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Intra-Cavity Tm:YAG-Ho:$GdVO_4$ Laser with near Diffraction Limited Beam Quality

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Abstract: In this study, an Er:YAG laser pumped intra-cavity Tm:YAG-Ho:$GdVO_4$ laser was built and debuted at room temperature. At an incident pump power of 9.2 W, this laser obtained a maximum output power of 1.6 W with a slope efficiency of 28.0%. Additionally, the M^2 factors at the maximum output power were measured to be 1.06 and 1.03 in the x and y directions, respectively. The results showed that the intra-cavity pumping method of combining thulium and holmium crystals as the gain medium was an effective way to obtain a 2 μm laser with near diffraction limited beam quality.

Keywords: intra-cavity; 2 μm laser; Ho:$GdVO_4$ crystal; Tm:YAG crystal

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1. Introduction

Solid-state holmium (Ho) lasers with the wavelength of 2.1 μm are desirable for many applications such as medical treatment, wind finding lidar, scientific research, etc. There are two common ways to achieve Ho laser radiation. One way is thulium (Tm) sensitization, where an 800 nm laser can be used as the pump source. However, this approach requires cooling the gain medium to the cryogenic temperature to reduce the synergistic up-conversion between Tm^{3+} and Ho^{3+} [1]. Another way is Ho-singly doping, where a 1.9-μm laser is used as the pump source, which is called in-band pumping, owing to the lower quantum defect and up-conversion loss. The Ho lasers could produce a much higher output power and optical-to-optical conversion efficiency at room temperature [2–9]. Currently, the pumps of 1.9 μm are almost Tm lasers, which have the disadvantage of a high thermal load and an extra optical path of the system.

Besides the in-band pumping, the intra-cavity pumping which puts the Tm and Ho gain mediums together into the same cavity is another efficient way to obtain the Ho lasers. The first intra-cavity pumping Ho laser employed a Tm:YAG-Ho:YAG structure at an 800 nm waveband in 1998 [10]. In 2003, a follow-up Tm:YLF-Ho:YAG structure was used, which had lower thermal effects compared with the Tm:YAG crystal [11]. In addition, in order to improve the pump absorption, Haizhou Huang et al. adopted a narrow linewidth laser diode (LD) to pump the intra-cavity Ho:YAG laser in 2016 [12]. Apart from the Ho:YAG laser, there have been many reports on the intra-cavity pumping of Ho:YAP, Ho:CaF_2, Ho:YLF and Ho:YVO_4 lasers in recent years [13–16].

$GdVO_4$ crystals have an excellent laser host material with higher thermal conductivity than YVO_4 and YAG [17]. LD pumped Tm:$GdVO_4$ and Nd:$GdVO_4$ lasers have been widely reported [18–23]. Furthermore, continuous-wave and Q-switched Ho:$GdVO_4$ lasers have also been confirmed by the Tm-laser at 1.94 μm [24,25]. However, Ho:$GdVO_4$ lasers based on an intra-cavity pumping structure have not been reported yet.

In this contribution, we built the first intra-cavity Tm:YAG-Ho:$GdVO_4$ laser at 2048.2 nm with an Er:YAG laser pump source. The highest output increased to 1.6 W with the incident pump of 9.2 W. Additionally, the laser's slope efficiency at this time was 28.0%. Surprisingly, the laser we built had a high beam quality, and the M^2 factors could reach 1.06 and 1.03 in the x and y directions, respectively.

2. Crystals and Lasers

The effective correspondence between the particular absorption wavelength of the gain medium and the emission wavelength of the pump source is a key factor for the successful construction of lasers [26]. In our experiments, a measure for the probability of the Tm:YAG crystal's absorption process being near 1.6 μm and the output spectrum of the homemade Er:YAG laser were selected, as shown in Figure 1. The strongest laser output peak at 1617 nm was close to one absorption peak of the Tm:YAG crystal and the single-pass absorption of the Tm:YAG crystal to the pump was measured to be about 91%.

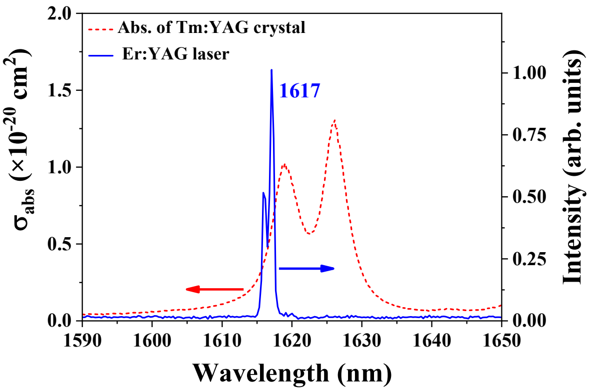

Figure 1. Absorption of the Tm:YAG crystal, including spectral curve of the Er:YAG laser.

Figure 2 shows the schematic of the intra-cavity Tm:YAG-Ho:$GdVO_4$ laser we built. The transverse diameter dimension of the Tm:YAG rod was 3 mm and the length was 10 mm, in which the Tm^{3+} concentration was 3 at.%. The spatial beam emitted from the Er:YAG laser was convergently coupled into a rod-shaped Tm:YAG crystal (r = 180 μm) The Ho:$GdVO_4$ crystal with the Ho^{3+} concentration of 1.0 at.% was *c*-axis cut, the dimension of which was 2 × 2 mm^2 in a cross section and 4 mm in length. The end-faces of Tm:YAG and Ho:$GdVO_4$ crystals were coated with antireflection coatings in both the pump and laser spectral ranges. The crystals were enfolded by the indium foils and placed in copper heat sinks. Here, the excellent ductility and thermal conductivity of the indium foils made them conducive to the full contact between the crystals and the surface of the copper heat sinks, thereby effectively controlling the crystal temperature. The temperatures of the two crystals were controlled at 18 °C with thermoelectric coolers (TEC). A flat input mirror M1 and a plano-concave output coupler M2 together formed the cavity with a physical length of 30 mm. Among them, M1 was coated at a high reflectivity of a 2.0~2.1 μm waveband and high transmittivity at the pump light band. The radius of the curvature of M2 was 100 mm with a transmittivity of 10% at 2.05~2.1 μm after coating. By implementing the ABCD matrix method, the radius of oscillating beam on the Tm:YAG crystal was calculated to be about 120 μm. It was very close to the size of the pump spot, resulting in a good overlap between the pump and oscillating beams.

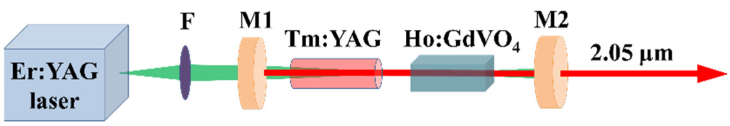

Figure 2. Experimental setup of the Tm:YAG-Ho:$GdVO_4$ laser.

3. Experimental Results

Firstly, the output optical characteristics of the Tm:YAG laser were studied when the Ho:$GdVO_4$ crystal was absent and another output coupler with the transmittivity of 3% at 1.9~2.1 μm was employed. As shown in Figure 3, the maximum output optical power of the Tm:YAG laser was 4.4 W at an incident pump power of 9.2 W, measured using a power meter of Coherent PM30. Here, the slope efficiency of Tm:YAG laser was

57.0%. Moreover, the M^2 of the Tm:YAG laser was assessed to be about 1.2 using the 90/10 knife-edge method.

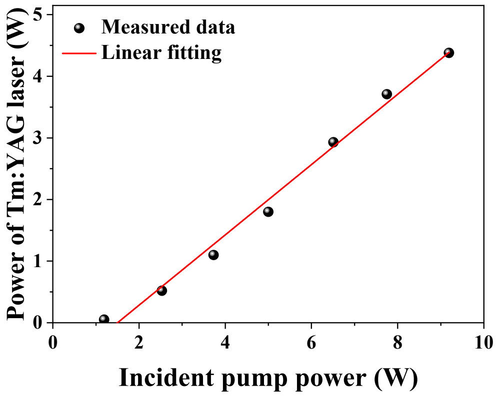

Figure 3. The output optical power of Tm:YAG laser varies with the incident pump.

The absorption spectrum of the crystal was an important reference for selecting the laser pump wavelength and determining the laser polarization mode. Figure 4 shows the output optical spectrum of the Tm:YAG laser and the absorption of the Ho:$GdVO_4$ crystal together. The central wavelength of the Tm:YAG laser at the maximum output power was 2014.1 nm with a full width at half maximum (FWHM) of 1.9 nm, measured with a spectrometer of Bristol 721A (Bristol Instruments, Inc., Victor, NY, USA). It can be seen from Figure 4 that the Ho:$GdVO_4$ crystal had strong peak absorption in both σ and π polarization directions around 2014 nm, which provided a feasible principle support for the construction of the intra-cavity Ho:$GdVO_4$ laser.

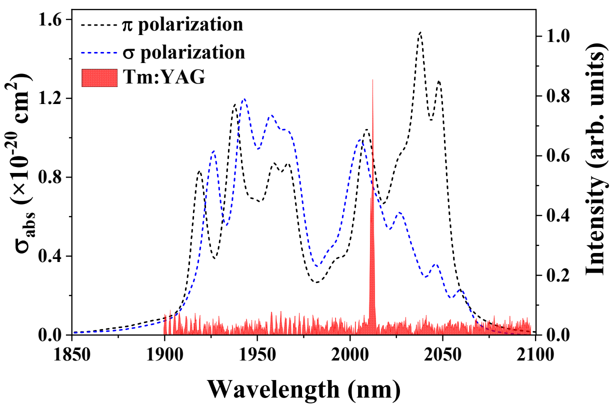

Figure 4. Output spectrum of the Tm:YAG laser and the absorption of the Ho:$GdVO_4$ crystal.

Figure 5 shows the experimentally measured power characteristics of the intra-cavity Ho:$GdVO_4$ laser as a function of the incident pump light. The laser obtained a maximum output power of 1.6 W when the pump power was 9.2 W and the center wavelength was 1617 nm. After fitting, the slope efficiency of the intra-cavity Ho:$GdVO_4$ laser was 28.0%. In addition, the power stability of the intra-cavity Ho:$GdVO_4$ laser was estimated. At a fixed incident pump power of 9.2 W, the output powers were recorded during 1 h, resulting in a power stability of 2.3%.

The spectrum of the Tm:YAG-Ho:$GdVO_4$ laser at the maximum output level is shown in Figure 6. The central wavelength was 2048.2 nm with a 0.2 nm linewidth. When the pump power was near the threshold, the laser wavelength of Tm:YAG was also observed. The theoretical slope efficiency was calculated to be 98.3% for the pump of Tm:YAG and the laser of Ho:$GdVO_4$. Under a Tm-wavelength of 2014.1 nm and Ho-wavelength of 2048.2 nm, the limited slope efficiency was estimated to be 98.3%. However, this slope efficiency value was difficult to realize. The main reason for this phenomenon was the low pump absorption efficiency of Ho crystal. The single-pass pump absorption of the Ho:GdVO_4 crystal was calculated to be 29.8% in this experiment. To increase the slope efficiency, stronger pump absorption was required. However, excessive pump absorption is not acceptable because Tm laser radiation needs to operate at a high power level. Therefore, the optimization of pump absorption of the Ho:GdVO_4 crystal was necessary for increasing the slope efficiency.

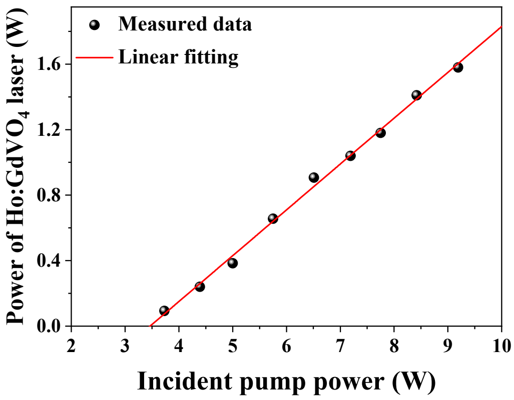

Figure 5. Power characteristics of the Tm:YAG-Ho:GdVO_4 laser.

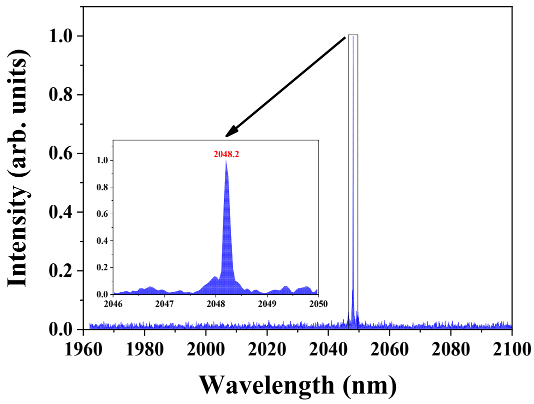

Figure 6. Spectrum of the Tm:YAG-Ho:GdVO_4 laser.

Measurement results of the M^2 of the intra-cavity Ho:GdVO_4 laser are shown in Figure 7. Under the strongest output of 1.6 W, M^2 factors could reach 1.06 (x direction) and 1.03 (y direction), which meant that the output laser beam was close to the diffraction limit.

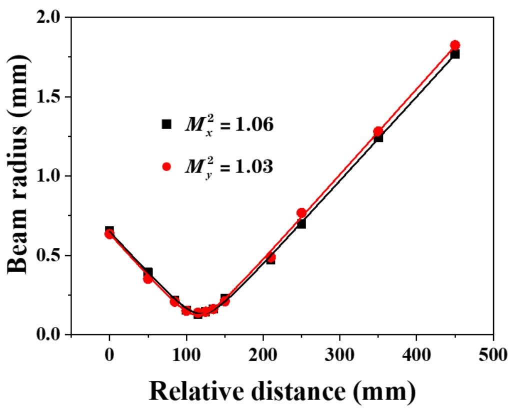

Figure 7. M^2 measurement of the Tm:YAG-Ho:GdVO_4 laser.

4. Conclusions

We built and debuted an intra-cavity Tm:YAG-Ho:$GdVO_4$ laser by applying an Er:YAG laser pump. With the pump power of 9.2 W, the output power of the intra-cavity Tm:YAG-Ho:$GdVO_4$ laser was 1.6 W. The slope efficiency and the central wavelength were 28.0% and 2048.2 nm, respectively. The M^2 factors could reach 1.06 (x direction) and 1.03 (y direction), which meant that the obtained laser beam was close to the diffraction limit. Compared with previous work on a diode-pumped Tm,Ho:$GdVO_4$ laser at a cryogenic temperature of 77 K [27], the output power and slope efficiency obtained in this work were low. However, the intra-cavity Ho:$GdVO_4$ laser operated at room temperature, so no cryogenic equipment was used in this work. This is beneficial to the use and maintenance of the Ho:$GdVO_4$ laser. Our experimental results indicated that the intra-cavity pumping with Tm and Ho gain media in the same cavity was an effective method to obtain two-micron lasers at room temperature. We believe that its slope efficiency and output optical power can be improved by optimizing the ability of Ho:$GdVO_4$ crystals to absorb pump light.

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