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Pulsed laser performance of Nd:GdCOB and Cr:Nd:GdCOB crystals

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Abstract: $Ca_4GdO(BO_3)_3$ (GdCOB) is a new self-frequency-doubling (SFD) crystal. Using xenon lamp as pump sources, we have realized the free run from 1061nm to 530.5nm in SFD Cr:Nd:GdCOB (bi-doped) crystal and Nd:GdCOB (uni-doped) crystal. The threshold energies for uni-doped crystal and bi-doped crystal are 1.0J and 0.92J, respectively; and the maximum output energies of green laser for two kinds of crystals are 1.96mJ and 2.46mJ, respectively. By using pulsed dye laser as pump source, we have obtained SFD red laser at 655nm and its fundamental frequency laser at 1331nm as well as achieved SFD green laser at 530.5nm from a Nd:GdCOB crystal.

Key words: self-frequency-doubling; phase-matching; uni-doped; dye laser; xenon lamp

Nd:GdCOB和Cr:Nd:GdCOB晶体的脉冲激光特性

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摘要: $Ca_4GdO(BO_3)_3$(GdCOB)是一种新型的自倍频晶体。利用氙灯作泵浦源, 对单掺的Nd:GdCOB和双掺的Cr:Nd:GdCOB两种自倍频晶体实现了1061nm~530.5nm自由运转的自倍频转换。单掺和双掺晶体的泵浦阈值能量分别为1.0J和0.92J, 自倍频光的最大输出能量分别为1.96mJ和2.46mJ。利用脉冲染料激光作泵浦源, 对Nd:GdCOB晶体获得了1331nm基频光和655nm自倍频红光运转, 并获得了530.5nm自倍频绿光输出。

关键词: 自倍频; 相位匹配; 单掺; 染料激光; 氙灯
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Introduction

Blue-green region lasers have potential applications in medicine, high brightness display, undersea applications, high density data storage and so on. Self-frequency-doubling (SFD) crystal can be used to realize the compactness and miniaturization of this kind of laser. One of the famous SFD crystals, NYAB, has large nonlinear coefficient, but its difficult growth with large size and homogeneity problem limits its further application and development[1,2].

Nd:$Ca_4GdO(BO_3)_3$(Nd:GdCOB) is a new SFD crystal. It belongs to monoclinic biaxial crystal system. Its cell parameters are $a = 0.8095(7)$nm, $b = 1.60018(6)$nm, $c = 0.3558(8)$nm, $\beta = 101.26°$. The transmission spectrum (350nm ~ 2700nm) of Nd:GdCOB crystal is little narrower than that of BBO crystal (200nm ~ 2600nm); its effective nonlinear coefficient is about 1.0pm/V, lower than BBO (2pm/V), higher than LBO (0.82pm/V) and equivalent to NYAB. Nd:GdCOB crystal has the advantages of high damage threshold (up to 1GW/cm^2) and easy growth with large size. GdCOB crystal can realize type I phase matching in the spectrum ranges 720nm ~ 1500nm and 840nm ~ 2000nm, including red, green, blue frequency doubling band. Its three primary fluorescence spectrums are: 936nm, 1061nm, 1331nm, and they can be frequency-doubled to 468nm (blue), 530nm (green), 665.5nm (red), respectively[3~6].

Using xenon lamp as pump source, we realize the free run from 1061nm to 530.5nm in SFD Nd:GdCOB crystal and Cr:Nd:GdCOB crystal, respectively. The experimental result shows that the output energy of Cr:Nd:GdCOB crystal is 25% higher than that of Nd:GdCOB crystal. Moreover, using Q-switched pulsed dye laser to pump

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Nd∶GdCOB crystal, we obtained not only SFD green laser output at 530.5nm and its fundamental frequency laser output at 1061nm but also observed SFD red laser output at 665.5nm and its fundamental frequency laser output at 1331nm. This paper reports the pulsed laser characteristics of Nd∶GdCOB crystal and Cr∶Nd∶GdCOB crystal.

1 Laser performance of Nd∶GdCOB crystal and Cr∶Nd∶GdCOB crystal under xenon lamp pumping

1.1 Manufacture of crystal and transmission spectrum

Ø30mm × 40mm Nd∶GdCOB(7% Nd) and Cr∶Nd∶GdCOB(1% Cr, 7% Nd) crystals have been developed by high-frequency heating Czochralski method. The crystals have excellent optical quality with no bubble. By using computer analogue, we obtain the phase matching curve of GdCOB and then know that GdCOB crystal can only realize type Ⅰ phase matching at 1061nm and the optimal phase matching angles are $\theta = 66.8°$, $\Phi = 47.4°$[7,8]. Both

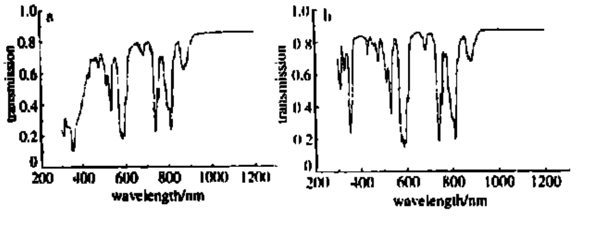

Fig. 1 The transmission spectra of Cr∶Nd∶GdCOB and Nd∶GdCOB
a— Cr∶Nd∶GdCOB b— Nd∶GdCOB

Nd∶GdCOB and Cr∶Nd∶GdCOB crystal samples are cut at type I phase matching and have a dimension of 3mm × 3mm × 7mm. They are not AR-coated at 1061nm and 530.5nm. The transmission spectrums of two crystals measured with HITACHI U-3500 spectrometer at room temperature are shown in Fig.1. Due to the sensitization of Cr^{3+}, when the wavelength is shorter than 500nm, the absorption of Cr∶Nd∶GdCOB crystal is apparently greater than that of Nd∶GdCOB crystal. Between 300nm and 1000nm, the ratio of the normalized absorption areas of two crystals is 1.5∶1, which shows that Cr∶Nd∶GdCOB crystal can absorb more xenon-lamp-pumped light and is more appropriately pumped by a xenon lamp. Meanwhile, Fig. 1 shows that the doping of Cr^{3+} ion haven't increased the absorption of Cr∶Nd∶GdCOB crystal for SFD light at 530.5nm.

1.2 Experiment

In this experiment, the length of resonator is 130mm and the dimension of xenon lamp is Ø5mm × 40mm. The pump light is focused by a 40mm-long, single silver-coated elliptical cylinder reflector. Both the plane-concave cavity and plane-plane cavity are used in the experiment. The output mirror M_2 has high reflection (99.9%) at 1061nm and high transmission (92%) at 530.5nm. For plane-concave cavity, the concave mirror M_1, which has a curvature radius of 250mm, has high reflection at 1061nm (99.8%) and 530.5nm(99.2%), and the crystal is placed near M_2. For plane-plane cavity, the plane mirror M_1 has high reflection at 1061nm(99.8%) and 530.5nm(99.4%), and the crystal is placed in the middle of cavity.

The experimental results show that the conversion efficiency of SFD laser in the plane-plane cavity is only 50% of that in the plane-concave cavity. This is because plane-concave cavity can increase the energy density of the oscillating fundamental-frequency laser. In the experiment, the scientech-362 energy meter is used to measure the energy of output laser, and a split prism is used to separate the fundamental frequency laser from SDF laser.

1.3 Experimental results and discussion

Fig. 2 gives the variation of output green laser energy versus pump energy for Cr∶Nd∶GdCOB

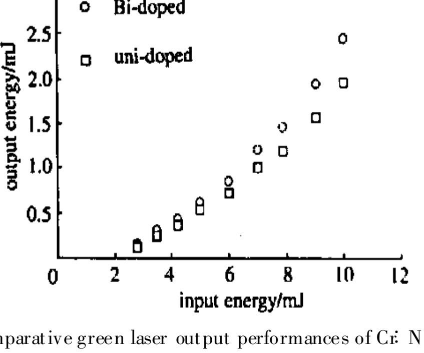

Fig. 2 Comparative green laser output performances of Cr∶Nd∶GdCOB and Nd∶GdCOB crystal under xenon lamp pumping

crystal and Nd∶GdCOB crystal. For Cr∶Nd∶GdCOB crystal, when the pump energy is 10J, the output energy of green laser is 2.46mJ, which corresponds to an increase of 25% in comparison to that of Nd∶GdCOB crystal. The figure shows that the output energies of two crystals have less difference when the pump energy is lower. But with increasing pump energy, the difference of the output energies of two crystals increases gradually. The reason may be that the pulsed xenon lamp mainly emits the continuous spectrum under a high electric current density. With increasing the electric current density, the increase rate of short wavelength is faster than that of long-wavelength. The Cr^{3+} of Cr∶Nd∶GdCOB crystal mainly absorbs the light of short-wavelength, and quickly transfers the absorbed energy to the excited Nd^{3+} ion. For the SFD green laser at 530.5nm, the pump threshold energies of Cr∶Nd∶GdCOB and Nd∶GdCOB are 0.92J and 1.00J, respectively.

2 Laser characteristics of Nd∶GdCOB crystal pumped by dye laser

From Fig. 1b, we know that there are two strong absorption peaks at 595nm and 811nm, which are suitable for dye laser and LD pump, respectively.

2.1 Experiment

In this experiment, a Nd∶GdCOB rod (7% Nd^{3+}, 3mm × 3mm × 10mm) cut at type Ⅰ phase matching is placed in the middle of a 30mm-long plane-plane cavity. Neither of two faces of the crystal has been AR-coated at 1061nm and 530.5nm. The mirror M_1 has high reflection at 1061nm (99.8%) and at 530.5nm (99.4%), and the output mirror M_2 has high reflection (99.8%) at 1061nm and high transmission (92%) at 530.5nm. The pump light from Datachrom-5000 *Q*-switch pulsed dye laser (595.0nm, pulse width 10ns and repetition rate 10Hz) is focused by a cylindrical lens (focal length 50mm) to the Nd∶GdCOB crystal. The dimension of light spot at the crystal is about 1mm × 7mm. The pump threshold energy is 1.2mJ, and the pulse width of the doubling frequency output laser is 9ns. A split prism is required to separate the fundamental frequency light when the doubling frequency output is measured.

2.2 Results and discussion

Fig. 3 shows the variation of output SFD laser energy versus pumping energy when the pumping wavelength λ_p is 595.0nm. When the pumping energy is 17.5mJ, the SFD output energy is 1.35mJ, corresponding to a conversion efficiency of 7.7%. Because the faces of crystal are not AR-coated and the output energy of our dye laser is low, the maximum SFD output energy is 1.35mJ in the experiment. We can expect that if the faces of crystal are coated AR film and the pump energy is increased, a higher conversion efficiency could be obtained. The threshold energy is about 1.2mJ and is lower in comparison with NYAB (2mJ). This is because Nd∶GdCOB crystal has good optical quality and its self-absorption at 530.5nm is only 50% of NYAB crystal's.

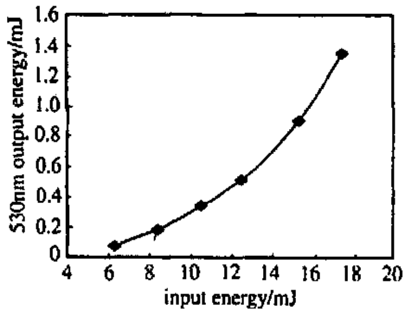

Fig. 3 The output SFD laser energy versus pumping energy (λ_p= 595nm)

The variety of the output 530.5nm laser energy versus pumping wavelength λ_p (591.5nm ~ 601.0nm) is plotted in Fig. 4. From Fig. 4, we can see that there is a narrow peak at 595.0nm and a few small peaks which are well in agreement with the absorption spectrum.

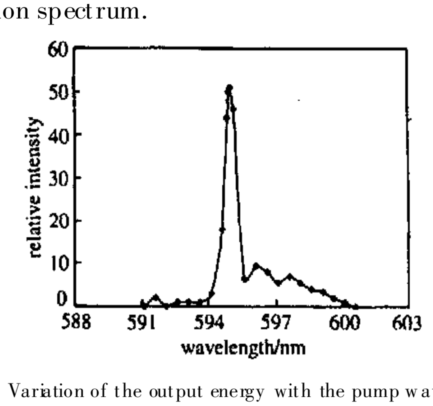

Fig. 4 Variation of the output energy with the pump wavelength

3 1331nm laser performances of Nd∶GdCOB crystal pumped by dye laser

3.1 Experiment

GdCOB is a monoclinic biaxial crystal with significant polarized absorption property. According to the polarized transmission spectrum of Nd:GdCOB, we know that the absorption efficiencies are obviously different at three polarization directions. We have processed two crystal samples with the same dimension of 3mm × 3mm × 8mm. The oscillating laser travels through one sample along x-axis (called x-axis sample) and the other along y-axis (called y-axis sample). The angles between the crystallophysic axes and the corresponding crystallographic axes are: $(x, c) = 12°$, $(z, a) = 23°$, $(y, b) = -180°$. Because of the linear polarization of the pump dye laser, we can obtain three pump modes ($E \parallel x$, $E \parallel y$, $E \parallel z$) by changing the angle between the polarization direction of the pump laser and the crystallophysic axes of the crystal.

In the experiment, Nd:GdCOB crystal is placed in the middle of a 40mm-long plane-plane cavity which is composed of reflective mirrors M_1 and M_2. The M_1 has a high reflectivity of 99.8% at 1331.0nm, and the transmittance of the output mirror M_2 is variable. The 1331.0nm output energy is the highest when the wavelength of dye laser is 595.5nm.

3.2 Experimental results and discussion

By respectively using three output mirrors which have transmittances at 1331nm of T_1(20.4%), T_2(24.5%), T_3(30.3%) respectively, we have make the experiment on the x-axis sample and the y-axis sample. The results are shown in Fig. 5a~ Fig. 5c, respectively. E_p stands for the polarization direction of pumping laser.

From Fig. 5, we know that the output energy of 1331.0nm fundamental frequency laser is highest at $E_p \parallel z$ and lowest at $E_p \parallel y$, which is well matched with the polarized transmission spectrum. The highest output energy at 1331.0nm is obtained when the transmissivity is T_1. For the pump energy of 14mJ, the output energies are 3.39mJ at $E_p \parallel z$, 2.95mJ at $E_p \parallel x$ and 1.85mJ at $E_p \parallel y$. The highest slope conversion efficiency is 24.2%. For the three output mirrors, under three pumping modes $E_p \parallel x$, $E_p \parallel y$ and $E_p \parallel z$, the highest and lowest pump threshold is 10.5mJ and 4.4mJ, respectively. Due to the limited pumping energy, we haven't found the saturated absorption phenomenon in the E_{out}-E_{in} curve. The measured pulse width is 9.2ns.

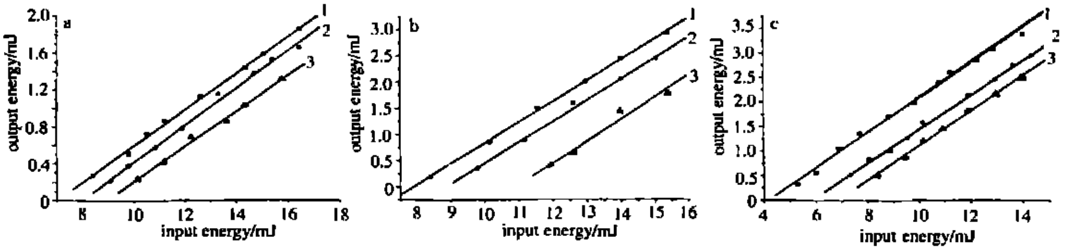

Fig. 5 Variation of the fundamental frequency output energy at 1331.0nm with pump energy
a– $E_p \parallel y$ b– $E_p \parallel x$ c– $E_p \parallel z$ 1– T_1= 20.41% 2– T_2= 24.92% 3– T_3= 30.33%

The SFD red laser output has been observed for both x-axis sample and y-axis sample. The wavelength of red laser measured by WDG5000-1 Grating monochromator is 665.5nm. Because the y-axis is more close to the phase matching direction, higher output of SFD red laser can be observed.

4 Conclusion

Nd:GdCOB crystal has five quite wide absorption bands which are suitable for the xenon lamp pumping. Due to the sensitization of Cr^{3+}, Cr:Nd:GdCOB crystal is more suitable for the xenon lamp pumping and the pump efficiency is increased by 25%. Moreover, Nd:GdCOB crystal is suitable for dye laser and LD pumping. In addition, Nd:GdCOB crystal has 3 strong fluorescence spectrums, therefore, red, green and blue laser can be obtained by SFD. This experiment is in progress in our laboratory.

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的金相组织依赖于激光功率, 当激光功率过高时, 过多的热量使枝晶明显长大, 同时使熔覆层的硬度降低。

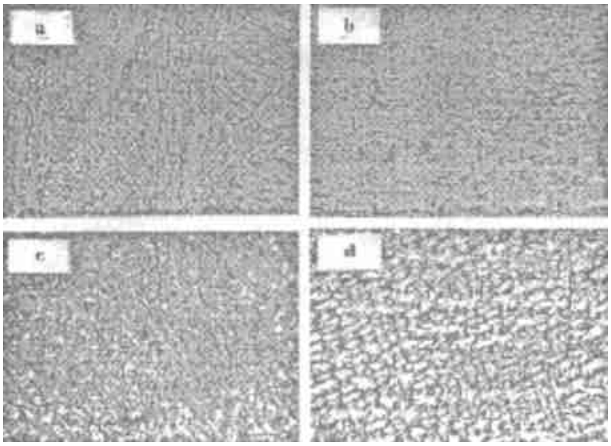

Fig. 2 Microstructure ($400^{\times}$) of Ni/ WC (a) and Ni/ WC incorporated with 0. 1wt% CeO_2(b~ d) cladded under different laser power
a- 1. 8kW b- 1. 5kW c- 2. 0kW d- 2. 3kW

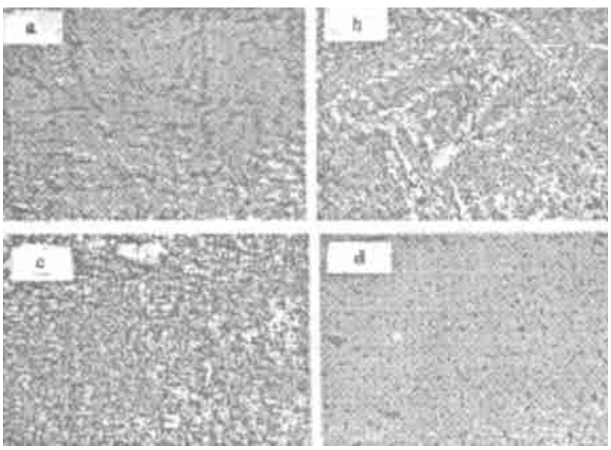

Fig. 3 Effect of the CeO_2 content on the microstructure of the cladding layer (laser power: 1. 8kW)
a- 0. 06wt% b- 0. 1wt% c- 0. 16wt% d- 0. 2wt%

图3a~ 图 3d 是 1. 8kW 激光功率下氧化铈含量分别为 0. 06wt% , 0. 1wt%, 0. 16wt% 和 0. 20wt% 时的熔覆层的金相组织。从图 3 可以看出, 当氧化铈含量较低时, 熔覆层中存在许多较大的块状物或二次晶臂很发达的放射状枝晶。随着氧化铈含量的增加, 晶粒细化的效果愈加明显, 因此会使熔覆层的硬度提高, 这与硬度测试结果相符合。当氧化铈的含量为 0. 20wt%, 熔覆层没有明显的晶粒结构特征, 甚至在冶金结合区也没有明显的枝晶生长。这种组织特征所对应的硬度虽然较低, 但对阻止裂纹产生有显著效果。

3 总 结

在 Ni60A+ 70wt% 镍包碳化钨合金粉末中掺入不同比例的微量 CeO_2, 能使镍基碳化钨金属陶瓷熔覆层中的裂纹大大减少, 使熔覆层的宏观质量得到改善, 使熔覆层的相组织得到细化。

(1) 在同种激光功率条件下, 随 CeO_2 的加入量的增大熔覆层的晶粒尺寸变小。

(2) 对于同样激光功率条件下, 不同 CeO_2 含量的熔覆层, 横截面硬度值不与其加入量成正比, 而是存在一 CeO_2(0. 16wt%) 掺入比例使得熔覆层的横截面硬度值最高。当激光功率为 2. 0kW 时, 掺入 0. 06wt%, 0. 1wt% , 0. 16wt% , 0. 2wt% CeO_2 熔覆层的横截面硬度值分别为 $750HV_{0.3}$, $800HV_{0.3}$, $970HV_{0.3}$, $700HV_{0.3}$。

(3) 随 CeO_2 含量的增加, 熔覆层的裂纹逐渐减少, 当其含量达到 0. 2wt% 时裂纹完全消失。这对于激光溶覆技术的实际应用具有一定意义。

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