longitudinal-mode Tm, Ho:YAG laser with etalons and the maximum output of 58 mW was achieved [10]. In 2010, Zhang et al. reported a continuously tunable frequency Tm,Ho:YLF laser with F–P etalons. Single frequency output power was 118 mW [11]. In 2011, Yao et al. reported a single-frequency Tm,Ho:YAP laser and up to 72.6 mW at 2102.5 nm with F–P etalons was obtained [12]. In 2015, we adopted double Fabry–Perot structure to realize the single-longitudinal-mode Tm,Ho:YVO_4 laser. Up to 95 mW was obtained at 2051.3 nm [13].

Initial work on single-longitudinal-mode lasers at 2 μm mainly concentrated on Tm,Ho co-doped crystals. However, co-doped crystals have reduced upper-state lifetimes and severe upconversion losses reduced energy storage efficiencies and increased thermal heat loads [14]. With the emergence of fiber lasers, holmium-doped lasers pumped by Tm-doped fiber lasers become an appealing research area. Compared with Ho:YAG crystal, Ho:YLF crystal has a longer upper laser level lifetime (around 14 ms) and higher emission cross section, good thermal and mechanical properties [15,16] and the output laser is polarized without any polarizer inserted into the cavity.

In this paper, we reported a Tm-doped fiber laser pumped single-longitudinal-mode Ho:YLF laser with two solid etalons. Up to 345 mW single-longitudinal-mode output power at 2051.6 nm was obtained under the absorbed pump power of 11.9 W, corresponding to a slope efficiency of 5.5% and an optical conversion efficiency of 2.9%. By changing the angles of the etalons, the

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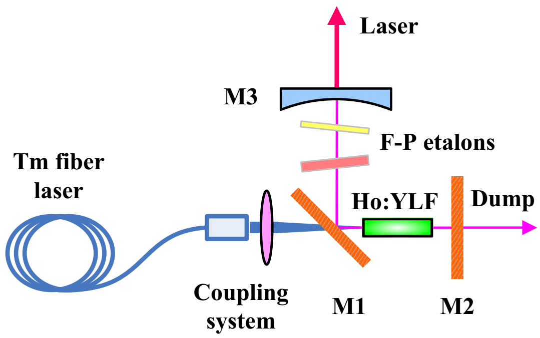

Fig. 1. Experimental setup of single-longitudinal-mode Ho:YLF laser.

wavelength can be tuned from 2051.6 nm to 2063.3 nm. As we know, single-longitudinal-mode Ho:YLF laser with intra-cavity F–P etalons is being reported for the first time.

2. Experimental setup

As shown in Fig. 1, a plane-concave cavity with simple structure is employed in the experiment with total cavity length of about 100 mm. The pump source is a Tm-doped fiber laser at 1940 nm, with a maximum CW output power of 25 W. The pump beam is first collimated and then focused onto the crystal by a plano-convex. The pump spot diameter in the crystal was around 200 μm. The Ho:YLF crystal had dopant concentrations of 0.5 at.% with dimensions of $4 \times 4 \times 20\ mm^3$. Both ends of the Ho:YLF crystal were coated with high transmission at 1940 nm ($T > 99.5\%$) and 2050 nm ($T > 99.2\%$). The crystal wrapped in indium foil and placed in a copper heat sink. The temperature of the crystal was controlled at 14 °C by a TEC cooler. Both M1 and M2 are plane mirrors coated with high transmission at 1940 nm and high-reflection at 2 μm. Pump radiation was removed by M2. M3 is an output coupler with a radius of curvature of 150 mm and a 30% transmission. Two F–P etalons (1 mm and 6 mm) with 20% reflectivity were inserted into the cavity for single-longitudinal-mode operation.

3. Experimental results and discussion

Output mode of the free-running (without F–P etalons) Ho:YLF laser measured by a Fabry–Perot interferometer with an 1.5 GHz free spectral range is first given. Typically multi-mode operation can be seen from Fig. 2. The blue line 'voltage' is the PZT's driving voltage of Fabry–Perot interferometer. The longitudinal modes over the 1.5 GHz free spectral range was given by Fabry–Perot interferometer. Shown as Fig. 2, many modes can be seen over the 1.5 GHz free spectral range and the laser operated at multi-mode. The output spectra of the free running Ho:YLF laser was measured by wavemeter (Bristol, 0.7 pm resolution). Fig. 3 shows the laser operating at multi-mode. The laser mode spacing of the free running laser was around 1.88 GHz. As shown in Fig. 3, the laser was simultaneously emitting at multiple lasing emission. The output power of the Ho:YLF laser with multimode was investigated. Fig. 4 shows the output power of the Ho:YLF laser as a function of the absorbed pump power. A maximum output power of 3.42 W was obtained at the absorbed pump power of 16.9 W, corresponding to an optical conversion efficiency of 20.2% and a slope efficiency of 24%.

1 mm in thickness and 6 mm in thickness etalons were inserted in the cavity to realize the Ho:YLF laser operating at single-longitudinal-mode. Shown as Fig. 5, the free spectra range voltage was around 12 V and only two peaks appeared over the 1.5 GHz free spectral range. The Ho:YLF laser operated on single-longitudinal-mode.

Fig. 6 shows the output wavelength of the single-longitude-mode Ho:YLF laser measured by wavemeter (Bristol, 0.7 pm resolution). The central wavelength was 2051.6 nm and only one

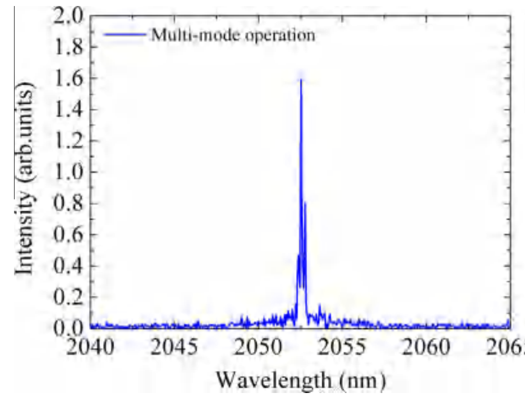

Fig. 3. Output wavelength of the free-running Ho:YLF laser.

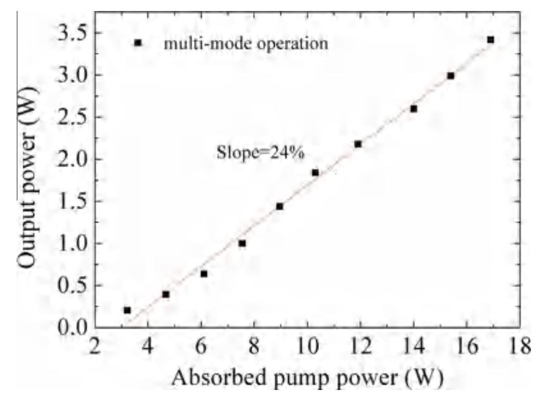

Fig. 4. Output power of the free-running Ho:YLF laser versus absorbed pump power.

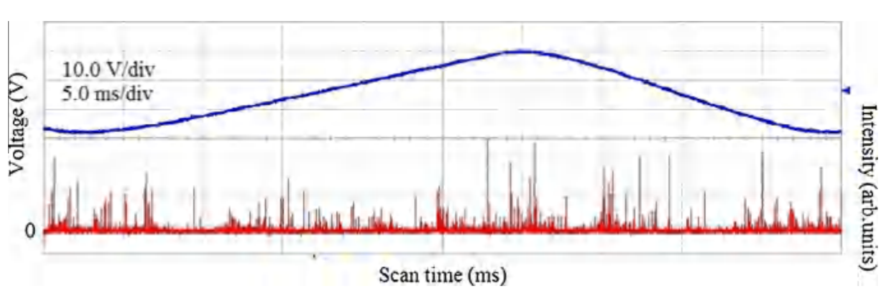

Fig. 2. Output mode of the free-running Ho:YLF laser.

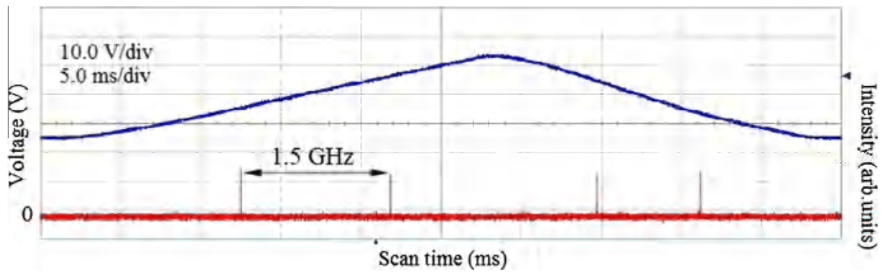

Fig. 5. F–P spectra of the single-longitude-mode Ho:YLF laser.

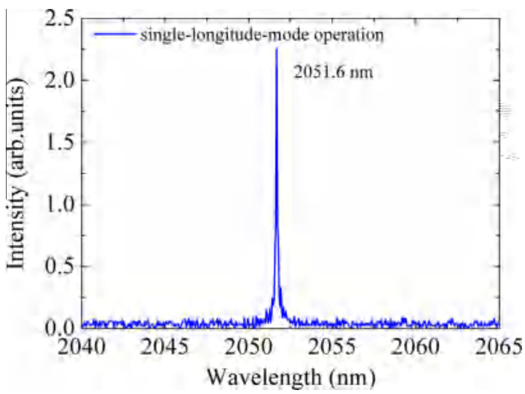

Fig. 6. Output spectrum of the single-longitude-mode Ho:YLF laser.

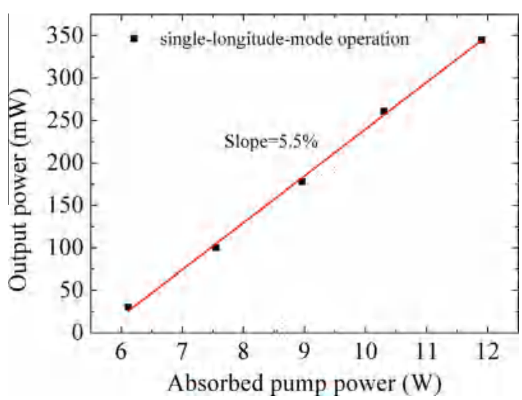

Fig. 7. Output power of the single-longitude-mode Ho:YLF laser.

mode existed in the laser cavity. The laser operated at π-polarisation which was measured by Glan prism. In addition, output power versus the absorbed pump power is shown in Fig. 7. The maximum single-longitude-mode output power of 345 mW was obtained at the absorbed pump power of 11.9 W, corresponding to a slope efficiency of 5.5% and an optical-to-optical efficiency of 2.9%. The low efficiency is due to the large loss caused by two F–P etalons with 20% reflectivity.

As we know, two efficient transitions exist in the energy levels of Ho:YLF, and the two main emission peaks locate at 2050 nm and 2064 nm, respectively. Therefore, near 2064 nm laser can also be obtained by tuning the angles of the etalons. As can be seen in Table 1, 2062.7 nm and 2063.3 nm were achieved and the maximum single-longitude-mode output power were respectively 270 mW and 194 mW. The maximum single-longitudinal-mode output power variation of different wavelength can be attributed to the different loss caused by F–P etalons and gain of modes oscillating in laser cavity.

Table 1
Output power with wavelength.

Output wavelength (nm)	Output power (mW)
2051.6	345
2062.7	270
2063.3	194

4. Conclusion

In summary, a 1.94 μm Tm-doped fiber laser end-pumped single-longitudinal-mode Ho:YLF laser at 2051 nm was demonstrated with intracavity etalons. The maximum single-longitudinal-mode output power of 345 mW was obtained under the absorbed pump power of 11.9 W, corresponding to a slope efficiency of 5.5% and an optical conversion efficiency of 2.9%. The wavelength can be tuned from 2051.6 nm to 2063.3 nm by regulating the angle of etalons. The single-longitudinal-mode Ho:YLF laser has potential applications on eye-safe coherent lidar, differential absorption lidar and optical remote sensing.

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