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Self-frequency-doubling property of Nd∶GdCOB at 1331.0nm

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Abstract: The phase matching angle of Nd∶GdCOB is calculated. Using Datachroom-5000 pulsed dye laser as pump source, we have realized the self-frequency-doubling laser from 1331.0nm to 665.5nm in Nd∶GdCOB crystal. The experiment results show that the threshold energy for the crystal is 14.2mJ; when the pump energy is 25mJ, the output 665.5nm laser energy is 0.62mJ and the corresponding conversion efficiency is 2.5%.

Keywords: self-frequency-doubling crystal; dye laser; phase matching; red laser

Nd∶GdCOB 晶体 1331.0nm 自倍频特性

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摘要: 计算了 Nd∶GdCOB 晶体的相位匹配角。用 Datachroom-5000 染料脉冲激光作为泵浦源, 在 Nd∶GdCOB 晶体中实现了由 1331.0nm 到 665.5nm 的自倍频激光运转, 阈值能量为 14.2mJ; 当泵浦能量为 25mJ 时, 665.5nm 激光的输出能量为 0.62mJ, 相应的转换效率为 2.5%。

关键词: 自倍频晶体; 染料激光; 相位匹配; 红光激光
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Introduction

Recently, the field of nonlinear optical material has become one of the hot pots of researches[1,2]. Self-frequency-doubling crystal can combine its laser emission of the optically active ions with the second-harmonic-generation property of the host. These properties of this kind of crystal may permit fabrication of compact laser source and make it more widely used in medicine, industry, science research, military engineering and so on. Nd∶$Ca_4GdO(BO_3)_3$, known as Nd∶GdCOB, is a new self-frequency-doubling laser crystal.

GdCOB crystallizes in the monoclinic biaxial crystal system. The values of the unit cell constants are $a = 0.8095(7)$ nm, $b = 1.6018(6)$ nm, $c = 0.3558(8)$ nm and $\beta = 101.26°$. Its transmission wave band is from 350nm to 2700nm and its phase-matching wave band is between 720nm and 1500nm. So it may be anticipated that self-frequency-doubling red, blue and green laser can be generated in it. Many calculations and experiments on the self-frequency-doubling from 1061nm to 530.5nm have been realized[3,4]. But the second-harmonic generation from 1331nm to 655.5nm is rarely reported.

In this paper, the phase matching curve of Nd∶GdCOB crystal at 1331nm, which is calculated by computer analogue, is shown. According to the calculated phase matching angle, we cut two specimens, which have a dimension of 3mm × 3mm × 8mm. Using Datachroom-5000 pulsed dye laser as pump source, we have realized the self-frequency-doubling red laser from 1331.0nm to 665.5nm in Nd∶GdCOB. The experiment results are well in agreement with the theory.

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1 Calculation of the optimal phase matching angle at 1331.0nm

GdCOB is a negative biaxial crystal. For biaxial crystal, the curved-surface of refractive index is a double-shelly guartic curved surface with rotational symmetry. Unlike the simple solution of uniaxial crystal, the phase matching curve of biaxial crystal is calculated only by computer analogue.

Defining $n_{\omega}(n_1)$, $n_{2\omega}(n_2)$ as the refractive indexes of the fundamental-frequency wave and the second-harmonic wave, according to the curved-surface equation of refractive index, we can give the corresponding indexes $n''(\omega)$, $n'(\omega)$ of fast-light and slow-light in the wave-vector direction:

$$n''(\omega) = \sqrt{2}/\sqrt{-B+\sqrt{B-4C}} \tag{1}$$

$$n'(\omega) = \sqrt{2}/\sqrt{-B-\sqrt{B-4C}} \tag{2}$$

where

$$B = -\sin^2\theta\cos^2\varphi(b+c) - \sin^2\theta\sin^2\varphi(a+c) - \cos^2\theta(a+b) \tag{3}$$

$$C = \sin^2\theta\cos^2\varphi(bc) + \sin^2\theta\sin^2\varphi(ac) + \cos^2\theta(ab) \tag{4}$$

$$a = n_x^{-2},\ b = n_y^{-2},\ c = n_z^{-2} \tag{5}$$

here, n_x, n_y, n_z are the main refractive indexes of biaxial crystal, B and C are the function of n_x, n_y, n_z and wavelength.

For type Ⅰ phase matching, $n_1' = n_2''$ (6)

while for type Ⅱ phase matching,

$$(n_1' + n_2'')/2 = n_2'' \tag{7}$$

According to the dispersive equation, i.e. the relation among n_x, n_y, n_z, and wavelength, the main refractive indexes of any wavelength, n_x, n_y, n_z, then B, C, can be found[5,6]. Using computer analogue, according to equation(6) and equation(7) respectively, we obtain the type Ⅰ and type Ⅱ phase matching curves of GdCOB crystal at 1331.0nm in the first quadrant.

Table 1 shows the angle range of GdCOB crystal in which the phase-matching can be realized. But in actual application, we need to consider not only the phase matching but also the size of effective nonlinear optical coefficient. We define the θ and φ, at which d_{eff} is a very large quantity, as the optimal phase matching direction. The type Ⅰ and type Ⅱ phase matching direction (θ, φ) of GdCOB crystal are showed in table 2.

Table 1 The phase matching angle range of GdCOB crystal

matching type	first quadrant		second quadrant	
	θ	φ	θ	φ
type Ⅰ	32°~90°	0°~34.8°	45°~90°	154°~180°
type Ⅱ	45°~90°	66°~90°	25°~90°	136°~180°

Table 2 The optimal phase matching direction of GdCOB crystal

matching type	first quadrant			second quadrant		
	θ	φ	d_{eff} (pm·V^{-1})	θ	φ	d_{eff} (pm·V^{-1})
type Ⅰ	65°	34.6°	0.463	66.5°	145.5°	0.642
tyep Ⅱ	82.5°	66.2°	0.254	90°	114°	0.242

From table 2, we know that the type Ⅰ phase matching effective nonlinear coefficients in the first and second quadrant are 0.463pm/V and 0.642pm/V respectively, which are larger than their corresponding type Ⅱ phase matching effective nonlinear coefficients, 0.254pm/V and 0.242pm/V respectively. This is why type Ⅰ phase matching is used more often than type Ⅱ phase matching in this kind of crystal.

2 Experiment

2.1 Manufacture of self-frequency-doubling crystal specimen

Nd∶GdCOB (7% Nd) crystal used in the experiment, which was developed by high-frequency-heating Czochrakski method, has a dimension of Ø25mm × 40mm, and has homogeneous transparency, good optical quality and no bubble impurity. Two crystal specimens are cut at type Ⅰ phase matching: for specimen 1, θ= 66.5°, φ= 145.5°(the second quadrant); for specimen 2, θ= 65°, φ= 34.6°(the first quadrant). Using plane $(20\bar{1})$, (401) and (010) as plane of reference, the respective angles of specimen 1 are 147.8°, 103.5° and 121.3°, while the respective angles of specimen 2 are 56°, 124.6° and 121°. Both of the specimens, having a dimension of 3mm × 3mm × 8mm, were not AR-coated on two laser-transmission faces and were not polished on four side faces.

2.2 Experimental setup

The experimental setup is shown in Fig.1. Nd∶

GdCOB rode is situated in a 4.8cm long plane-plane cavity and pumped by Datchroom-5000 tunable pulsed dye laser with a pulse width of 10ns and a repeat rate of 10Hz. The pump light is focused by a cylinder len with a focal length of 10cm. The dimension of the focal spot is about 1mm × 7mm. The rear mirror M_1 has high reflections at 1331.0nm and 665.5nm, which are 99.8% and 99.5% respectively. The output mirror M_2 has a high reflection (99.8%) at 1331.0nm and a high transmission (96.2%) at 665.5nm. When the wavelength of the pump laser is 595.0nm and the pump energy is larger than 14.2mJ, the first harmonic oscillation generates in the plane-plane cavity and the self-frequency-doubling red laser emits from the output mirror. Because of the higher energy density of oscillating 1331.0nm laser in the cavity, the output 665.5nm laser from M_2 contains some 1331.0nm laser. A filter, which has a high reflection at 1331.0nm and a high transmission at 665.5nm, is used to separate 1331.0nm laser from 665.5nm laser. The EPM-1000 energy meter is used to measure the output energy of 665.5nm laser.

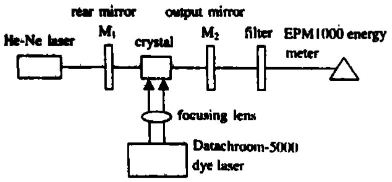

Fig.1 The experimental setup

2.3 Experimental results and discussion

Fig.2 shows the transmission spectrum curve of Nd∶GdCOB crystal, which was measured with EPM-1000 energy meter. When the pump wavelength was tuned to 595.0nm, the varieties of the output 665.0nm laser energy of specimen 1 vs pump energy is plotted in Fig.3 while the output 665.5nm laser energy of specimen 2 is too small to be measured.

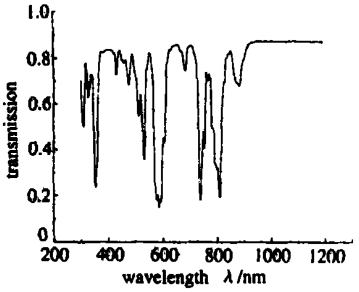

Fig.2 The transmission spectrum of Nd∶GdCOB

From Fig.2, we know that Nd∶GdCOB crystal has five absorption bands, and the narrow band centered at 595.0nm has the largest absorption, and the band centered at 812nm also has a large absorption. So we can conclude that Nd∶GdCOB crystal is very suitable to be pumped by tunable dye laser and also can be pumped by laser diode. When the pump wavelength is 595.0nm, the threshold pump energy of crystal specimen 1 is 14.2mJ. Fig.3 shows that the increase of the output energy of 665.5nm laser is small at the beginning and then become larger and larger when the pump energy increases. This is because that $E_{\mathrm{out}}^{2\omega}$ is in direct proportion to E_{in}.

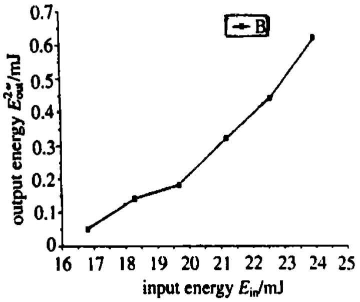

Fig.3 Variation of $E_{\mathrm{out}}^{2\omega}$ with E_{in} for 665.5nm (specimen 1)

Using WDG500-1 grating monochromator to measure the wavelength, we know that the self-frequency-doubling laser wavelength of Nd∶GdCOB is 665.5nm, and then the corresponding fundamental wavelength is 1331.0nm.

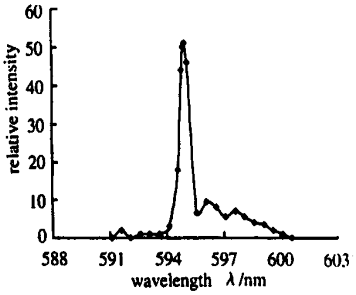

Fig.4 Variation of relative intensity with pump wavelength

Fig.4 shows the variation curve of the relative intensity when the pump wavelength changes from 591.5nm to 601.0nm. We notice that there is a maximum peak at 595.0nm, the width of which is very small. The left of the maximum has one little peak and the right has two little peaks. These results are consistent with the absorption curve of the crystal.

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续表

双波长补偿法	精度较高, 能够同时补偿光强变化及机械扰动的影响	结构复杂, 不适于远程测量
神经网络法	可进行光强补偿, 改善线性, 并且无须额外的硬件, 应用灵活	实时性不强, 精度不很高

强度型光纤传感补偿技术是提高这类传感器精度和稳定性的关键, 其研究仍然比较活跃, 并呈现出许多新特点, 如: (1) 补偿结构与光纤强度传感结构的一体化使得其结构变得紧凑, 受外界干扰更少; (2) 高精度、高稳定性、能同时实现对多种外界干扰的补偿方法是目前乃至今后的研究重点; (3) 采用神经网络的补偿法是一种不增加硬件成本、不引入新的干扰因素的软件补偿方法, 并有望通过设计优化的网络来实现其它补偿方法无法实现的功能。

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In both of the specimens, the self-frequency-doubling laser can be observed. But because of the limitation of the output energy, the variety of $E_{\mathrm{out}}^{2\omega}$ of specimen 2 vs E_{in} can not be plotted, while that of $E_{\mathrm{out}}^{2\omega}$ of specimen 1 vs E_{in} can. According to theoretical calculation, the type Ⅰ phase matching effective nonlinear coefficients of GdCOB crystal in the first and second quadrant are 0.463pm/V and 0.642pm/V respectively. That is to say, the effective nonlinear coefficient of specimen 1 (the second quadrant) are much larger than that of specimen 2 (the first quadrant). Then the frequency-doubling efficiency of specimen 1 is much larger than that of specimen 2. So the experimental results prove the rightness of theoretical calculation.

3 Conclusion

According to nonlinear theory, the phase matching angles of Nd: GdCOB crystal at 1331.0nm in the first quadrant and the second quadrant are calculated. Two crystal specimens are cut at two optimal phase matching angle respectively. When using 595.0nm dye laser as pump source, the threshold energy of specimen 1 is 14.2mJ; the output 665.5nm laser is 0.62mJ; the corresponding conversion efficiency is 2.5%. Although self-frequency-doubling red laser of specimen 2 can be observed, its output energy is too small to be measured. These experimental results are well consistent with theoretical calculation. If the pump energy is increased, and the two faces of crystal are AR-coated at 1331.0nm and 665.5nm, we predicate that the threshold pump energy can be decreased and the conversion efficiency of self-frequency-doubling laser can be increased. This work is in progress in our group.

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