LD Pumped Nd:$GdVO_4$/KTP Intracavity-frequency-doubling Laser

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Abstract Based on the measuring of thermal focal length and 1.06 μm fundamental property of Nd:$GdVO_4$, the intracavity-frequency-doubling property of LD pumped Nd:$GdVO_4$/KTP laser has been studied with a three-mirror folded cavity. When pumped by low power LD laser outputted from a single-fiber with the diameter of 200μm, the green laser has a threshold of 26 mW and an optical-to-optical efficiency of 17.3%. When pumped by high power LD laser outputted from a multi-fiber with the diameter of 1.55 mm, the green laser has a threshold of 200 mW and an optical-to-optical efficiency of 19.35%.

Keywords Nd:$GdVO_4$; Laser diode; Thermal focal length; Green laser
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0 Introduction

Because green laser, locating in the sensitive wavelength range of eye, has short wavelength, high-energy photon and high transmission in water, it is extensively used in information storage, under-water communication, laser spectroscopy, holography, laser navigation, oceanic prospecting and laser medicine. Its high brightness and homochromatism make it also a good choice of green light source in color printing and color display.

Nd:YVO_4, for its high absorption coefficient at 809 nm, large stimulated emission cross-section at 1.06 μm and higher allowance of Nd-doped level than Nd:YAG without concentration quenching[1,2], has been one of the popular materials which can be pumped by 808 nm LD. But it has some disadvantages such as low thermal conductivity and complete cleavage. Compared with Nd:YVO_4, Nd:$GdVO_4$ has not only high absorption coefficient at 809 nm and large stimulated emission cross-section at 1.06 μm (7.6×10^{-19} cm^3) but also high thermal conductivity. The thermal conductivity along its C axis is 11.7W/(m·K)[3], which is comparable to that of Nd:YAG and much larger than that of Nd:YVO_4 (5.4 W/(m·K)[4]). Therefore, Nd:$GdVO_4$ is more suitable to be applied to DPSL (laser-diode-pumped solid-state laser). We use a plane-plane cavity to measure the thermal focal lengths of Nd:$GdVO_4$ and Nd:YVO_4 with the same size. The ratio of their thermal focal length is about 1:0.6. 10.52W CW laser at 1.06 μm is obtained by using a plane-concave cavity. The optical-to-optical conversion efficiency is 50%. 1.81 W green laser is realized by intracavity-frequency-doubling in three-mirror folded cavity. The optical-to-optical conversion efficiency is 19.35%.

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1 Experiment and result

1.1 Thermal focal length and fundamental-frequency operation

The schematic diagram of our experimental setup for measuring the thermal focal length is shown in Fig. 1.

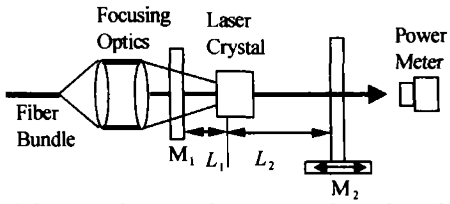

Fig. 1 Schematic diagram of measuring thermal focal lengths of crystals

M_1 is a plane mirror with one surface HR-coated at 1064 nm and HT-coated at 808 nm. M_2 is a plane mirror with 15% transmission at 1064 nm and serves as output coupler. The crystals employed in our experiment are Nd:$GdVO_4$ ($3\times3\times5$ mm^3) and Nd:YVO_4 ($3\times3\times5$ mm^3) with the same Nd^{3+} concentration of about 1%. According to the g parameter conditions for which the resonator is stable with the thermal focal length f_T, one can easily obtain

$$0<g_1g_2<1 \tag{1}$$

$$0<(1-L_1/f_T)(1-L_2/f_T)<1 \tag{2}$$

When the magnitude of L_1 is small enough, the condition $0<1-L_1/f_T<1$ can always be met within the interest of the thermal focal length f_T. As a result, the condition $L_2<f_T$ must be met to get a stable resonator. When $L_2>f_T$, the resonator is unstable; when $L_2=f_T$, the laser oscillating begins to become unstable. In experiment, the laser crystal is set very close to mirror M_1. When the laser has been made operating at one fixed magnitude L_2, increase the pump power, the output laser power will finally become zero at some pump level. The thermal focal length f_T

corresponding to this pump power is equal to the value of L_2. The results are shown in Fig. 2.

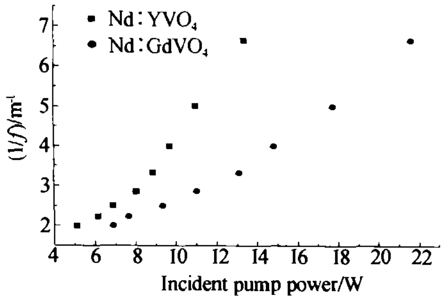

Fig. 2 Thermal focal lengths of Nd:$GdVO_4$ and Nd:YVO_4 (Transmission of output mirror $T = 15\%$)

The thermal focal length f_T is expressed by the following equation[4]

$$f_T = \frac{\pi K_c \omega_p^2}{P_{ph}(dn/dT)}\left[\frac{1}{1-\exp(-\alpha l)}\right] \tag{3}$$

From above equation, we know the ratio of f_T is determined mainly by thermal conductivity K_c. The ratio of f_T of Nd:$GdVO_4$ and Nd:YVO_4 obtained in experiment is about 1:0.6, which is approximately in accord with estimated theoretical calculation. That is to say, the thermal lensing effect of Nd:$GdVO_4$ is much weaker than that of Nd:YVO_4. So Nd:$GdVO_4$ is more suitable than Nd:YVO_4 to be applied in high power DPSL.

1.06 μm CW laser is obtained by using a 60 mm plane-concave cavity. The concave mirror with a radius of 200 mm is AR-coated at 809 nm and HR-coated at 1.06 μm on the inside surface. The transmission of the output mirror is 5%, 15% or 30%. The Nd:$GdVO_4$(1 at%) specimen with the dimension of 4×4×6 mm^3 is AR-coated at 1.06 μm and 809 nm on the pump face and AR-coated at 1.06 μm on the other face. The varieties of the output 1.06 μm laser power vs pump power are plotted in fig. 3. In fig. 3, We notice that the optimal transmission of the output mirror is 15%. Under this condition, the system has high slope efficiency, and the output power is still not saturated. When the pump power is 21 W, the output power is 10.52 W, corresponding to an optical-to-optical conversion efficiency of 50%.

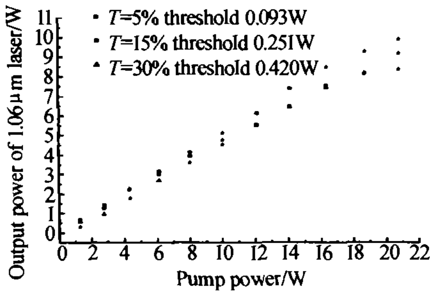

Fig. 3 Variation of 1.06 μm laser power with pump power

1.2 Intracavity-frequency-doubling in three-mirror folded cavity

According to the theory of transmission matrix and the thermal focal length measured in former experiment, we design a three-mirror folded cavity, which is showed in Fig. 4. In this Fig., M_1 and M_2 are concave mirrors with a radius of 150 mm and 100 mm respectively. M_1 is AR-coated at 809 nm and HR-coated at 1.06 μm, and M_2 is AR-coated at 0.53 μm and HR-coated at 1.06 μm. M_3 is a plane mirror with high reflection at 0.53 μm and 1.06 μm. The folded angle of the cavity is 15°. Nd:$GdVO_4$ specimen, which has a dimension of 4×4×6 mm^3, is placed near M_1.

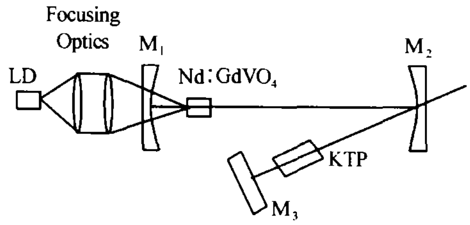

Fig. 4 Sketch of three-mirror folded cavity

The two laser-transmission faces of Nd:$GdVO_4$ crystal are AR-coated at 1.06 μm and its pump face is AR-coated at 809 nm. KTP crystals in the experiment has a dimension of 4×4×6 mm^3 and is cut at type Ⅱ phase matching. It is placed near M_3 and AR-coated at 1.06 μm on two laser-transmission faces. Both the Nd:$GdVO_4$ and KTP crystal are respectively wrapped in two indium foils and held in two copper blocks, and then cooled by two semiconductor coolers. We use two LDs, LD(a) and LD(b), as pump sources. LD(a) has an output single-fiber with the diameter of 200 μm. LD(b) has an output multi-fiber with the diameter of 1.55 mm. EPM-1000 power meter is used to measure the output power. The results are plotted in Fig. 5 and Fig. 6. Fig. 5 shows that, when the pump power of LD(a) is 1.18 W, the frequency-doubling laser output is 205.1 mW, and the corresponding optical-to-optical conversion efficiency is 17.3%. Fig. 6 shows that, when the pump power of LD(b) is 10.03 W, the frequency-doubling laser output is 1.92 W, and the corresponding optical-to-optical conversion efficiency is 19.2%.

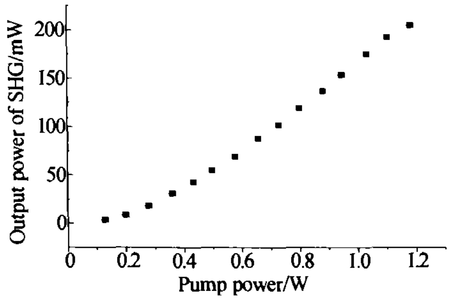

Fig. 5 Variation of 1.06 μm laser power with pump power for LD(a)

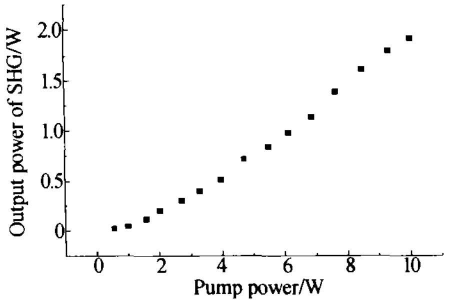

Fig. 6　Variation of 1.06μm laser with pump power for LD(b)

Comparing Fig. 5 with Fig. 6, we can see that, under the same condition, the threshold of laser system pumped by LD(a) is 26 mW, which is much lower than that of laser system pumped by LD(b), 200 mW. The reason is that, after being coupled to Nd:$GdVO_4$ crystal by Focusing Optics, light spot in the crystal pumped by the LD(a) has much smaller dimension than that in the crystal pumped by the LD(b). (The dimension of the former spot is 50 μm, and that of the later spot is 0.25 mm.) That is to say, the pump power density of LD (a) is much larger than that of LD(b). Because the second harmonic power is in direct proportion to the square of the fundamental-frequency power, higher pump power density leads to lower threshold.

But, in Fig. 5, when the pump power is high, the slope efficiency begins to decline. This is because the pump power density is too high. Besides leading fundamental-frequency power density to increase, higher pump power density also causes the temperature of the crystal center to increase. Temperature increasing not only aggravates the thermal lensing effect but also lowers the absorption of crystal to pump light[5]. These two factors make the fundamental-frequency power density in cavity decrease. Therefore, when the pump power intensity is higher than a certain value, the decrease effect exceeds the increase effect. At this time, the increase of the power.intensity will decrease the slope efficiency.

2 Conclusion

Using a LD with 200 μm-diameter single-fiber and a LD with 1.55 mm-diameter multi-fiber as pump sources, we study the laser property of Nd:$GdVO_4$ crystal, a new type of laser crystal suitable for pumping with LD. The ratio of the thermal focal lengths of Nd:$GdVO_4$ and Nd:YVO_4 is 1:0.6. When the pump power is 21 W, the output fundamental- frequency laser at 1.06 μm is 10.52 W, and the corresponding optical-to-optical conversion efficiency is 50%. When the pump power is 9.3 W, 1.8 W frequency-doubling green laser is obtained by intracavity-frequency-doubling in a three-mirror folded cavity, the corresponding optical-to-optical conversion efficiency is 19.35%. The experiment results demonstrate that Nd:$GdVO_4$ crystal, for its high conductivity, is more suitable to be pumped by high power LD. We believe that Nd:$GdVO_4$ crystal, along with the improvement of its quality, will become a more promising material than Nd:YVO_4 in high power DPSL.

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LD泵浦的Nd:$GdVO_4$/KTP腔内倍频激光器

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摘 要 基于对Nd:$GdVO_4$晶体热焦距的测量及其1.06 μm激光基本性能，用三镜折叠腔研究了半导体激光器(LD)泵浦的Nd:$GdVO_4$/KTP晶体的内腔倍频性质．当用从直径为200 μm的单光纤输出的低功率的半导体激光泵浦时，绿光的阈值是26 mW，光光转换效率为17.3%．当用从直径为1.55 mm的光纤束输出的高功率的半导体激光泵浦时，绿光的阈值是200 mW，光光转换效率为19.35%．

关键词 Nd:$GdVO_4$；半导体激光器；热焦距；绿光

Hou Xueyuan was born in 1948, in Shandong Province. He graduated from Shandong University in 1974, majoring in optics. He is now a professor in Information Science & Engineering College, Shandong University. His present research interests are laser technology and its application. He has published more than 30 research papers and a book named " laser devices and their applications".