# All solid-state passively $Q$-switched frequency-doubled intra-cavity Nd:$GdVO_4$/KTP laser

**Chuanbo Gong (龚传波), Changshui Chen (陈长水), Bian Wu (吴 边), Qingli Zhang (张庆礼), Xianyou Wu (吴先友), and Shaotang Yin (殷绍唐)**

*Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Hefei 230031*

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In this paper, laser frequency-double and passive $Q$-switching are studied. The optimum coupling at end-pump and optimum design of resonator are also investigated. The maximum output power of $TEM_{00}$ is 1.68 W at 1.06-$\mu$m wavelength. Optic-optic conversion efficiency is 48.6%, and the slope efficiency is 56.3%. The maximum output of green light is 0.235 W. The smallest pulse-width of green light is 27.42 ns, optic-optic conversion efficiency of green light is 7%, and beam quality factor $M^2 < 1.2$. Thermal lens effect is discussed.

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Passively $Q$-switched all-solid-state lasers have attracted a great deal of attentions for scientific, industrial, and military applications[1,2]. Compared with actively $Q$-switched devices that required high-voltage switching electronics, passively techniques can reduce the cost and improve the reliability. In recent years, interest has been concentrated on the use of $Cr^{4+}$:YAG as a saturable absorber because of its improved thermo-mechanical properties. $Cr^{4+}$:YAG has large absorption across-section near 1.064 $\mu$m and better stability, especially at high repetition rate[3−7]. The laser crystal is one of the most important components of a LD-pumped solid state laser, and it can determine the efficiency of the laser. The main advantages of Nd:$YVO_4$ are the combination of high absorption cross-section, wide absorption bandwidth, and low intrinsic losses. Both $YVO_4$ and $GdVO_4$crystals belong to the group of oxide compounds crystallizing in a Zircon structure with a tetragonal space group[8]. Compared with Nd:$YVO_4$, Nd:$GdVO_4$ crystals have almost entirely similar lasing properties, and have much higher absorption coefficient and larger absorption cross-section than that of Nd:$YVO_4$. Some experiments have shown that Nd:$GdVO_4$ crystal is excellent LD-pumped solid state laser crystal[9−11]. Nd:$GdVO_4$ crystal is characterized by its unexpected high thermal conductivity along the (110) direction. The conductivity of Nd:$GdVO_4$ along (110) direction is equivalent to that of Nd:YAG, and is almost twice as that of Nd:$YVO_4$, therefore Nd:$GdVO_4$ is also more competitive in high-power laser generation. However, the high-power LD pumped Nd:$GdVO_4$ laser at 1.064 $\mu$m and operation intra-cavity frequency-doubled have been reported.

Figure 1 shows the setup for LD-pumped Nd:$GdVO_4$ laser. The pumping source is a fiber-coupled diode laser with maximum output power of 4 W and a numerical aperture (NA) of 0.11 at center wavelength of 808 nm and room temperature of 18 °C. A optical fiber focusing lens focus the LD laser from the end of the fiber to the end of Nd:$GdVO_4$ crystal. A laser experiment is performed with a 3-mm-thick crystal. The $Nd^{3+}$ ion concentration in the crystal is 3.5 at.-%, and the dimension of the crystal is 5×3×3 $mm^3$. The rear face of the crystal is coated with a high reflection (HR) film at 1.06 $\mu$m, and high transmission (HT) film at 0.808 $\mu$m, and the front face is coated with a HT film at 1.064 $\mu$m. Nd:$GdVO_4$ crystal is cooled by the copper. Two faces of $Cr^{4+}$:YAG are coated HT films at 1.064 $\mu$m. KTP is coated HT films at 1.064 and 0.532 $\mu$m. A 3×3×5 $mm^3$ KTP crystal is cut for II phase matching at 1.064 $\mu$m ($\theta = 90°$, $\phi = 23.4°$). The output mirror is HT at 0.532 $\mu$m and HR at 1.064 $\mu$m, which is a flat mirror.

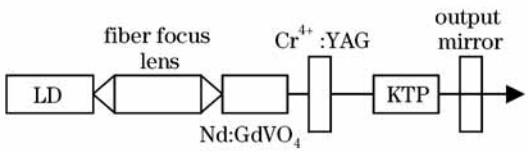


Fig. 1. LD-pumped passively $Q$-switched Nd:$GdVO_4$ laser with frequency-doubled intra-cavity.

High efficiency and high quality $TEM_{00}$ is easily gotten at end pumping because mode of pumping matches with that of $TEM_{00}$ in space. At low pumping power, mode-matching demands that radius of $TEM_{00}$ is less than that of pumping light, and at high pumping power it is opposites[12]. Pumping light is delivered by optical fiber, which is focused to end of Nd:$GdVO_4$ crystal by fiber focusing lens (see Fig. 2). Relationship between object distance and image distance along with magnification is[13]

$$L_2 = \frac{1}{n_0\sqrt{A}} \frac{n_0 L_1 \sqrt{A}\cos(\sqrt{A}z) + \sin(\sqrt{A}z)}{n_0 L_1 \sqrt{A}\sin(\sqrt{A}z) - \cos(\sqrt{A}z)}, \quad (1)$$

$$M = \frac{-1}{n_0 L_1 \sqrt{A}\sin(\sqrt{A}z) - \cos(\sqrt{A}z)}, \quad (2)$$

where $n_0 = 1.60$ is center refractive of optical fiber lens, $A = 0.298$ is focusing constant, $z = 5.22$ mm is length

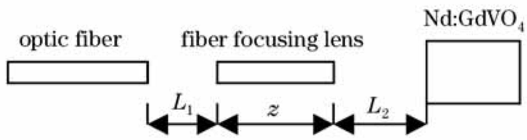


Fig. 2. Relationship of object distance and image distance in optic fiber focusing lens.

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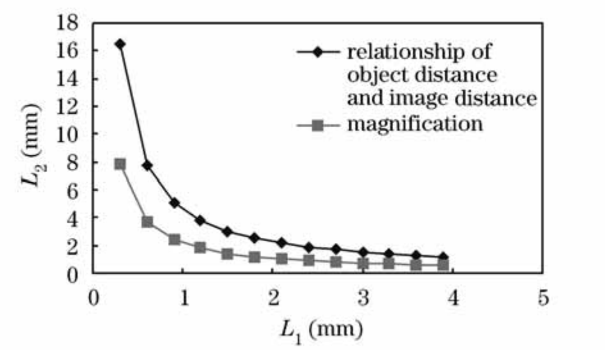


Fig. 3. Relationship of self-focusing lens object distance and image distance along with magnification.

of optical focusing lens, $D = 2$ mm is diameter of optical focusing lens, $L_1$ is object distance of optic fiber focusing lens, $L_2$ is image distance of optic fiber focusing lens, $M$ is magnification.

Figure 3 shows the relationship between self-focusing lens object distance and image distance along with magnification. To ensure high coupling efficiency, object distance is less than 2 cm. In the experiment, radius of pumping light is approximately 300 $\mu$m, which is focused by optical fiber lens.

At high power pumping, thermal effect of laser-crystal affects output power of laser and beam quality of laser. Thermal focusing length is[14]

$$f = \frac{\pi K_{\rm c}\omega_{\rm p}^2}{p_{\rm th}({\rm d}n/{\rm d}t)}\left(\frac{1}{1-\exp(-\alpha l)}\right), \quad (3)$$

where $K_{\rm c} = 11.7\ {\rm m^{-1}K^{-1}}$ is conductivity of Nd:GdVO$_4$, $\omega_{\rm p}$ is waist of pumping light, $P_{\rm th} = 0.24P_{\rm abs}$ is thermal power, $P_{\rm abs}$ is absorption power of pumping light. $\alpha$ is absorption coefficient. ${\rm d}n/{\rm d}t = 4.7\times10^{-6}\ {\rm K^{-1}}$ is thermal coefficient of crystal.

Thermal focusing length of Nd:GdVO$_4$ is calculated at pumping power of 4 W. Thermal focusing length of 17 cm is measured by Ref. [15] in the experiment at room temperature. The equivalent resonator of Fig. 1 is shown in Fig. 4. The end face of Nd:GdVO$_4$ is equivalent to rear concave mirror of resonator, whose curvature radius is $\rho_4 = 2f$[16]. The resonator is analysed as

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} 1 & l_5 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & \frac{l_4}{\eta_4} \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & l_3 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & \frac{l_2}{\eta_2} \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & l_1 \\ 0 & 1 \end{pmatrix},$$

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} b & d \\ a & c \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} b & a \\ d & c \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -\frac{2}{\rho_4} & 1 \end{pmatrix},$$

where $l_1 = 25$ mm, $l_2 = 5$ mm, $l_3 = 9.7$ mm, $l_4 = 0.3$ mm, $l_5 = 15$ mm, $\rho_4$ is rear mirror, $\eta_2 = 1.77$ and $\eta_4 = 1.82$ are refractive indexes of KTP and Cr$^{4+}$:YAG, respectively.

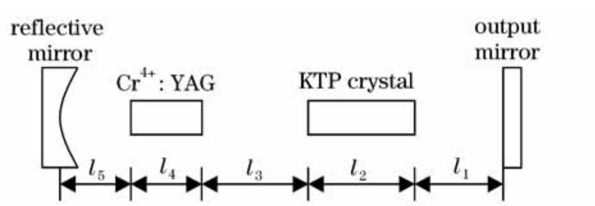


Fig. 4. Equivalent resonator.

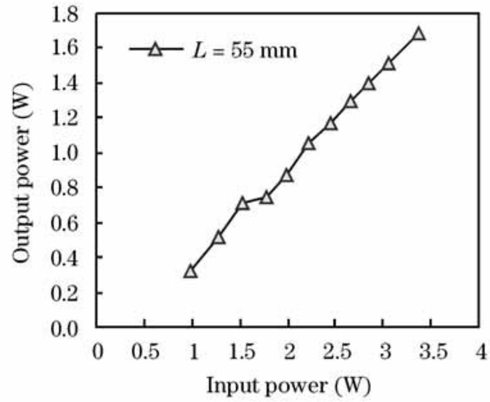


Fig. 5. Output power of 1064 nm versus input power.

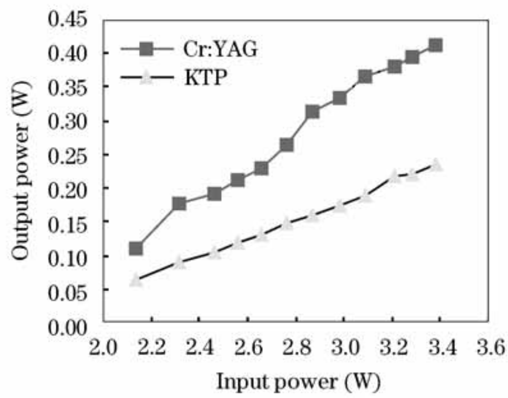


Fig. 6. Output power of $Q$-switch and double frequency versus input power.

Then $\left|\frac{1}{2}(A+D)\right| = 0.0533 < 1$ indicated the resonator is stable resonator at pumping power of 4 W

$$\omega_{\rm s} = \left(\frac{\lambda}{\pi n}\right)^{\frac{1}{2}} \frac{|B|^{\frac{1}{2}}}{\left[1-\left(\frac{D+A}{2}\right)^2\right]^{\frac{1}{4}}} = 25.59 \quad \mu{\rm m} < \omega_{\rm p}, \quad (4)$$

where $\omega_{\rm s}$ is optical radius of laser, $\lambda$ is wavelength of laser, $n = 1$ is refractive index of air.

The above result shows that our program is content to mode matching condition of end pumping.

Figure 5 shows CW output power (without the Cr$^{4+}$:YAG crystal) of Nd:GdVO$_4$ lasers as a function of incident pump power at 1.064-$\mu$m wavelength. Output mirror is coated with 95% film. The maximum output power of TEM$_{00}$ is 1.68 W, optic-optic conversion efficiency is 48.6%, and the slope efficiency is 56.3%. The threshold is 0.011 W. Figure 6 shows output powers of passively $Q$-switching and double frequency as function of incident pump power with saturable absorber

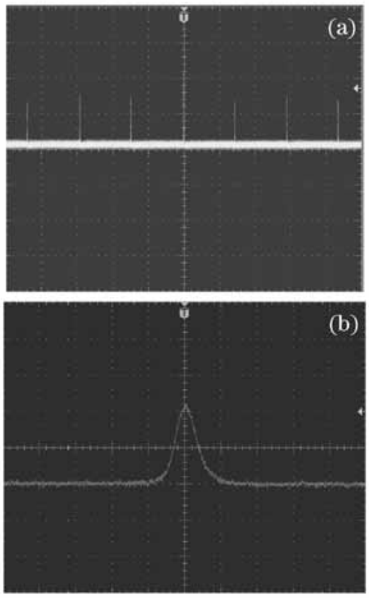


Fig. 7. Profiles of pulse repetition frequency (a) and pulse width (b).

of $T = 90\%$. Thresholds are 80 and 30 mW, respectively. Maximum output power is 0.411 and 0.235 W, respectively. Figure 7 shows pulse train and pulse width of green light, respectively. There are 33-kHz pulse repetition rate and 27.42-ns pulse width of green light at pump power of 3.8 W. The $M^2$ of green light is measured as $M_x^2 = 1.08$ and $M_y^2 = 1.13$.

In the paper, high efficiency passively $Q$-switched operation at end pumped intra-cavity frequency-doubled $Nd:GdVO_4$/KTP laser is reported. We studied the optimum coupling at end-pump and optimum design of resonator. The maximum output power of $TEM_{00}$ is 1.68 W at 1064-nm wavelength, optic-optic conversion efficiency is 48.6%, and slope efficiency is 56.3%. The maximum output of green is 0.235 W. The smallest pulse-width is 27.42 ns. Optic-optic conversion efficiency of green light is 7%, and $M^2 < 1.2$, thermal lens effect is discussed and calculated.

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