

Article

Efficient Ho:YVO₄ Laser Double-Pass-Pumped by a Wavelength-Stabilized Laser Diode

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Abstract: A Ho:YVO₄ laser double-pass-pumped with a 1.91 μm wavelength-stabilized laser diode is presented in this paper. The maximum output power was up to 8.7 W, with a wavelength of 2052.4 nm and a slope efficiency of 37.4%. The M^2 factors in the x and y directions were 1.8 and 1.6 at the maximum output power, respectively.

Keywords: laser; Ho:YVO₄; double-pass-pumping; laser diode



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1. Introduction

Today, 2 μm solid-state lasers have many applications in optical measurement, wind finding lidars, atmospheric monitoring, space communication, and medical treatment. Diode-pumped Tm, Ho co-doped gain-mediums, which take advantage of the two-for-one process pumped by ~ 792 nm, have been used extensively to yield 2 μm lasers. However, Tm, Ho co-doped lasers with quasi-three-level rely on energy-transfer processes and exhibit losses in radiation and irradiation, which lead to large heat loading of the gain-mediums in room-temperature operation [1]. In order to yield more powerful and brighter lasers, liquid nitrogen temperature is always needed [2]. In contrast, singly Ho-doped lasers by direct-resonant-pumping [3–10] to obtain 2 μm lasers have the advantage of high conversion efficiency and less thermal loading because of the weaker quantum defect between the laser and pump; thus, operation at room temperature is possible.

The spectral characteristics of the Ho:YVO₄ crystal around 2 μm at room temperature have been previously reported [11]. The long fluorescence decay lifetime and the large emission cross section make the Ho:YVO₄ crystal an outstanding host for 2 μm lasers. Moreover, the large absorption cross section corresponding to 1.94 μm makes the Ho:YVO₄ crystal efficiently and resonantly pumped by 1.9 μm Tm-fiber and Tm-bulk lasers, and the continuous wave and Q-switching operations of the Ho:YVO₄ laser have been also demonstrated under the pumping of FBG-locked Tm-fiber and Tm:YAP bulk lasers [12–14]. A cryogenically cooled Tm, Ho:GdVO₄ laser with an output power of 7.4 W was reported by Du et al., which required the assistance of sophisticated cryogenic cooling systems at a temperature of 77 K [15]. An efficient room-temperature Q-switched Ho:YVO₄ laser pumped by a 1940 nm Tm-fiber laser was reported by Ding et al., which generated an average output power of 11.4 W [16]. The beam quality of the Tm-fiber pumped Ho:YVO₄ laser was better than the laser in this present work because fiber lasers has better optical output characteristics than semiconductor lasers.

In this paper, we report the first (as far as we know) Ho:YVO₄ laser double-pass-pumped by a 1.91 μm wavelength-stabilized laser diode (LD). At a total absorbed pump power of 30.2 W, the maximum output power was up to 8.7 W, with a central wavelength of 2052.4 nm and slope efficiency of 37.4% with the absorbed pump power. The beam quality (M^2) factors were 1.8 and 1.6 in the x and y directions, respectively.

2. Experimental Setup

Figure 1 shows the absorption cross sections of the Ho:YVO₄ crystal and the radiation spectrum of the LD. The strongest absorption peak is located at 1.94 μm , as in many previous reports. However, the strong absorption of the Ho:YVO₄ crystal led to serious thermal loading. Thus, the slightly weaker absorption of 1.91 μm was selected in this experiment, which could reduce the absorption and improve the thermal distribution uniformity.

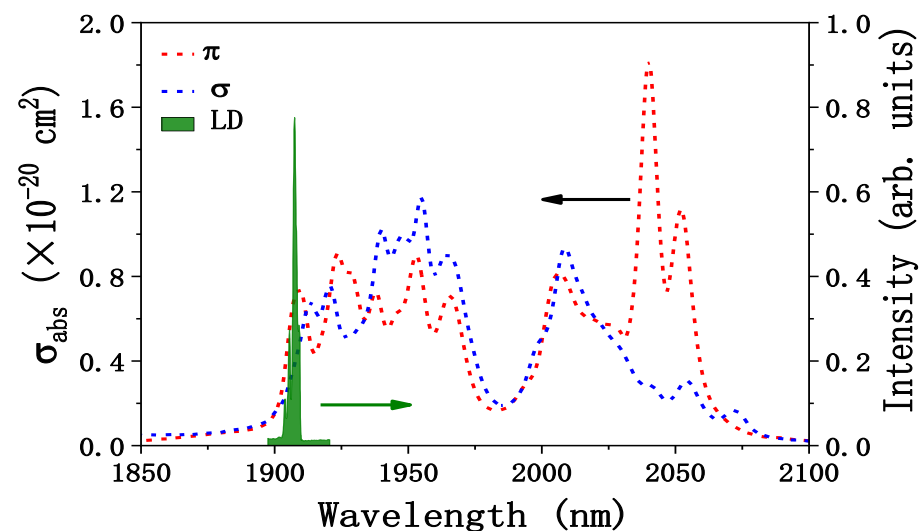


Figure 1. Absorption cross sections of the Ho:YVO₄ crystal and the radiation spectrum of the LD.

Figure 2 shows the experimental scheme of the LD double-pass-pumped Ho:YVO₄ laser. A wavelength-stabilized and fiber-coupled LD (QPC Corp., Los Angeles, USA) was employed as the pump, the core diameter and NA of which were 600 μm and 0.22, respectively. The central wavelength of the LD was 1.91 μm , with a linewidth of about 2 nm (FWHM) at the maximum output power of 40 W. The Ho:YVO₄ crystal was *a*-cut, the dimension of which was $3 \times 3 \text{ mm}^2$ in cross section and 30 mm in length, and the doping concentration of the Ho³⁺ was 0.5 at.%. The crystal, both end-faces of which were anti-reflection coated at 1.9~2.1 μm , was wrapped in a heat sink made of copper and controlled at 15 $^{\circ}\text{C}$ using a thermoelectric cooler (Tecooler technology Co., Ltd., Shenzhen, China). The pump beam was reshaped with the focal lens of F1 and F2 and shot into the center of the crystal (with a radius of about 0.3 mm). The single-pass absorption of the crystal corresponding to the 1.91 μm pump was measured to be 51% when the cavity was absent. Although the overall cost of the above scheme is a little high, we can still accept that. We believe that with the improvement of semiconductor technology, the price of semiconductor lasers will become lower and lower.

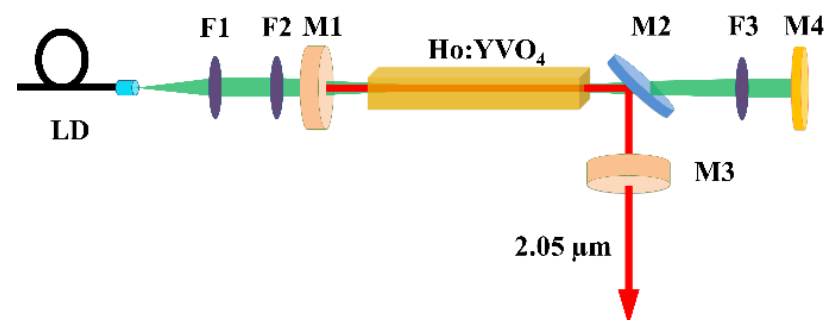


Figure 2. Experimental scheme of the Ho:YVO₄ laser.

The cavity (with a physical length of 50 mm) was L-shaped and consisted of an input mirror M1, a 45° reflectance mirror M2, and an output mirror M3, which were coated with high transmittance at 1.91 μm ($T > 99.97\%$) and high reflectance at 2.05 μm ($R > 99.98\%$), high transmittance at 1.91 μm ($T > 99.97\%$) and high reflectance at 2.05 μm ($T > 99.98\%$) with an angle of 45°, and partial reflectance at 2.05 μm , respectively. M1 and M2 were flat mirrors, whilst the plano-concave M3 had a curvature radius of 500 mm. A flat mirror M4 with high reflectance at 1.91 μm and a focal lens F3 (focal length of 30 mm) were employed to reflect the pump back to the crystal. In this way, the total pump absorption was increased to about 76%.

3. Experimental Results

Figure 3 shows that the output power depends on the absorbed pump power of the Ho:YVO₄ laser. With an output mirror transmittance of 10%, the maximum output power was 5.6 W with respect to the absorbed pump power of 30.2 W, corresponding to a slope efficiency of 23.6%. When the output mirror transmittance was 30%, the maximum output power and slope efficiency increased to 7.9 W and 34%, respectively. The maximum output power and slope efficiency reached the optimum values of 8.7 W and 37.4%, respectively, in the case of an output mirror transmittance of 50%. Although using diode pumping instead of pumping with a 1.04 μm laser based on a Tm-doped fiber or a Tm-doped crystal and via a double-pass pumping scheme is novel here, the efficiencies of the above scheme are lower than expected. In future work, we will use a 1940 nm diode laser instead of the present 1910 nm diode laser, increasing the single-pass absorption of the laser crystal and reducing the non-radiative loss, quantum defects, and thermal effects, which are all beneficial for improving the conversion efficiency.

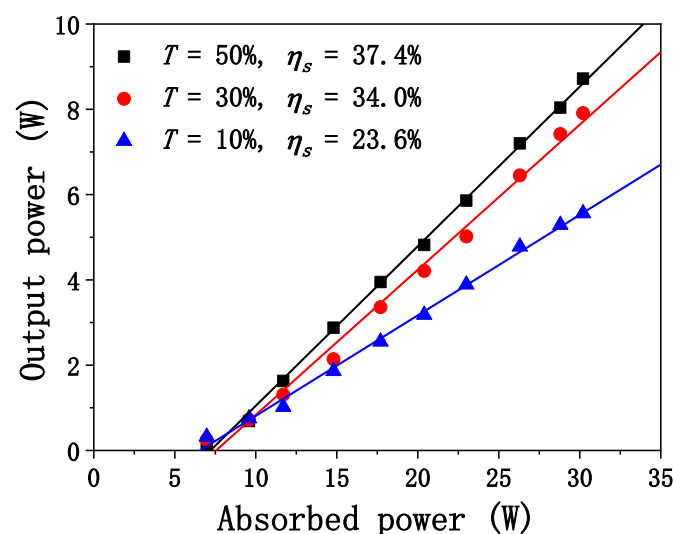


Figure 3. Output power dependence on the absorbed pump power of the Ho:YVO₄ laser.

The output spectrums of the Ho:YVO₄ laser at different transmittances of the output mirrors (shown in the Figure 4) were measured with the spectrum analyzer Bristol 721A (with a resolution of ± 0.2 ppm). The central wavelength was 2066.1 nm at an output mirror transmittance of 10%. The laser emission line width (FWHM) was less than 1 nm. With the other two transmittances, the central wavelengths were blue-shifted to 2052.4 nm, which can be attributed to the low resonator loss. With the three transmittances of the output mirrors, there were no other emission peaks observed in the experiment.

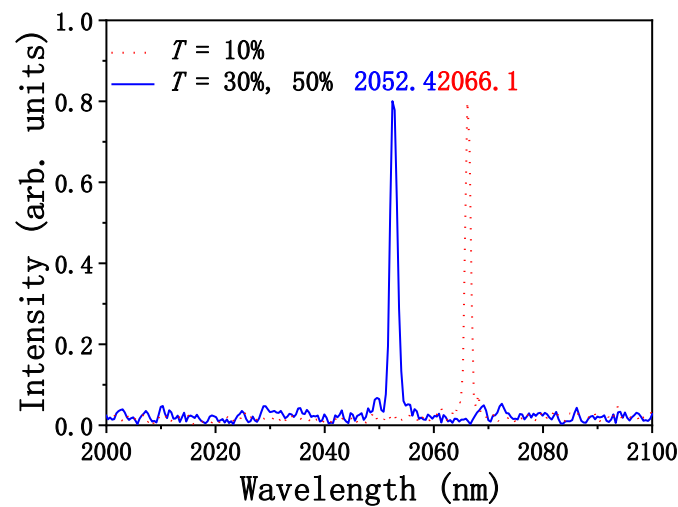


Figure 4. Output spectrum of the Ho:YVO₄ laser.

We measured the beam quality factor M^2 at the full output power of 8.7 W, taking advantage of the knife-edge method. Figure 5 shows the that laser beam radii depend on the location relative to the focal lens of 150 mm, which was used for leading out the waist of the oscillating beam in the cavity. The distance of the focal lens from the output coupler was about 100 mm. Using Gaussian fitting, the M^2 factors were calculated to be 1.8 and 1.6 in the x and y directions, respectively, which were better than those of the previous work, for example, Ref. [12]. Under the above experimental conditions, the stability of the laser resonator is judged by the ABCD matrix method [17] (the thermal focal length of the crystal was 500 mm at low pump power and 230 mm at high pump power).

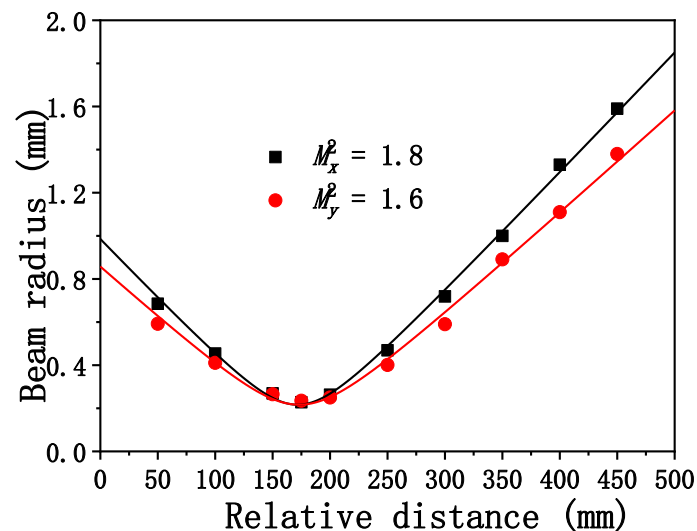


Figure 5. Beam quality of the Ho:YVO₄ laser.

4. Conclusions

Using a 1.91 μm wavelength-stabilized LD as the double-pass pump source, we demonstrated a continuous-wave Ho:YVO₄ laser. At an absorbed pump power of 30.2 W, the maximum output power was 8.7 W at 2052.4 nm, corresponding to a slope efficiency of 37.4%. The M^2 factors in the x and y directions were 1.8 and 1.6, respectively. The results imply that the LD double-pass-pumped Ho:YVO₄ laser is an efficient way to generate the 2 μm laser. In future work, we will use a 1940 nm LD instead of the present 1910 nm LD, increasing the single-pass absorption of the laser crystal and reducing the non-radiative loss, quantum defects, and thermal effects, which are all beneficial for improving the conversion efficiency.

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