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# High-power continuous-wave diode-end-pumped intracavity-frequency-doubled $Nd:GdVO_4$/LBO red laser

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ABSTRACT

A high-power continuous-wave (CW) diode-end-pumped intracavity-frequency-doubled red laser is reported here. The laser consists of a 0.3 at.% $Nd:GdVO_4$ crystal as laser gain medium, a type II non-critical phase-matched (NCPM) LBO crystal or a type I critical phase-matched (CPM) LBO crystal as frequency-doubler, and a three-mirror-folded cavity. At incident pump power of about 41 W, maximum output powers of 3.8 W and 3 W at 671 nm are obtained with corresponding optical-to-optical conversion efficiency of 9.3% and 7.5%, respectively. During half an hour, the instability of the red beam is less than 3% at output of 3 W.



## 1. Introduction

High-power all-solid-state red lasers are very useful laser sources in many applications, such as optical storage, laser color display, medical treatment, laser scan and laser printing. Moreover, they are the perfect candidate of pumping sources of femtosecond kerr-lens mode-locked laser based on Cr:LiSAF, Cr:LiSGAF, and Cr:LiSCAF crystals. In many practical applications, they have eventually become commercially available.

The intracavity frequency doubling of a neodymium-doped laser operating at transitions near 1.3 μm ($^4F_{3/2}$–$^4I_{13/2}$) is a very efficient method to obtain high-power all-solid-state red beams. In the last 10 years, a lot of researches on the all-solid-state intracavity-frequency-doubled red lasers have been reported [1–5]. In these works, the most popular gain mediums were Nd:YAG, $Nd:YVO_4$ and $Nd:GdVO_4$ crystals, due to their good laser properties at around 1.3 μm. And the commonly used frequency-doubler was LBO crystal (type I, critical phase-matched), because of its small walk-off angle and large damage threshold.

Compared with CW operation mode, high-power red beams can be achieved rather easily in the quasi-continuous-wave (QCW) operation mode, due to the higher intracavity power density, which can greatly promote the conversion efficiency of frequency-doubling. Nowadays, high-power QCW all-solid-state red lasers with output power of more than 10 W have been reported several times several years ago [6–8]. In 2006, Peng et al. [9] even successfully scaled the output of QCW all-solid-state intracavity-frequency-doubled diode-side-pumped 659.5-nm Nd:YAG laser up to 28 W.

For the severe thermal problem mainly caused by the low quantum efficiency and low intracavity power density, the developments of all-solid-state red laser operating at CW mode are very slow. With diode-side-pumped configuration, the incident pump power can be increased up to near several hundreds watts, which can make up the objection of low quantum efficiency and intracavity power density more or less. In 1999, Y. Inoue et al. [10] reported a 6.1-W CW intracavity-frequency-doubled diode-side-pumped Nd:YAG laser operating at 659.5 nm. However, these diode-side-pumped red lasers mentioned above all have the own limitations of bad beam qualities, which will greatly affect their applications. In fact, diffraction-limited CW red beams can be easily achieved, if diode-end-pump configuration is used. $Nd:YVO_4$ and $Nd:GdVO_4$ crystals are the most popular gain mediums of diode-end-pumped

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intracavity-frequency-doubled red lasers. The damage thresholds of the two crystals are not very high, and the thermal problems of diode-end-pumped laser systems are more severe than that of diode-side-pumped laser systems. High-power CW red beam can not be obtained easily by just increasing the incident pump power. The pump structure, Nd iron concentration, choice of frequency-doubler and cavity design must be carefully optimized, if high-power CW diode-end-pumped red outputs are wanted. During nearly 10 years researches, the maximum output powers of CW diode-end-pumped red lasers ever reported are about 3 W [11,12]. Nowadays, the maximum output power of CW diode-end-pumped red beam ever generated was reported by Yao et al. [13] in 2005. To obtain high-power CW red beam, she had to develop a two thermal lens diode-double-end-pumped cavity with a long $Nd:YVO_4$ crystal and achieved 3.38 W CW red output. After that, no higher output of CW diode-end-pumped red laser is reported.

In this paper, we demonstrate a more powerful CW diode-end-pumped red laser source. With a low doped concentration $Nd:GdVO_4$ crystal as laser gain medium and a type II NCPM LBO crystal as frequency-doubler, a maximum output power of 3.8 W at 671 nm is obtained with an optical-to-optical conversion efficiency of 9.3%. And during half an hour, the instability of red output is less than 3% at output of 3 W.

## 2. Experimental setup

A simple three-mirror-folded cavity with a diode-end-pumped structure was used in our experiments, as depicted in Fig. 1. The pumping source was a high-power and high-brightness fiber-coupler laser diode, its maximum output power was 100 W. The fiber of this pumping source had a 400-μm fiber-core diameter and its numerical aperture was 0.22. A multi-lens optical coupler was involved in this experiment, it could focus the pump beam into the gain medium with a spot size of 400 μm, and it also had a transmission of larger than 95% at 808 nm.

The gain medium is a very important part of a diode-end-pumped laser system. The thermal conductive of the $Nd:GdVO_4$ crystal is nearly twice of that of $Nd:YVO_4$ crystal, which makes it is more suitable for high-power laser systems. According to Ref. [14], in a high-power diode-pumped solid-state laser system, laser gain mediums with low doped levels have better performance than that with high doped levels. Moreover, output power of as high as 26.3 W at 1.34 μm had been obtained with a 0.3 at.% $Nd:GdVO_4$ crystal in our previous work [15]. Thus, the same $Nd:GdVO_4$ (a cut, $3 \times 3 \times 10$ mm) crystal was used as gain medium in this experiment too. At both of its ends, anti-reflection (AR) coatings at 808 and 1342 nm ($R < 0.2\%$) were coated. To suppress the strong parasitical oscillation at 1063 nm, these coatings also had high transmission (HT, $T > 99\%$) at this transition. For the sake of decreasing thermal effects, the laser crystal was tightly wrapped in a water-cooled copper mount. And to improve the thermal contact between the gain medium and copper mount, an indium foil was used. And the temperature of cooling-water was controlled at 20 ± 0.5 °C.

The resonator consisted of three mirrors, $M_1$, $M_2$ and $M_3$. All of these three mirrors were plane-concave dichroic mirrors, and their radiuses of concave surfaces were 250 mm, 150 mm and 50 mm, respectively. $M_1$ had high reflection at 1342 nm (HR, $R > 99.8\%$) and HT at 808 nm ($T > 95\%$). $M_2$ had HR at 1342 nm ($R > 99.8\%$) and HT at 671 nm ($T > 95\%$), thus the red beam generated can export from this mirror. $M_3$ had HR at both 1342 nm ($R > 99.8\%$) and 671 nm ($R > 99\%$). All these coatings were coated on the concave surfaces of these three mirrors. Moreover, these coatings also had high transmission (HT, $T > 99\%$) at 1063 nm to suppress the strong parasitical oscillation at this wavelength. To decrease the dispersion induced by the folded-mirror $M_2$, the folded-angle should be as small as possible, in our experiment, it was less than 10°.

Two LBO crystals were involved in the experiment as the intracavity-frequency-doubler. Their parameters were type I CPM ($\theta = 86.1°$, $\varphi = 0$) and type II NCPM ($\theta = 0°$, $\varphi = 0°$), respectively. And their dimensions were both $3 \times 3 \times 20$ mm. As we have mentioned above, in the most papers ever reported, type I CPM LBO crystal was used. However, compared with the type I CPM crystal, the type II NCPM crystal has the advantage of zero walk-off angle, though its $d_{eff}$ is a little lower. And this little disadvantage can be made up by a longer crystal length. AR coatings at 1342 nm and 671 nm ($R < 0.2\%$) were coated on the both ends of the LBO crystals. Duo to the low temperature bandwidth of phase matching, a precise active thermoelectric temperature-control system was used. For reliable heat transfer, the LBO crystals were also wrapped with indium foil and mounted in the copper heat sinks. And the precision of the whole temperature-control system can reach ±0.1 °C. In our experiment the temperatures of copper block were controlled at 24.2 °C (type I CPM LBO) and 41.3 °C (type II NCPM LBO), respectively.

## 3. Analysis of cavity

For a solid-state laser, the thermal lensing effect of laser gain medium induced by the pumping radiation greatly affects the stability of laser cavity and the laser beam quality. Especially, in the intracavity-frequency-doubled red laser system, the quantum efficiency from the pump radiation to fundamental wave is rather low, which means that the thermal problem of such laser system is really more severe. Thus, in order to obtain high-power and high beam quality laser output, the parameters of laser cavity must be carefully optimized. There are something should be mentioned before the cavity design procedure. First of all, the whole laser must be running at $TEM_{00}$ mode. According to Ref. [16], if the ratio between the spot sizes of laser beam and pumping beam in the laser gain medium is about 0.8–1:1, then diffraction-limited laser operation will be achieved. In our experiments, the minimum diameter of the pumping radiation in the $Nd:GdVO_4$ crystal was 400 μm. Therefore, the diameter of laser beam in the $Nd:GdVO_4$ crystal

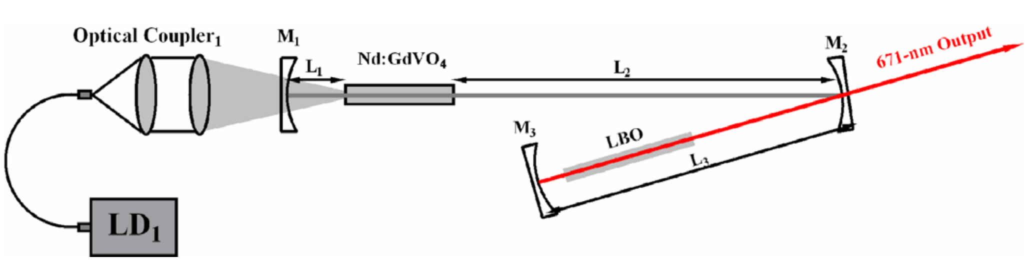


**Fig. 1.** Experimental setup.