OPTOELECTRONICS LETTERS Vol.11 No.1, 1 January 2015

Output characteristics of $Nd:GdVO_4$ crystals laser with dual *c*-axis orthogonal gains end-pumped by two fiber-coupled diode lasers[*]

LIN Hai-feng (林海峰), XIONG Fei-bing (熊飞兵), and HUANG Jian-ping (黄剑平)**

School of Optoelectronic and Communication Engineering, Xiamen University of Technology, Xiamen 361024, China

(Received 15 September 2014; Revised 29 September 2014)

©Tianjin University of Technology and Springer-Verlag Berlin Heidelberg 2015

The output characteristics of neodymium-doped gadolinium vanadate ($Nd:GdVO_4$) crystals laser with dual *c*-axis orthogonal gains end-pumped by two fiber-coupled diode lasers are investigated. With two 1 W semiconductor diode lasers pumping, the output power of TEM_{00} laser is 920 mW, and the optical conversion efficiency is close to 46%. By changing the relative orientations of both $Nd:GdVO_4$ crystals, the polarization characteristics of laser are varied. In particular, by keeping the *c*-axes of two $Nd:GdVO_4$ crystals orthogonal to each other and adjusting two diode pump lasers to operate at the same power level, the completely unpolarized light is obtained.

Document code: A **Article ID:** 1673-1905(2015)01-0030-3

DOI 10.1007/s11801-015-4163-6

Compared with Nd:YAG and $Nd:YVO_4$ crystals, neodymium-doped gadolinium vanadate ($Nd:GdVO_4$) is an attractive and efficient laser material for diode pumping, and has been widely researched in recent years[1-5]. $Nd:GdVO_4$ has a large absorption cross section of 5.2×10^{-19} cm^2, a large emission cross section of 7.6×10^{-19} cm^2 at 1.06 μm and a wide absorption bandwidth at pump wavelength of 808 nm[6-8]. Especially, the thermal conductivity of $GdVO_4$ which is 12.3 W/mK along the 001 direction is twice higher than that of YVO_4, and is even higher than that of YAG[9]. Such unique spectroscopic and thermal properties make $Nd:GdVO_4$ crystal be a promising gain medium substituting for Nd:YAG and $Nd:YVO_4$ in compact all-solid-state lasers.

The all-solid-state laser with high power and high stability has been researched widely. It is well known that the scaling-up of high power is limited by the thermal induced fracture of gain medium. One method of overcoming this limitation is using two similar crystals as gain media in a single laser cavity[10]. Since two crystals share the total pump power, the system is scalable to higher pump power. This approach also leads to higher conversion efficiency because the laser output from two crystals can receive more gain compared with using only one crystal. Further, due to two crystals share the total pump power, induced thermal aberrations and birefringence effects are less in dual-gain systems, which leads to better beam quality[11].

In this paper, we report a compact and highly efficient $Nd:GdVO_4$ crystal laser with dual *c*-axis orthogonal gains in a single cavity. With two 1 W fiber-coupled diode lasers pumping, 920 mW output laser at 1 064 nm is obtained, corresponding to an optical conversion efficiency of 46%. Further, by changing the relative orientations of both $Nd:GdVO_4$ crystals, the polarization characteristics of laser are varied. In particular, by keeping the *c*-axes of both $Nd:GdVO_4$ crystals orthogonal to each other and adjusting two diode pump lasers to operate at the same power level, the completely unpolarized light is obtained.

The schematic diagram of the dual-gain $Nd:GdVO_4$ crystals laser is shown in Fig.1. The pump source consists of two 1 W fiber-coupled diode lasers (manufactured by Coherent company). The wavelengths of the maximum emission at 25 °C for these are 808.7 nm and 809.0 nm, respectively, and the full width at half maximum (FWHM) is 1.2 nm. The fiber tip has a diameter of 100 μm and a numerical aperture of 0.1. We refer to the diode laser for crystal1 (C1) as LD1 and that for crystal2 (C2) as LD2. The pump beam from LD2 is collimated by the plano-convex lens L3 with focal length of 25 mm. Then the beam of LD2 is reflected and focused on C2 with the help of a flat plate mirror (M) kept at 45° to the pump beam direction. When the flat plate mirror is kept at 45° to the propagation direction, it reflects above 99% light at 808 nm and transmits above 90% light at 1 064 nm. The spot sizes of LD1 and LD2 in both $Nd:GdVO_4$ crystals are Φ50 μm. The overall losses by the coupling optics are less than 5%. The resonator consists of two $Nd:GdVO_4$ crystals with size of 3 mm×3 mm×1 mm and Nd^{3+}-doping atom concentration of 3%, and their *c*-axes are orthogonal to each other. The left side of C1 and the

---

[*] This work has been supported by the National Natural Science Foundation of China (No.11104234).

[**] E-mail: hflin@xmut.edu.cn

right side of C2 shown in Fig.1 are coated with antireflection coating at 808 nm (AR at 808 nm) and high-reflection coating at 1 064 nm (HR at 1 064 nm), which act as the resonator mirrors, and the other sides of C1 and C2 are coated with AR at 1 064 nm. The length of compact flat-flat cavity is about 5 mm. C2 could be rotated with respect to C1. The quarter wave plate (QWP) and the polarizer are used to analyze the state of polarization of the output laser beam. The transmitted beam from the polarizer is detected by photodiode (PD) after attenuation.

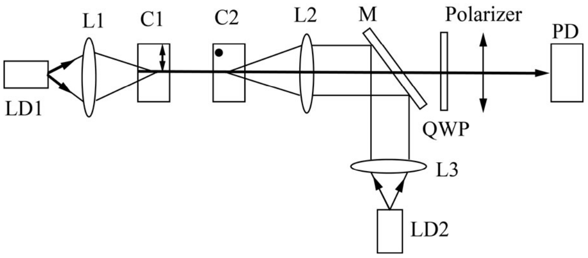

Fig.1 The schematic diagram of the dual-gain Nd:GdVO$_4$ crystals laser

Fig.2 shows the light conversion efficiency curve for the dual-gain laser when only C1 or C2 is pumped. The laser beam from C1 pumped by LD1 (with LD2 off) is designated as laser1, and that from C2 pumped by LD2 (with LD1 off) is designated as laser2. The output from laser1 or laser2 can be measured separately. The absorbed pump power at the threshold is estimated by a linear fitting to the experimental data. The absorbed pump power threshold for laser1 is about 200 mW with a slope efficiency of nearly 44%. And the threshold and slope efficiency of laser2 are the same as those of laser1. The reason is that in this configuration, there are the same laser mode size and intra-cavity losses for laser1 and laser2.

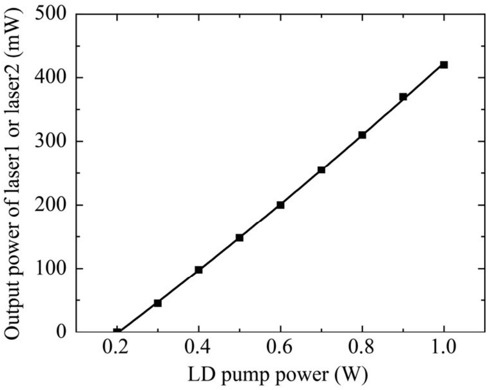

Fig.2 The light conversion efficiency curve for dual-gain laser when only C1 or C2 is pumped

When two gain crystals are pumped at the same time, the light conversion efficiency curves for the Nd:GdVO$_4$ crystal laser are shown in Fig.3. It is shown that the overall slope efficiency is 46% at 1 064 nm with absorbed pump power threshold of 220 mW. For comparison, the sum of the laser output powers from two individual gains is also plotted for the same amount of absorbed pump power as shown in Fig.3. It can be seen from Fig.3 that the output power from the dual orthogonal gain crystals is always higher than the sum of the individual laser powers. The higher extraction efficiency for laser oscillation in our configuration arises because the longitudinal modes in solid-state lasers with birefringent intra-cavity elements are split into two orthogonal polarization modes[12] which are preferentially amplified by crystal C1 or C2. Therefore, the residual gain in one crystal will be extracted by the laser beam from the other crystal. Even if the gain in one of the crystals is kept below the threshold, the increase of output power is still observed. The relative power enhancement factor (G) is defined as

$$G = \Delta P / P_{\mathrm{sum}} , \tag{1}$$

where ΔP is the power enhancement in the dual-gain cavity, and P_{sum} is the sum of the individual laser powers with two crystals pumped separately. The relative power enhancement with respect to the absorbed pump power is shown in the inset of Fig.3.

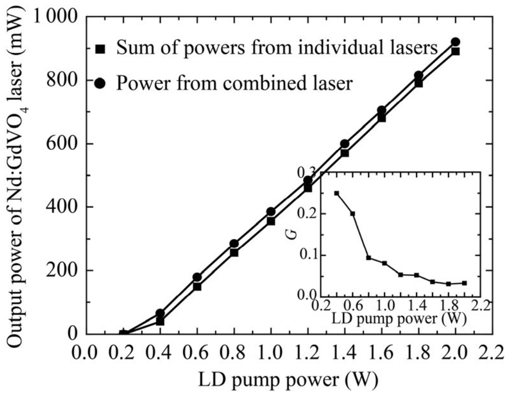

Fig.3 The light conversion efficiency curves for the dual Nd:GdVO$_4$ crystals laser and the sum of the individual powers from laser with crystal1 or crystal2

From the inset of Fig.3, it is clear that relative output power enhancement is 25% at lower absorbed pump power, and it is saturated to a value of less than 10% at the higher absorbed pump power. The maximum power obtained from this laser configuration is 960 mW at the total incident pump power of 2 W.

Polarization characteristics of the output laser beam from this dual-gain laser are analyzed by a QWP and a polarizer. The polarizer has an extinction coefficient of ~10^{-5} in crossed condition. With rotating the polarizer, the maximum and minimum powers of the output laser beam are measured, respectively. The output light beams from laser1 and laser2 are linearly polarized. It is further confirmed by inserting the QWP with its *c* axis at 45° to the *c* axis of the crystals. Both laser beams become circularly polarized after passing through the QWP, which confirms that the output light from the dual-gain laser with only C1 or C2 pumped is orthogonally polarized. With gain in both crystals, the output beam becomes partially polarized. In Fig.4, we show that the degree of polarization for the output laser with the dual gains is varied by changing the output power of laser2. When the power of laser2 is zero, the output beam is linearly polarized. As the power of laser2 is increased, the degree of polarization decreases. In particular, when the power of laser2 is equal to that of laser1, the dual-gain laser is totally depolarized. To confirm that the beam is unpolarized, a QWP is inserted before the polarizer. If the beam is circularly or elliptically polarized, the QWP will transform it into a linearly polarized beam which will show a variation of transmission through the polarizer with rotation across the beam. However, the QWP has no effect on the transmission through the polarizer as it is rotated across the beam, which confirms that the beam from the dual-gain laser is unpolarized when powers of light from laser1 and laser2 are equal. The observed polarization behavior is to be expected because the dual-gain laser is oscillating in orthogonally polarized mutually incoherent modes. Therefore, the resulting polarization direction and the degree of polarization are determined by the relative power of the two modes.

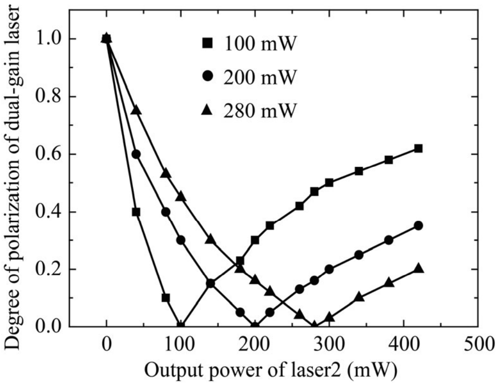

Fig.4 The degree of polarization of the dual-gain laser at different powers of laser1 when the output power of laser2 is varied

Fig.5 shows the degree of polarization of the output laser with rotating the *c* axis of C2. Since Nd:GdVO$_4$ crystal is birefringent crystal, which acts as a polarizer in the intra-cavity, the degree of polarization of output beam is varied with rotating the *c* axis of C2. When the *c* axis of C2 is rotated to 0°, which means that the *c* axis of C2 parallels to that of C1, the output laser is linearly polarized. As both *c* axes of two Nd:GdVO$_4$ crystals are set to be orthogonal to each other, the output beam of dual-gain laser is totally depolarized. When the temperature of dual *c* axis orthogonal Nd:GdVO$_4$ crystals laser is controlled at 25.0±0.1 °C by the Peltier TEC module, and two 1 W diode lasers are used as pump sources, the output power is 960 mW, and the fluctuation is less than 20 mW, which is measured once per minute for an hour. The stability of the laser is less than 3%.

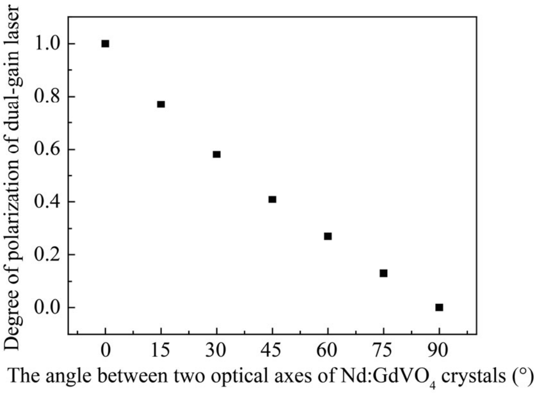

Fig.5 The degree of polarization of the output laser with rotating the *c* axis of C2 when both Nd:GdVO$_4$ crystals are pumped by 1 W diode lasers

In conclusion, the polarization state of the output beam is controlled by changing the relative orientation of both Nd:GdVO$_4$ crystals, and the higher extraction efficiency is obtained in the dual-gain single cavity Nd:GdVO$_4$ laser with two semiconductor diode lasers pumping.

References

[1] F. Tan, F. X.Yu and L. L.Wang, Journal of Russian Laser Research **35**, 295 (2014).

[2] Yufei Ma, Xin Yu, Frank K. Tittel and Xudong Li, Optics Communications **285**, 1911 (2012).

[3] Zuo-han Li, Ji-ying Peng, Yi Zheng, Ye Yang and Jin-hua Kou, Optoelectronics Letters **10**, 423 (2014).

[4] A. Agnesi, A. Guandalini, G. Reali, S. Dell'Acqua and G. Piccinno, Optics Letters **29**, 56 (2004).

[5] Yong-Ji Yu, Xin-Yu Chen, Chao Wang, Chun-Ting Wu, Miao Yu and Guang-Yong Jin, Optics Communications **304**, 39 (2013).

[6] C. Czeranowsky, M. Schmidt, E. Heumann, G. Huber, S. Kutovoi and Y. Zavartsev, Optics Communications **205**, 361 (2002).

[7] P. A. Loiko, K. V. Yumashev, N. V. Kuleshov and A. A. Pavlyuk, Applied Physics B **102**, 117 (2011).

[8] PENG Ji-ying and ZHENG Yi, Journal of Optoelectronics·Laser **24**, 415 (2013). (in Chinese)

[9] Julien Didierjean, Emilie Herault, François Balembois and Patrick Georges, Optics Express **16**, 8995 (2008).

[10] Chen Y. F., Lan Y. P. and Wang S. C., Optics Letters **25**, 1016 (2000).

[11] C. Pfistner, R. Weber, H. P. Weber, S. Merazzi and R. Gruber, IEEE Journal of Quantum Electronics **30**, 1605 (1994).

[12] Sten Helmfrid and Kimio Tatsuno, Journal of Optical Society American B **11**, 436 (1994).