A novel orthogonally linearly polarized Nd:YVO_4 laser*

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We presented a novel orthogonally linearly polarized Nd:YVO_4 laser. Two pieces of a-cut grown-together composite YVO_4/Nd:YVO_4 crystals were placed in the resonant cavity with the c-axis of the two crystals orthogonally. The polarization and power performance of the orthogonally polarized laser were investigated. A 26.2-W orthogonally linearly polarized laser was obtained. The power ratio between the two orthogonally polarized lasers was varied with the pump power caused by the polarized mode coupling. The longitudinal modes competition and the corresponding variable optical beats were also observed from the orthogonally polarized laser. We also adjusted the crystals with their c-axis parallele to each other, and a 40.7-W linearly polarized TEM_{00} laser was obtained, and the beam quality factors were $M_x^2 = 1.37$ and $M_y^2 = 1.25$.

Keywords: orthogonally linearly polarized laser, composite Nd:YVO_4, optical beat frequency
PACC: 4225J, 4260D

1. Introduction

The orthogonally polarized lasers are new attractive devices for various applications, especially in precision measurement, such as the precision measuring of length, displacement, angle, velocity, pressure, magnetic field, and so on.[1−5] The orthogonally polarized laser also can be used for scientific research such as using for lasing cooling of atoms.[6] There are two traditional kinds of orthogonally polarized laser, the Zeeman dual-frequency laser[7] and the four-frequency ring laser.[8] In recent years, Zhang *et al.* reported a new kind of orthogonally polarized laser, in which an additional birefringence element was inserted into the resonant cavity which leads to the orthogonally polarized laser output.[1,9−12] The birefringence element can be obtained by the natural birefringence of the element, or using the elastic-photo effect or electric-photo effect of the element to obtain the performance of birefringence.[13] The He–Ne orthogonally polarized lasers[1] and the Nd:YAG orthogonally polarized lasers[12,14,15] based on this principle have been reported. All the orthogonally polarized lasers mentioned above all need additional element to achieve orthogonally polarization, which makes the system complex, and the output powers of these lasers are always relatively low.

The Nd^{3+}-doped yttrium orthovanadate (Nd:YVO_4) was known for a long time as a material with low threshold and high efficiency.[16] The optical properties of Nd:YVO_4 are listed in Table 1.[17−20] With the emergence of diode pumping, Nd:YVO_4 has become an important solid-state laser material because it has very attractive features, such as a large stimulated emission cross section and a high absorption of the pump wavelength. Nd:YVO_4 is also a natural birefringence crystal. The stimulated absorption cross section and the stimulated emission cross section along c-axis are as large as σ_{12} =60×10^{-19} cm^2 and σ_{21} =27×10^{-19} cm^2, which are almost five- and four-times larger than those of the a-axis respectively. Therefore, since the gain of the o-light (or named σ-polarization) is much lower than that of e-light (or named π-polarization) and the o-light cannot oscillate when the Nd:YVO_4 was pumped at 808 nm ($^4I_{9/2} \rightarrow {}^4F_{5/2}$) and lasing at 1064 nm ($^4F_{3/2} \rightarrow {}^4I_{11/2}$), and the output laser was linearly polarized e-light.

In this paper, we use two pieces of grown-together composite a-cut YVO_4/Nd:YVO_4 crystals as the gain medium, and keep the c-axis of the two crystals orthogonally, and each composite crystal is end-pumped with fibre-coupled laser diode. Since the natural birefringence, the output laser for each crystal is π-

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polarized, then the orthogonally linearly polarized laser can be obtained. This novel high power orthogonally linearly polarized Nd:YVO_4 laser has the merit of without any additional elements to achieve orthogonal polarization, which decrease the complexity of the laser system. To the best of our knowledge, this is the first report of this kind of orthogonally linearly polarized laser. We will investigate the polarization and power performance of the orthogonally linearly polarized laser. The polarized mode coupling and longitudinal modes competition both are observed. A 26.2-W orthogonally polarized laser is obtained in continuous wave (CW) operation. We can also adjust the crystals to keep their c-axis parallele, and obtain a 40.7-W linearly polarized TEM_{00} laser with the beam quality factors measured as $M_x^2 = 1.37$ and $M_y^2 = 1.25$ respectively.

Table 1. Optical properties of Nd:YVO_4 for 1% Nd doping concentration.[17−20]

parameters	unit	value
pump wavelength $\lambda_{\rm p}$	nm	808
laser wavelength $\lambda_{\rm l}$	nm	1064
stimulated absorption cross section σ_{12}	10^{-19} cm^2	60.1(π), 12.0(σ)
stimulated emission cross section σ_{21}	10^{-19} cm^2	27(π), 7(σ)
fluorescence lifetime $\tau_{\rm f}$	μs	90
gain linewidth $\Delta\lambda_{\rm l}$ (FWHM)	nm	0.51
peak absorption coefficient $\alpha_{\rm p}$	cm^{-1}	31.4(π), 9.2(σ)
absorption bandwidth $\Delta\lambda_{\rm p}$	nm	15.7
reflective index n	unit	1.958(a), 2.168(c)

2. Experimental setup

The experimental setup of the orthogonally linearly polarized Nd:YVO_4 laser is shown schematically in Fig. 1. The a-cut composite YVO_4/Nd:YVO_4 crystals were used as the gain medium, which was supplied by the Beijing KE-GANG Electro-Optics Co. Ltd. The composite crystal was a grown together YVO_4–Nd:YVO_4 crystal, the undoped YVO_4 cap with cross section of 3×3 mm^2 and 2-mm length, and the 0.3 at% Nd:YVO_4 crystal with the dimension of 3×3×8 mm^3. Both end faces of the composite crystal were AR coated at 1064 nm, and the end face of the undoped YVO_4 cap was also dichroic AR coated at 808 nm. We use the composite crystal and low doping concentration of 0.3 at% Nd:YVO_4 in order to achieve a relatively uniform absorption and reduce the thermal gradient and the mechanical stress to prevent thermal fracture and serious thermal lensing effect. In our experiment, two pieces of a-cut composite crystals of this kind were used, and the c-axis of one crystal was perpendicular to the optical platform, which is defined as the s-direction, and the c-axis of the other crystal is parallel to the optical platform and perpendicular to the p-direction, which is defined as the p-direction. The crystals were wrapped with indium foil and placed in copper heat sinks using water-cooling with 13 °C cooling water.

The fibre-coupled laser diode module of Jenoptik JOLD-45-CPXF-1L was used as the pump source. The coupling fibre is a 400-μm core diameter fibre with numerical aperture of 0.22. An adjustable lens group was used to image the pump mode from the fibre onto the Nd:YVO_4 crystal, and by adjusting the lens group, the radius of the pump waist spot in the crystal can be adjusted to match the laser mode. In the experiment, the radius of waist spot of the pump mode was controlled at about 0.4 mm ∼ 0.45 mm. The temperature of the laser diode was controlled by the thermoelectric cooling module (TECM), and the centre wavelength of the laser diode could be temperature-tuned by adjusting the temperature of the LD with TECM. The diode module was achieved with the wavelength tuning coefficient of about 0.3 nm/°C as measured, and the central wavelength of the diode was controlled at 808.6 nm to achieve the peak absorption while the temperature of the LD was controlled at 23.5 °C. The two pumping-coupling modules were gained with the identical configuration. The dichroic mirrors were AR coated at 808 nm and HR coated at 1064 nm for lasers at the incidence angle of 45° with the transmissivity more than 98% and reflectivity higher than 99.9% respectively. A planar–planar resonator was used, and the output coupler (OC) has the transmissivity of 60%. The resonant cavity has the cavity lengths of $L_{\rm L} = 15$ cm and $L_{\rm R} = 20$ cm as shown in Fig. 1.

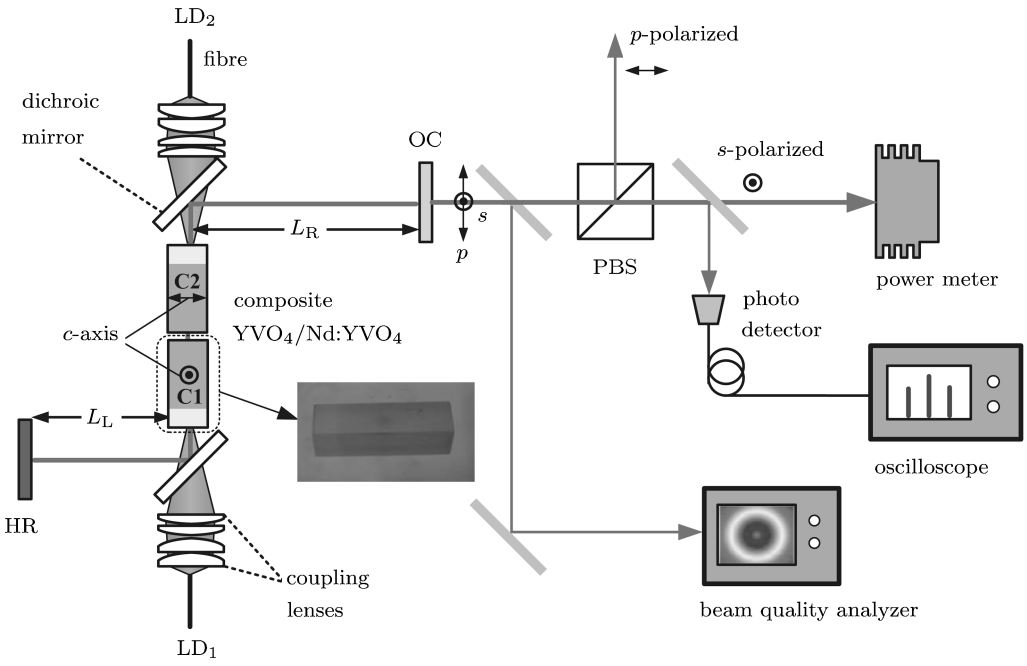


Fig. 1. The experimental setup of the orthogonally linearly polarized Nd:YVO_4 laser.

3. Experimental results and discussions

A polarization beam splitter (PBS) was used as the polarization analyzer, and an OPHIR-30(150)A-LP1-DIF power meter was used to measured the laser power. The initial direction of the light transmitting axis of the PBS was parallel to the s-direction, and the rotation angle of the PBS θ was defined as the rotation angle of the light transmitting axis of the PBS relative to the s-direction. When the crystals were pumped only by LD1, the pump power was absorbed by the crystal C1. Since the c-axis of C1 was parallel to s-direction, therefore, the polarization direction of the output laser was also parallel to s-direction for the very larger stimulated emission cross section of π-polarization (along c-axis) than that of σ-polarization (along a-axis). When the crystals were pumped only by LD2, the polarization direction of the output laser was paralleled to p-direction. Figure 2 shows the measured and calculated results of the transmitted light intensity varying with θ when the crystals were pumped only by LD1 or only pumped by LD2, from which we can see that when the crystals were pumped by LD1, the measured transmitted light intensity I_t varying with θ can be fitted well by the Malus' law

$$I_t = I_s \cos^2(\theta) \tag{1}$$

and the angle difference $\Delta\theta$ of the light transmitting axis direction when the crystals were pumped by LD1 and by LD2 was $\pi/2$, i.e, when the crystals were pumped by LD2, the measured transmitted light intensity varying with θ was fitted well by

$$I_t = I_p \cos^2\left(\theta - \frac{\pi}{2}\right), \tag{2}$$

which means that the polarization directions of the output were orthogonal when the crystals were only pumped by LD1 or only pumped by LD2 respectively.

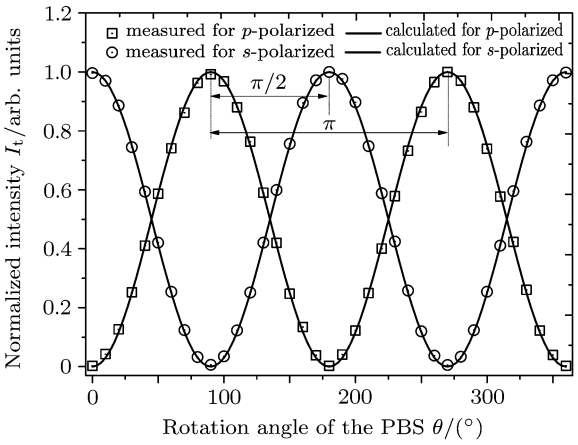


Fig. 2. The measured transmitted light intensity I_t compared with that calculated for s- and p-polarized laser varying with the rotation angle of PBS θ respectively.

When the crystals were both pumped by LD1 and LD2, as shown in Fig. 3, the measured transmitted

light intensity of the output laser varying with θ can be well fitted by the following expression

$$I_{\rm t} = I_s \cos^2(\theta) + I_p \cos^2\left(\theta - \frac{\pi}{2}\right). \quad (3)$$

We rotated the PBS to obtain the highest power output of p-polarization, and then inserted a quarter wave plate and rotated it, and the light extinction was not observed. This means that the output laser is orthogonally linearly polarized laser but not elliptically polarized laser. The power ratio P_p/P_s between the orthogonally polarized output of s-polarization ($P_{\rm s}$) and p-polarization (P_p) is varied when the pump power is increased. Figure 4 shows the total output power and the power ratio P_s/P_p varying with the pump power.

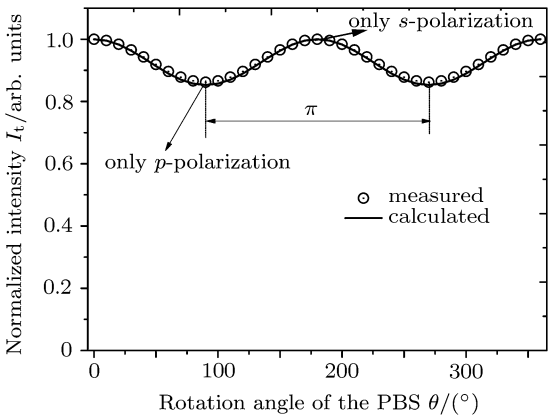


Fig. 3. The measured transmitted light intensity $I_{\rm t}$ compared with that calculated for the orthogonally linearly polarized laser varying with the rotation angle of PBS θ.

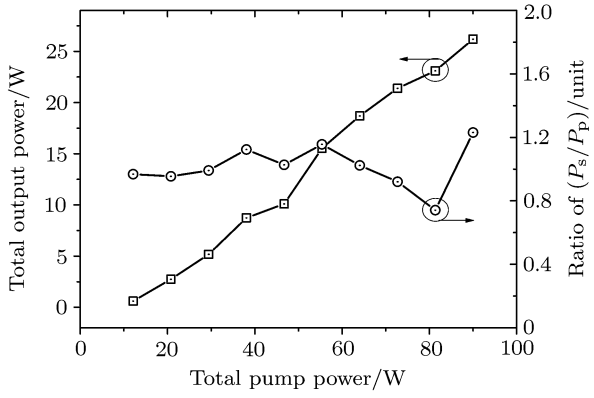


Fig. 4. The total output power and the power ratio between the s-polarization and p-polarization varying with the pump power for the orthogonally linearly polarized laser.

From Fig. 4 we can see that the total output power is increased when the pump power increases. When the total pump power is less than 30 W, the power ratio P_s/P_p is about 1, which induces $I_{\rm t} = 1$, and increasing the pump power to a higher level which corresponds to a higher gain, the polarization mode coupling occurs,[21,22] and the ratio P_s/P_p is deviated from 1. The power ratio P_s/P_p can be easily adjusted by changing the pump power of LD1 or LD2. The highest 26.2-W orthogonally linearly polarized laser is obtained with the power ratio of $P_s/P_p = 1.2$.

The optical beat frequency was observed for the s- (or p-) polarization of the orthogonally linearly polarized laser measured using a high-speed silicon photoelectric detector and an Agilent Infinium oscilloscope with 1.5-GHz bandwidth. The optical beat frequency was caused by the frequency pulling and multi-longitudinal modes competition. In our experiment, the longitudinal mode spacing of the laser can be calculated as

$$\Delta\lambda = \frac{\lambda^2}{2L^*} \approx 1.4 \times 10^{-3} \text{ nm}, \quad (4)$$

where $\lambda = 1064$ nm is the wavelength of the laser, $L^* = L_{\rm L} + L_{\rm R} + n_c l \approx 40$ cm is the physics cavity length, where l is the length of the composite crystal. The corresponding longitudinal mode frequency spacing is $\Delta\omega = c/(2L^*) \approx 37.5$ MHz, where c is the light velocity in vacuum. Since the gain linewidth $\Delta\lambda_l$ (FWHM) of Nd:YVO_4 is about 0.51 nm which is much wider than the longitudinal mode spacing, therefore, there are many longitudinal modes oscillating and which leads to the frequency pulling and multi-longitudinal modes competition-hoping,[23,24] and then the optical beats with different frequency differences $\Delta\Omega$ will be observed. The patterns of optical beats with different frequency differences $\Delta\Omega$ are shown in Fig. 5.

We also placed the two crystals C1 and C2 with their c-axis parallel to the p-direction, thus, the linear polarized laser can be achieved. The highest 40.7-W CW linear polarized laser was obtained corresponding to the optical–optical efficiency of 45.2% and absorbed–optical efficiency of 54.3% respectively. The beam quality of the linear polarized laser was measured using a Spiricon M2-200s laser beam analyzer, and the beam quality factors M^2 were measured as $M_x^2 = 1.37$ and $M_y^2 = 1.25$ in the horizontal direction and vertical direction, respectively. The beam quality measurement result and spatial form for the linearly polarized $\rm TEM_{00}$ laser at 40.7 W are shown in Fig. 6.

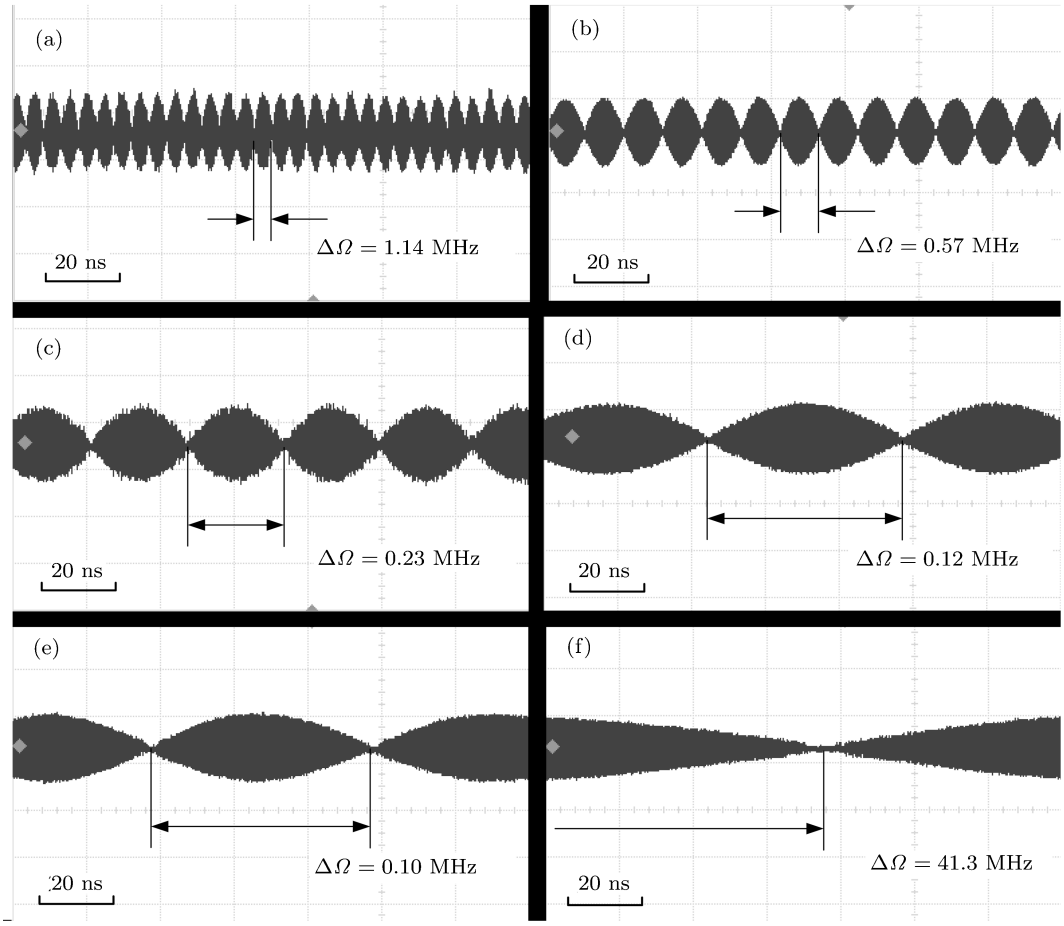


Fig. 5. The patterns of the optical beat with different frequency differences $\Delta\Omega$.

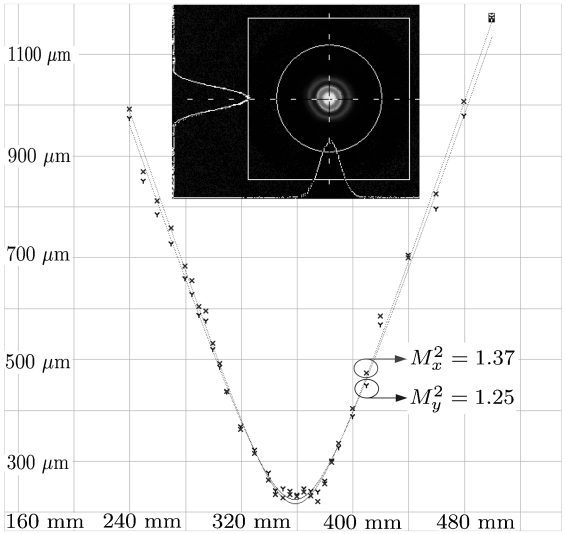


Fig. 6. The beam quality measurement and spatial form for the linearly polarized TEM_{00} laser at 40.7 W.

4. Conclusion

We presented a novel orthogonally linearly polarized Nd:YVO_4 laser. Two pieces of grown-together composite a-cut YVO_4/Nd:YVO_4 crystals were placed in the resonant cavity with their c-axis orthogonally. Because of the natural birefringence and much larger stimulated emission cross section of π-polarization than that of the σ-polarization, the orthogonally linearly polarized laser can be obtained. In the experiment, 26.2-W orthogonally polarized laser was obtained in CW operation. The polarization and power performance of the orthogonally linearly polarized laser were investigated in detail, and the polarized mode coupling and longitudinal modes competition were observed. We also adjusted the crystals to keep their c-axis parallel, and 40.7-W linearly polarized TEM_{00} laser was obtained and the beam quality factors were measured as $M_x^2 = 1.37$ and $M_y^2 = 1.25$. In the next step, we will design the orthogonally linearly polarized Nd:YVO_4 laser with single longitudinal mode using the longitudinal mode selection technique. Meanwhile, the pulsed orthogonally linearly polarized Nd:YVO_4 laser can be configured when the inter-cavity Q-switch is inserted in the laser resonance.

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