Measurement of output characteristics of Tm:YAG laser at 25–300 K

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ABSTRACT

In this paper, output characteristics of a laser diode end-pumped Tm:YAG laser in a wide temperature range were investigated. In this laser system, a Tm:YAG crystal was cooled in a cryostat with liquid helium or liquid nitrogen as coolant. At the temperature of 88 K, a maximum output power of 4.68 W is achieved when the incident pump power is 8.9 W, and the optical–optical conversion efficiency is 52.6%, with a slope efficiency of 56.1%. The dependence of the output characteristics of Tm:YAG on temperature was experimentally studied in the temperature range of 25–300 K.

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1. Introduction

In recent years, all-solid-state lasers operating at around 2 μm spectral region have received considerable interest due to their eye-safe propagation through atmosphere. Lasers with a wavelength of around 2 μm are needed urgently for medicine, optical communications and remote sensing [1–5]. Compared with other laser materials, Tm 3+ doped materials are more suitable for pumping with commercially available diode lasers, and due to efficient cross-relaxation process, two Tm 3+ ions will be excited for each absorbed 785 nm pump photon [6]. Among all the Tm-doped crystals, YAG crystal has the advantages of high mechanical strength and large thermal conductivity which can withstand more heat in a high-power laser system. For these reasons, much work has been done on the development of Tm:YAG laser [7–10]. However, because of the quasi-three-level laser properties of Tm 3+ ions and their small stimulated-emission cross sections at room temperature, it is very difficult to design efficient lasers based on Tm:YAG crystal. The thermo-population density on the lower laser level increases the re-absorption losses in the laser cavity, and then increases the laser threshold and decreases the slope efficiency. Intense pumping should be used to overcome the high threshold, but if the pumping intensity is excessively high, upconversion processes in the excited Tm 3+ ion will occur, and these processes will deplete the population inversion and generate more heat, thus decrease laser efficiency. Moreover, temperature plays an important role in quasi-three-level laser system, and lowering temperature can reduce thermo-population on the lower laser level, then decrease the re-absorption losses, so it is an effective approach for improving the properties of Tm:YAG laser. This temperature effect has attracted considerable attention from researchers. In 1999, Li et al. [11] reported a diode-pumped Tm:YAG laser, and their experimental results show that under the same pumping power, the output power increases by 90% when the crystal temperature varies from 20°C to –20°C. Lin et al. [12] introduced a diode-pumped CW 2 μm Tm:YAG laser in 2007; the output power at 5°C, 10°C, 15°C, and 20°C was measured respectively; the results show that the crystal temperature greatly affects the output power of Tm:YAG laser. In 2011, Cao et al. [4] investigated the output characteristics of Tm:YAG crystal at different temperatures; this temperature range is 8–16°C. However, due to the complexity of cryogenic system, the study on the effect of temperature on the output characteristics of Tm:YAG laser is limited to room temperature. Under such conditions, we developed a laser diode end-pumped Tm:YAG laser cooled with a liquid helium cooling system. This paper demonstrates a Tm:YAG laser in which the crystal was cooled using a liquid helium cryostat, and end-pumped by a 30 W fiber coupled diode laser. Using this cryostat, the temperature range of 25–300 K was achieved, then the investigation of temperature-dependency of output characteristics of Tm:YAG laser was carried out.

2. Experimental results and discussion

2.1. Experimental setup

The layout of the LD end-pumped Tm:YAG laser is shown in Fig. 1. The pump source is a fiber coupled laser diode with a core...
diameter of 400 μm and a numerical aperture of 0.22. The laser diode was fixed on a copper heat sink and its emission was temperature tuned to 785 nm wavelength. The pump beam is focused into the Tm:YAG crystal by a 1:1 coupling system.

A 3% Tm-doped Tm:YAG laser crystal is used as the active material. The size of the Tm:YAG crystal is 3 mm × 3 mm × 8 mm, and both sides of the crystal are plane polished, parallel, and coated antireflection at 785 nm (R < 0.2%) and 2020 nm (R < 0.2%). Fig. 2 shows the schematic view of cooling system of the crystal. The laser crystal is mounted on a copper heat sink and cooled by coolant such as liquid helium (LHe) or liquid nitrogen (LN2); to reduce the radiative heat load on the copper heat sink, a 80 K shield is used, and a film heater is pasted on the surface of the copper heat sink to heat laser crystal; thus when LHe is used as the coolant to cool the crystal, the crystal temperature can be adjusted from 30 K to 300 K, and when LN2 is used, the temperature range of the crystal could be 80–300 K. Both sides of the crystal were antireflection coated at both 785 nm and 2020 nm. The Tm:YAG resonator used is of plane-concave geometry, and the mirrors are mounted on optical adjusting racks which are fixed on the copper heat sink, as shown in Fig. 2. The pump input mirror is a plane mirror with high reflectivity at the wavelength of 2020 nm (R > 99.8%) and high antireflectivity at wavelength of about 785 nm (R < 0.2%). The output coupler is a concave mirror with a 200 mm radius of curvature, and it is coated for a 3% transmission at 2 μm. The two windows are made of quartz and are sealed with rubber O-rings.

2.2. Cooling performance of the cooling system

When liquid nitrogen is used as the coolant, the cool-down curve of the cooling system is shown in Fig. 3, and the cool-down curve for the liquid helium cooling system is shown in Fig. 4. For the liquid nitrogen cooling system, at the beginning of the cooling process, the crystal temperature decreases sharply, and the cooling rate gets lower and lower. At the end of the cooling process, the crystal temperature is 80 K; this temperature is stable, and the whole cooling time is 20 min. For the liquid helium cryostat, the whole cooling process includes three steps, and the first step is pre-cooling process in which liquid nitrogen is used to pre-cool Tm:YAG crystal; it takes 10 min for this step. The liquid nitrogen left in the liquid helium pool evaporates in the second step, and this process lasts for more than 15 min. In the third step, the liquid helium is filled into the cryostat to cool Tm:YAG crystal, and the lowest temperature obtained is 5.3 K; this process lasts about 10 min, and the whole cooling time is less than 40 min.

2.3. Output characteristics of Tm:YAG laser at cryogenic temperature

To investigate the temperature-dependency of output characteristics of Tm:YAG laser, many experiments have been performed. The experimental results shown in Figs. 5–7 are obtained under
the condition that liquid nitrogen is used as coolant in the cryostat, and the experimental results shown in Fig. 8 are obtained when liquid helium is used as the coolant. For the incident pump power of 5.2 W, 7.0 W, and 8.9 W, the output power as a function of crystal temperature is shown in Fig. 5, and output power versus the pump power is shown in Fig. 6. From Fig. 6 it can be seen that the laser output power is essentially linear with respect to incident pump power, and under the pump power of 8.9 W, the maximum output power of 4.68 W is achieved with the crystal temperature at 88 K; the optical-to-optical conversion efficiency is 52.6%, and a linear fit to the data yields a slope efficiency of 56.1%. From Figs. 5 and 7 we can see that the output power drops and the threshold raises dramatically with the rise of the crystal temperature, especially when the temperature exceeds 170 K. Because in quasi-three-level system, the lower laser level is in the ground-state manifold, its population grows rapidly as the temperature rises; this will highly increase the reabsorption losses in the laser cavity, and finally results in the decrease of output power and the increase of threshold.

Fig. 8 shows the output power of Tm:YAG crystal in the temperature range of 25–300 K. Low pump power can prevent Tm:YAG crystal temperature from rising up too high, so the pump power of 5.4 W and 9.5 W are used in this experiment, and the crystal lowest temperature rises from 5.3 K to 25 K when the pump power is increased from 0 W to 9.5 W. From Fig. 8 we can see that output power curve is similar to the result shown in Fig. 5 in the temperature range of 80–300 K, and in the temperature range of 25–80 K, the output power drops irregularly with the decrease of the crystal temperature. This is because except the thermal population density in the lower laser level and reabsorption in the cavity, the output efficiency is also influenced by absorption peak and absorption bandwidth of Tm:YAG crystal which will shift at cryogenic temperature, and the mismatch between the wavelength of pumping diode and the absorption peak of Tm:YAG crystal will strongly affect the lasing efficiency.

3. Conclusion

In conclusion, we have demonstrated a Tm:YAG laser in which the Tm:YAG crystal is cooled in a cryostat. This laser is end-pumped by a 30 W fiber coupling laser with emission wavelength of 785 nm. Using this laser system, experimental investigation on output characteristics of Tm:YAG crystal in the temperature of 25–300 K is carried out. The output power, lasing threshold as a function of crystal temperature is obtained. At 88 K, a maximum output power of 4.68 W is achieved when the incident pump power is 8.9 W, and the optical–optical conversion efficiency is 52.6%, with a slope efficiency of 56.1%. Experimental results show that crystal temperature plays an important role in quasi-three-level laser. In the temperature range of 80–300 K, lower temperature will lead to higher efficiency of the laser system. When the crystal temperature is below 80 K, decreasing temperature is not the right way for getting higher slope efficiency.
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