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5.3 W deep-blue light generation by intra-cavity frequency doubling of Nd:GdVO4

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ABSTRACT We report the efficient compacted deep-blue laser at 456 nm generation by intra-cavity frequency doubling of a continuous-wave (cw) laser operation of a diode-pumped $Nd:GdVO_4$ laser on the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition at 912 nm. The different long LiB_3O_5 (LBO) crystals, cut for critical type I phase matching at room temperature, are used for second harmonic generation (shg) of the laser. At an incident pump power of 30 W, up to 5.3 W of cw output power at 456 nm is achieved with 15-mm-long LBO (3.8 W with 10 mm-long LBO). The conversion efficiency is 17.7% from pump diode input to second harmonic wave output.

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1 Introduction

Diode-pumped solid-state lasers in the visible spectral range have applications in the fields of measurement technique, printing and display technology, etc. The diode-pumped quasi-three-level Nd^{3+}-doped laser, which operates on the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition, was first introduced by Fan and coworkers [1, 2] who had realized a Nd:YAG laser at 946 nm. The generation of blue light at 473 nm was demonstrated with intra-cavity second harmonic generation (shg). The highest cw power achieved from such a laser system so far has been 2.8 W at 473 nm [2]. In order to reach wavelengths in the deeper blue (below 460 nm), other host crystals have to be investigated. Among such crystals, $Nd:YVO_4$ is an attractive well known material and an intra-cavity doubled $Nd:YVO_4$ ground-state laser exhibiting 2 W of output power at 457 nm is available commercially [3]. YVO_4 has the tetragonal space group $I4_1$ and which creates polarized transitions. The laser crystal used in our experiments is $Nd:GdVO_4$, which was introduced by Zagumennyi et al. [4] and the same space group as YVO_4. Its advantages with regard to $Nd:YVO_4$ are a broader absorption near 808 nm and a twofold higher than the thermal conductivity of $11.7\,\mathrm{W m^{-1} K^{-1}}$ in $\langle 110 \rangle$ direction [5]. This is very important for quasi-three-level lasers because, first of all, it leads to a smaller temperature gradient and therefore to a smaller thermal lens. Secondly, it decreases the absolute temperature in the laser crystal, so the re-absorption losses due to the thermal population of the lower laser level are reduced. Another reason for using $Nd:GdVO_4$ for solid-state lasers is the accidental degeneration of the upper laser level [6], so the whole inversion contributes to the gain. The laser wavelength of the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition in $Nd:GdVO_4$ (912 nm) is slightly shorter than in $Nd:YVO_4$ (914 nm). The crystal field splitting of $409\,\mathrm{cm^{-1}}$ is about two times smaller than in Nd:YAG ($857\,\mathrm{cm^{-1}}$), so the Boltzmann factor of the lower laser level is 5% at room temperature compared to 0.7% for Nd:YAG and larger cooling condition is required to lower the threshold. On the other hand the effective emission cross-sections are higher than those of Nd:YAG. Diode-pumped $Nd:GdVO_4$ lasers operating at 1.06 and 1.34 μm have already been developed. Also shg to the green (532 nm) and red (670 nm) spectral regions have been demonstrated [7–11]. A blue laser with $Nd:GdVO_4$ as host material has been demonstrated by Schmidt et al. [12] for the first time, the output power was 30 mW. The highest cw power achieved from such a laser system so far has been 840 mW at 456 nm [13]. In this paper we report a $Nd:GdVO_4$ laser with 5.3 W output power at 456 nm, it is the highest to our knowledge.

2 Experimental setup

A schematic of the intra-cavity deep-blue laser is shown in Fig. 1. The laser crystal is a $3 \times 3 \times 5\,\mathrm{mm^3}$, 0.1% Nd^{3+}-doped $GdVO_4$. It is wrapped with indium foil and mounted in the copper heat sink. The pump source is a high-brightness fiber-coupled laser diode from LIMO with 30 W of output power at 808 nm with a 400-μm fiber core diameter and a N.A. of 0.22. The pump light is imaged by two plane-convex lenses ($f = 10$ mm) into the laser crystal. The left side of the laser crystal is looked as the input mirror and highly reflecting for the fundamental wave at 912 nm and highly transmitting at 1064 nm for suppression of the strong four-level transition in Nd^{3+}. The left side of the laser crystal is AR coated at 808 nm and 1064 nm, HR coated at 912 nm, the other side of the laser crystal is AR (anti-reflective) coated at 912 nm. The concave face of M_1 is HR (high reflective) at 912 nm; HT (high transmittive) at 1340 and 456 nm. The radius of the concave face is 50 mm and 200 mm for M_1 and M_2 respectively. L_1 and L_2 are the length of the arms in the cavity. L_1 is about 69 mm,

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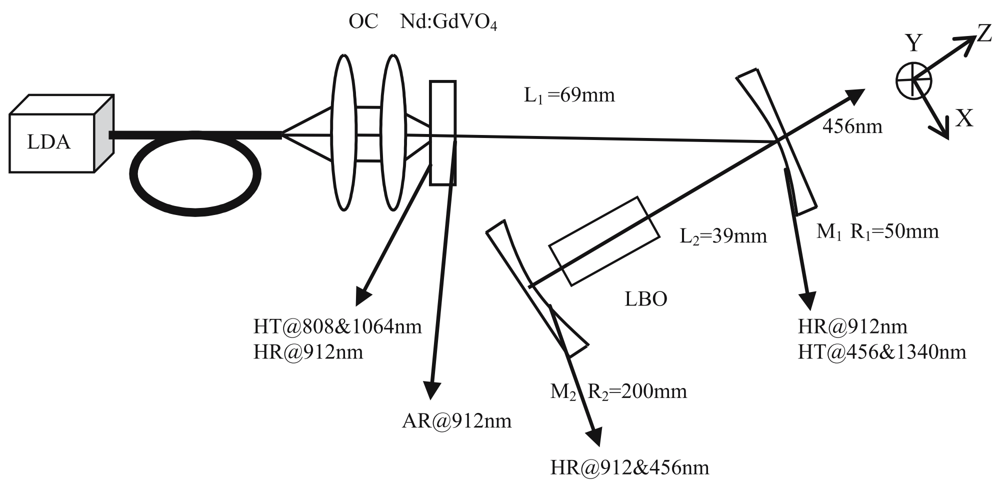

FIGURE 1 Experimental setup of the frequency-doubling laser at 456 nm

L_2 is about 39 mm. The LD, the whole cavity, and the crystal are cooled by thermoelectric cooler (TEC) for an active temperature control with stability of $\pm 0.1\,°C$. LBO is a $2 \times 2 \times 15\,mm^3$ nonlinear crystal ($\theta = 90°$, $\varphi = 21.7°$). Although $KNbO_3$ is the most commonly used nonlinear material for intra-cavity frequency doubling the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ of Nd^{3+}-doped laser mainly because of its high nonlinearity. However, it has some disadvantages such as a very small temperature and spectral acceptance bandwidth, the possibility of domain reversal and photo-refractivity, and the difficulty in producing. LBO is selected as the doubling material in our experiment, due to its small walk-off angle and large spectral and angular acceptance bandwidth. Both facets of the LBO crystal are coated for antireflection at 456 and 912 nm to reduce the reflection losses in the cavity. It is mounted in a copper block, which is also fixed on a TEC for an active temperature control.

The resonator is insensitive towards thermal lens and combines stability and a small focus of 50 μm on the mirror M_2. The laser mode in the laser crystal has to match the pump mode as good as possible to avoid re-absorption losses due to the thermal population of the lower laser level. Therefore different pump focuses have been tested yielding a pump spot radius of 310 μm for the configuration in Fig. 1. The laser crystal absorbed 55% of the pump power at 808 nm.

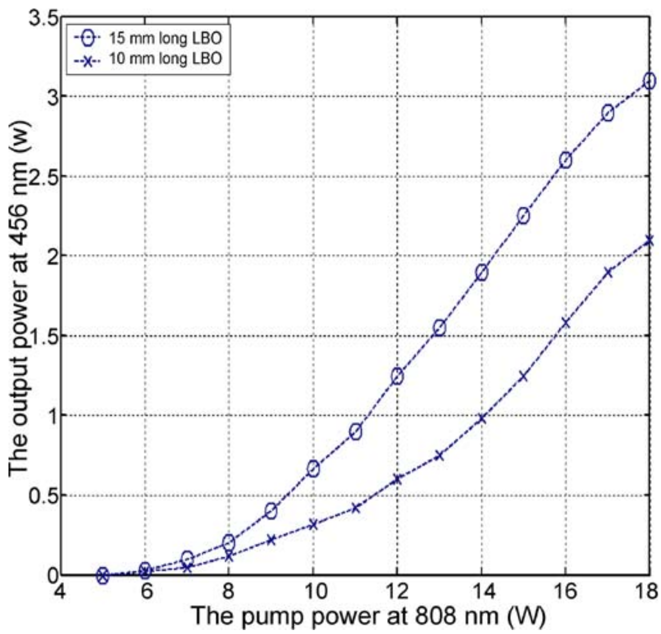

FIGURE 2 The dependence of the output power at 456 nm on the incident pump power

3 Experimental results

The laser output at 912 nm was linear polarized, so it is not necessary to insert a Brewster plate for the frequency doubling. For the shg experiment, two different length LBO crystals are inserted into the cavity close to the end mirror M_2, they are 10 mm and 15 mm long, respectively. The longer one generates higher output power at 456 nm than the shorter one. The dependence of the blue output power on the incident pump power is shown in Fig. 2. The threshold of the blue laser is about 5 W, at the pump power of 30 W, corresponding to an output power of 5.3 W at 456 nm with 15-mm-long LBO (3.8 W with 10-mm-long LBO), light to light conversion efficiency is about 17.7% (12.7% with 10-mm-long LBO). The M^2 factor is used to describe the beam quality, we use the profile analyzer (PHOTON beam profiler) to measure the M^2 factors in the X and Y directions. The result shows that the M^2 factors are about 1.2 and 1.9 in X and Y directions, respectively. The asymmetry of the M^2 factors in the two directions is result from the walk-off between the fundamental wave and the second wave in Y directions of LBO. The X direction is parallel to the paper plane and the Y direction is perpendicular to it, they are shown in Fig. 1. The BIBO frequency doubler also can be used as the frequency doubler, but the quality of the output light is dissatisfying to us. So further experiments are canceled.

We also carry out some stability testing of the deep-blue laser by monitoring the blue output power with power-meter (Coherent). At the same time, we investigate the noise characteristic of the laser in high frequency by digital oscilloscope (Tektronix).The fluctuation of the output power is less than 3% in 2 hours and the chaotic blue-noise in high frequency is very low and shown in Fig. 3a. The low chaotic noise state is stable when the environments without large fluctuations. The chaotic noise of the 456 nm output in this experiment is much lower than the noise we have investigated in Nd:YAG intra-cavity frequency 473 nm laser experiment in the past.

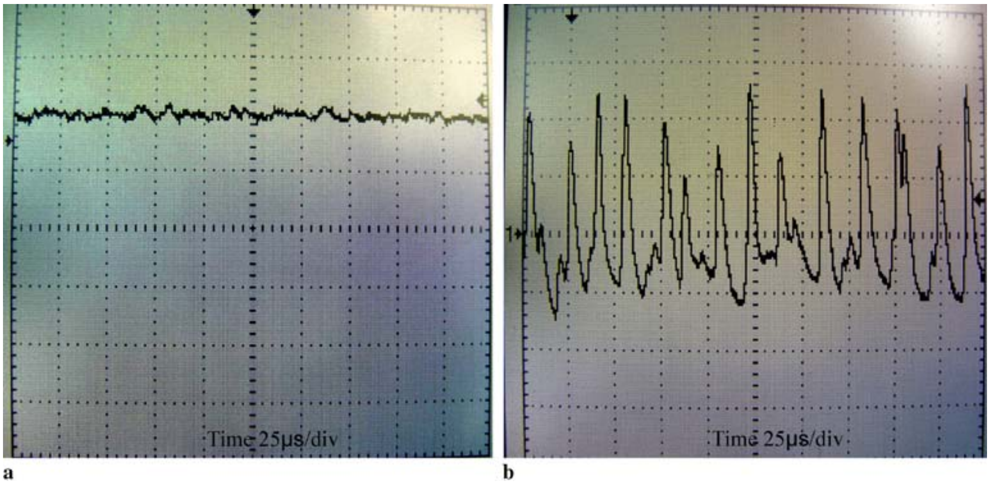

FIGURE 3 Time trace of the output power. (**a**) Chaotic noise of the output measured in this Nd:GdVO$_4$/LBO 456 nm laser experiment setup (**b**) characteristic chaotic noise of Nd:YAG/LBO 473 nm laser in free operation. The *vertical axis* refers to output amplitude (20 mV/div), the *horizontal axis* refers to time (25 μs/div)

The characteristic noise in Nd:YAG 473 nm output is shown in Fig. 3b. As we all known, the essence of the "blue problem" is that chaotic fluctuation of the doubled output power, may exist in such intra-cavity-doubled lasers due to longitudinal-mode coupling and sum frequency generation [14]. The power stability and the chaotic noise of the output are admirable in our experiment. We believe that some physical properties in Nd:GdVO$_4$, such as the larger thermal conductivity superior to Nd:YVO$_4$ and polarized transitions different from Nd:YAG, may make the chaotic noise lower and less obvious than that in intra-cavity Nd:YVO$_4$ and Nd:YAG blue laser. The fact that thermal conductivity of Nd:GdVO$_4$ is larger than that of Nd:YVO$_4$ is attributed to the little effect of the temperature fluctuation of the laser crystal on the population of lower level in the quasi-three-level laser system, and so enhances the stability of the laser output in low frequency investigated by power meter. The polarized transitions of the Nd:GdVO$_4$, unlike in Nd:YAG, is also beneficial for enhancing the stability of the intra-cavity frequency doubling because the frequency doubler of LBO and the laser crystal of Nd:GdVO$_4$ makes a special BF (birefringent filter). LBO looks like a wave plate and Nd:GdVO$_4$ looks like a polarizer.The special BF is able to force the intra-cavity frequency doubling laser to operate only several longitude mode coexisted and is very important to the stable and low chaotic noise output of the blue laser in high frequency investigated by digital oscilloscope [15]. At the same time, we also estimate the effect of the internally reflected blue light at M$_2$ on the noise characteristics. The results indicate that the reflected blue light significantly affects the phase locking, which suppresses the blue problem [16].

4 Summary

An efficient compacted deep-blue diode-pumped laser has been demonstrated by using Nd:GdVO$_4$ and LBO crystals a gain medium and a nonlinear crystal for intra-cavity frequency doubling. A compacted three-mirror folded cavity is employed to enhance the conversion efficiency. At an incident pump power of 30 W, the maximum output power at 456 nm can amount to 5.3 W with the fluctuation less than 3% in 2 hours.

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