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Tunable single-longitudinal-mode operation of a sandwich-type YAG/Ho:YAG/YAG ceramic laser



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HIGHLIGHTS

• Single-longitudinal-mode Ho:YAG ceramic laser is demonstrated for the first time.

• A 1908 nm all-fiber Tm-doped fiber laser was used as pump source.

• By inserting etalons, the maximum single-longitudinal-mode output power was 530 mW.

• Single-longitudinal-mode operation in the range of 2091.1-2092.1 nm was demonstrated.

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ABSTRACT

We present a 2.09 µm single-longitudinal-mode sandwich-type YAG/Ho:YAG/YAG ceramic laser pumped by a Tm-doped fiber laser for the first time. A pair of F-P etalons was used to achieve tunable singlelongitudinal-mode operation. The maximum single-longitudinal-mode output power of 530 mW at 2091.4 nm was obtained with an absorbed pump power of 8.06 W, corresponding to an optical conversion efficiency of 6.6% and a slope efficiency of 12.7%. Wavelength tunable was achieved by tuning the angle of etalons and the wavelength could be tuned from 2091.1 nm to 2092.1 nm, corresponding to a tuning frequency of 68 GHz. The M² factor was measured to be 1.23.

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1. Introduction

Single-longitudinal-mode (SLM) lasers with eye-safe wavelength around 2 μ m spectral region have been widely used in fields of medicine, coherent Doppler Lidar, differential absorption Lidar, high-resolution spectroscopy and so on [1,2]. Moreover, 2 μ m SLM lasers as seed sources of Lidars, it is essential to meet the requirements of laser power, wavelength tunable, frequency stability and low thermal load [3]. Up to date, various methods have been employed to achieve 2 μ m SLM operation, such as the microchip laser [4,5], coupled cavity [6], twisted-mode-cavity [7], and the lasers with F-P etalons [8]. Among them, the SLM laser with intracavity etalons is the most common way to realize continuously tunable and has been widely investigated in recent years [9,10].

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For high-power operation in the 2 μ m wavelength regime, more and more researches have being focused on Ho-doped laser due to its low quantum defect and high efficiency, such as YAG [11], YLF [12,13], and YAP [14]. Among these laser gain crystals, Ho:YAG crystal has been extensively studied to obtain continuous-wave and Q-switched operation in 2 µm wavelength for good thermomechanical properties and favorable spectroscopic properties [15–17]. Compared with Ho:YAG single crystal, the superior laser performance of Ho:YAG ceramic had been proven, such as fabricated easier and shorter time, low cost feasibility of larger size, higher holmium concentration, and more complex structures (e.g. "sandwich" structures) [18,19]. Due to these advantages, Ho: YAG ceramic materials become a promising substitute for single crystal Ho:YAG for 2.1 µm application and has unique research potential. In particular, composite and sandwich-type ceramic material for it's more superior heat dissipation performance become a hot topic of high-power solid-state laser. In 2010, Zhang et al. reported a 1 at.% Ho:YAG ceramic slab end-pumped by a Tm: YLF laser. The maximum output power was 1.95 W with a pump



power of 6.7 W [20]. In 2013, Wang et al. reported a Ho:YAG ceramic laser pumped with a laser diode at \sim 1.13 µm. The maximum CW output power of 1 W was obtained with a slope efficiency of 20.6% [21]. In 2014, Wang et al. demonstrated a Q-switched Ho: YAG ceramic laser resonantly pumped by a Tm:YLF laser. The maximum CW output power was 4.62 W with a slope efficiency of 41.3%. For Q-switched, output energy of 10.2 mJ was measured with the pump power of 15.28 W [22].

In this letter, a SLM sandwich-type YAG/Ho:YAG/YAG ceramic laser pumped by 1908 nm Tm-doped fiber laser was demonstrated for the first time to the best of our knowledge. By inserting F-P etalons, a maximum SLM output power of 530 mW at 2091.4 nm was achieved with an absorbed pump power of 8.06 W, corresponding to an optical conversion efficiency of 6.6% and a slope efficiency of 12.7%. Regulating the angle of the etalons, SLM operation in the range of 2091.1–2092.1 nm was demonstrated, corresponding to a tuning frequency of 68 GHz. The beam quality M^2 of 1.23 was measured at 2091.4 nm with the highest output power. The results in this paper show that the Ho:YAG ceramic is a very promising substitute for single crystal Ho:YAG for obtaining 2 µm SLM operation in the future (see Fig. 1).

2. Experimental setup

The schematic diagram of the experimental setup is depicted in Fig. 2. The laser cavity of an L-shaped plano-concave resonator with total cavity length of about 105 mm was used. The input mirror M1 has 99% transmission at 1.9 µm and 99.8% reflectivity at 2.1 µm. 45° plane mirror M2 was coated with high transmission (T > 98%) at 1.9 µm and high reflectivity (R > 99%) at 2.1 µm. Output coupler was a plane-concave mirror with a curvature radius of 150 mm with transmission of 30%. The distance between M1 and M2 was 45 mm and between M2 and M3 was 55 mm. Sandwich-type YAG/Ho:YAG/YAG ceramic with dimensions of $3 \text{ mm} \times 3 \text{ mm} \times 15 \text{ mm}$ consisted of a 1.25 mm thick undoped YAG, 0.5 mm thick 1 at.% doped active region and 1.25 mm thick undoped YAG. The design of sandwich structure is suitable for high-power laser due to the thermal conductivity of YAG layer is higher than the doping layer. Two YAG layers can act as heatsink system during laser operation process. Both sides of the sandwich-type YAG/Ho:YAG/YAG ceramic were antireflection coated at 1.9 μ m and 2.1 μ m and the sandwich-type ceramic was placed as close as possible to the mirror M1 and cooled by a thermoelectric cooler. Temperature of the sandwich-type YAG/Ho: YAG/YAG ceramic was held at 13 °C. The finesse value of this cavity is around 17.6. The laser mode spacing of the free running sandwich-type YAG/Ho:YAG/YAG ceramic laser is around 1.67 GHz. 1 mm and 6 mm thickness etalons made from YAG with 20% reflectivity at 2 µm were inserted in the cavity to obtain the SLM operation. By changing the angles the two F-P etalons, the wavelength of the SLM sandwich-type YAG/Ho:YAG/YAG ceramic



Fig. 1. Schematic set-up of the SLM sandwich-type YAG/Ho:YAG/YAG ceramic laser.



Fig. 2. (a) Laser output power versus the absorbed pump power. (b) Laser spectrum of free-running sandwich-type YAG/Ho:YAG/YAG ceramic laser.

laser can be tuned. Owing to the smaller relaxation oscillation of Tm-doped fiber laser compared with Tm-doped solid state laser, 1908 nm all-fiber Tm-doped fiber laser by ourself with a maximum output power of 20 W was used as pump source, which is beneficial for the stability of the SLM sandwich-type YAG/HO:YAG/YAG ceramic laser. Fiber with 25 μ m core diameter and a NA of 0.22 were used. The pump radiation from the fiber laser was focused into the sandwich-type YAG/HO:YAG/YAG ceramic with an appropriate system of two plano-convex lenses and the pump light was about 250 μ m.

3. Experimental results and discussion

The free-running (without F-P etalons) sandwich-type YAG/Ho: YAG/YAG ceramic laser characteristics are first illustrated. The maximum output power of 3.92 W is achieved at the absorbed pump power of 18.7 W with a threshold of approximately 2.0 W, corresponding to optical conversion efficiency of 20.9% and then slope efficiency of 23.3%, shown in Fig. 2(a). As can be seen in Fig. 2(b), the laser is simultaneously emitting at multiple lasing emission and the central laser wavelength is 2091.0 nm and 2091.8 nm recorded by the wavemeter (Bristol, 0.7 pm resolution), respectively.

Fig. 3 shows the longitudinal mode of free-running sandwichtype YAG/Ho:YAG/YAG ceramic laser, measured by a Fabry-Perot (F-P) interferometer with a free spectral range of 1.5 GHz and the laser typically ran on multimode oscillation.

In order to achieve SLM oscillation, 1 mm and 6 mm F-P etalon were inserted into the cavity. The angle of the two etalons is regulated to meet only one mode in the transmission peak and has the highest gain, and then the laser can run on SLM. Fig. 4 shows the



Fig. 3. F-P spectra of the free-running sandwich-type YAG/Ho:YAG/YAG ceramic laser.



Fig. 4. (a) SLM laser output power as a function of the absorbed pump power. (b) Laser spectrum of SLM sandwich-type YAG/Ho:YAG/YAG ceramic laser.

SLM laser characteristics. Up to 530 mW SLM output power is achieved under an absorbed pump power of 8.06 W, corresponding to optical conversion efficiency of 6.6% and slope efficiency of

12.7%, shown in Fig. 4(a). As shown in Fig. 4(b), the center wavelength of SLM sandwich-type YAG/Ho:YAG/YAG ceramic laser is 2091.4 nm (around 0.7 nm spectral bandwidth).

The spectra of the sandwich-type YAG/Ho:YAG/YAG ceramic laser was measured by a scanning F-P interferometer (1.5 GHz free spectral range). As can be seen in Fig. 5, the free spectra range voltage was around 16 V and the sandwich-type YAG/Ho:YAG/YAG ceramic laser was running on SLM operation.

By changing the angles the two F-P etalons, the wavelength of the SLM sandwich-type YAG/Ho:YAG/YAG ceramic laser can be tuned. The maximum continuous tunable range of wavelength depends on the parameters of the etalons and length of the resonator and it may be changed by modified of the etalon thickness. In this experiment, we obtained the maximum continuous tunable range of wavelength of 1 nm, shown as Fig. 6. By regulating the angle of the F-P etalons, the wavelength of the SLM sandwichtype YAG/Ho:YAG/YAG ceramic laser could be tuned from 2091.1 nm to 2092.1 nm, corresponding to a tuning frequency of 68 GHz.

Fig. 7 shows the SLM output power with different wavelength. Under the wavelength of 2091.1 nm and 2092.1 nm, the maximum output power is respectively 368 mW and 507 mW with an absorbed pump power of 8.89 W, corresponding to the slope efficiency of 8.9% and 11.1%. Under the wavelength of 2091.6 nm and 2091.8 nm, the maximum output power is respectively 514 mW and 280 mW with the absorbed pump power of 9.82 W and 8.06 W, corresponding to the slope efficiency of 9.8% and 8.0%. The variations of the maximum SLM output power and slope efficiency under different wavelength can be attributed to the different loss caused by F-P etalons and gain of modes oscillating in cavity.

The output beam quality factor M^2 of single-longitude-mode sandwich-type YAG/Ho:YAG/YAG ceramic laser at 2091.4 nm was measured at the highest output power by knife-edge technique at several positions. As can be seen in Fig. 8, the data were fitted according to the Gaussian beam propagation equation and M^2 was 1.23.



Fig. 5. F-P spectra of the SLM sandwich-type YAG/Ho:YAG/YAG ceramic laser at 2091.4 nm.



Fig. 6. F-P spectra of the SLM sandwich-type YAG/HO:YAG/YAG ceramic laser tuned by F-P etalons (a) 2091.1 nm and (b) 2092.1 nm.



Fig. 7. SLM output power with different wavelength.



Fig. 8. M² of single-longitude-mode sandwich-type YAG/Ho:YAG/YAG ceramic laser at 2091.4 nm.

4. Conclusion

In conclusion, we have demonstrated a Tm-doped fiber laser pumped single-longitude-mode sandwich-type YAG/HO:YAG/YAG ceramic laser with intra-cavity etalons. A maximum output power of 530 mW near 2091.4 nm is obtained at the absorbed pump power of 8.06 W, corresponding to a slope efficiency of 12.7%. The wavelength tunable range of the sandwich-type YAG/Ho: YAG/YAG ceramic laser was from 2091.1 nm to 2092.1 nm, corresponding to a tuning frequency of 68 GHz. The beam quality factor M^2 was 1.23. The results reveal that Ho:YAG ceramic is an excellent laser medium which could replace single crystal Ho:YAG for 2 µm laser single-longitude-mode operation in the future.

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