

intra-cavity Nd:GdVO₄/KTP laser

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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 TEM₀₀ is 1.68 W at 1.06- μm 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 Cr⁴⁺:YAG as a saturable absorber because of its improved thermo-mechanical properties. Cr⁴⁺:YAG has large absorption cross-section near 1.064 μm 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:YVO₄ are the combination of high absorption cross-section, wide absorption bandwidth, and low intrinsic losses. Both YVO₄ and GdVO₄ crystals belong to the group of oxide compounds crystallizing in a Zircon structure with a tetragonal space group^[8]. Compared with Nd:YVO₄, Nd:GdVO₄ crystals have almost entirely similar lasing properties, and have much higher absorption coefficient and larger absorption cross-section than that of Nd:YVO₄. Some experiments have shown that Nd:GdVO₄ crystal is excellent LD-pumped solid state laser crystal^[9-11]. Nd:GdVO₄ crystal is characterized by its unexpected high thermal conductivity along the (110) direction. The conductivity of Nd:GdVO₄ along (110) direction is equivalent to that of Nd:YAG, and is almost twice as that of Nd:YVO₄, therefore Nd:GdVO₄ is also more competitive in high-power laser generation. However, the high-power LD pumped Nd:GdVO₄ laser at 1.064 μm and operation intra-cavity frequency-doubled have been reported.

Figure 1 shows the setup for LD-pumped Nd:GdVO₄ laser. The pumping source is a fiber-coupled diode laser

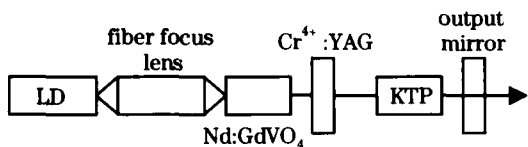


Fig. 1. LD-pumped passively Q-switched Nd:GdVO₄ laser with frequency-doubled intra-cavity.

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:GdVO₄ crystal. A laser experiment is performed with a 3- μm -thick crystal. The Nd³⁺ ion concentration in the crystal is 3.5 at.-%, and the dimension of the crystal is 5 $\times$ 3 $\times$ 3 mm³. The rear face of the crystal is coated with a high reflection (HR) film at 1.06 μm , and high transmission (HT) film at 0.808 μm , and the front face is coated with a HT film at 1.064 μm . Nd:GdVO₄ crystal is cooled by the copper. Two faces of Cr⁴⁺:YAG are coated HT films at 1.064 μm . KTP is coated HT films at 1.064 and 0.532 μm . A 3 $\times$ 3 $\times$ 5 mm³ KTP crystal is cut for II phase matching at 1.064 μm ($\theta = 90^\circ$, $\phi = 23.4^\circ$). The output mirror is HT at 0.532 μm and HR at 1.064 μm , which is a flat mirror.

High efficiency and high quality TEM₀₀ is easily gotten at end pumping because mode of pumping matches with that of TEM₀₀ in space. At low pumping power, mode-matching demands that radius of TEM₀₀ 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:GdVO₄ crystal by fiber focusing lens (see Fig. 2). Relationship between object distance and image distance along with magnification is^[13]

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

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

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

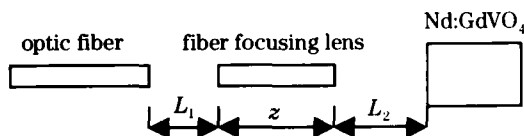


Fig. 2. Relationship of object distance and image distance in optic fiber focusing lens.

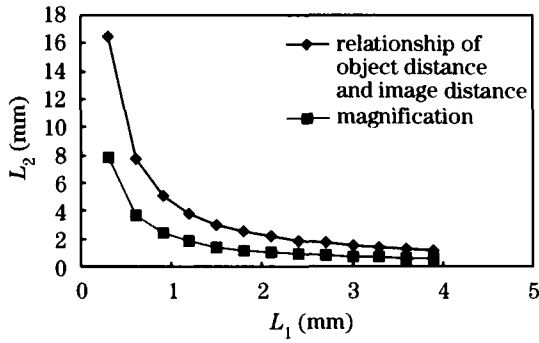


Fig. 3. Relationship of self-focusing lens object distance and image distance along with magnification.

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 $300 \mu\text{m}$, 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]

$$f = \frac{\pi K_c \omega_p^2}{P_{th} (dn/dt)} \left(\frac{1}{1 - \exp(-\alpha l)} \right), \quad (3)$$

where $K_c = 11.7 \text{ m}^{-1} \text{K}^{-1}$ is conductivity of Nd:GdVO_4 , ω_p is waist of pumping light, $P_{th} = 0.24 P_{abs}$ is thermal power, P_{abs} is absorption power of pumping light. α is absorption coefficient. $dn/dt = 4.7 \times 10^{-6} \text{ K}^{-1}$ 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

$$\begin{aligned} \begin{pmatrix} a & b \\ c & d \end{pmatrix} &= \begin{pmatrix} 1 & l_5 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{l_4}{\eta_4} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & l_3 \\ 0 & 1 \end{pmatrix} \\ &\times \begin{pmatrix} 1 & \frac{l_2}{\eta_2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & l_1 \\ 0 & 1 \end{pmatrix}, \\ \begin{pmatrix} A & B \\ C & D \end{pmatrix} &= \begin{pmatrix} b & d \\ a & c \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\ &\times \begin{pmatrix} b & a \\ d & c \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{2}{\rho_4} & 1 \end{pmatrix}, \end{aligned}$$

where $l_1 = 25$ mm, $l_2 = 5$ mm, $l_3 = 9.7$ mm, $l_4 = 0.3$ mm, $l_5 = 15$ mm, ρ_4 is rear mirror, $\eta_2 = 1.77$ and $\eta_4 = 1.82$ are refractive indexes of KTP and $\text{Cr}^{4+}:\text{YAG}$, respectively.

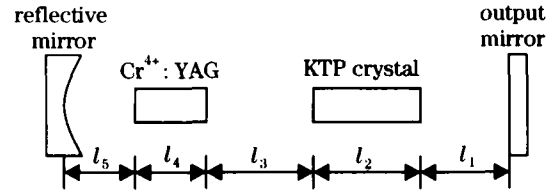


Fig. 4. Equivalent resonator.

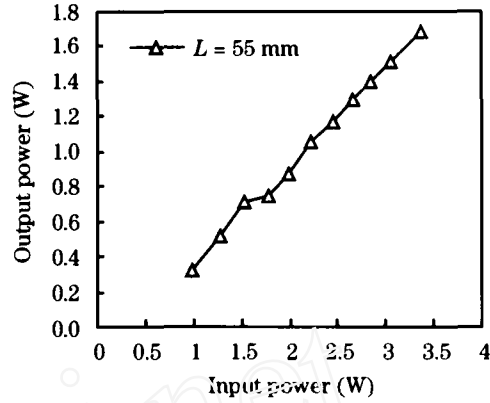


Fig. 5. Output power of 1064 nm versus input power.

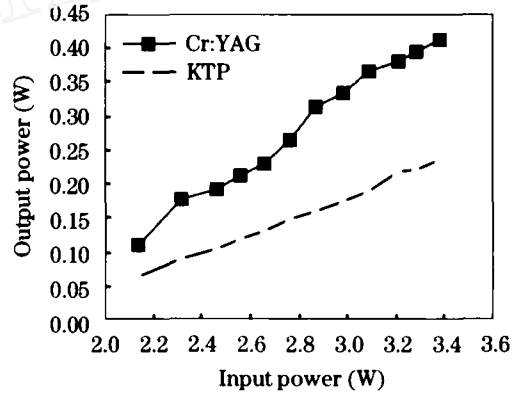


Fig. 6. Output power of Q -switch and double frequency versus input power.

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

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

where ω_s is optical radius of laser, λ 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 $\text{Cr}^{4+}:\text{YAG}$ crystal) of Nd:GdVO_4 lasers as a function of incident pump power at $1.064\text{-}\mu\text{m}$ 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

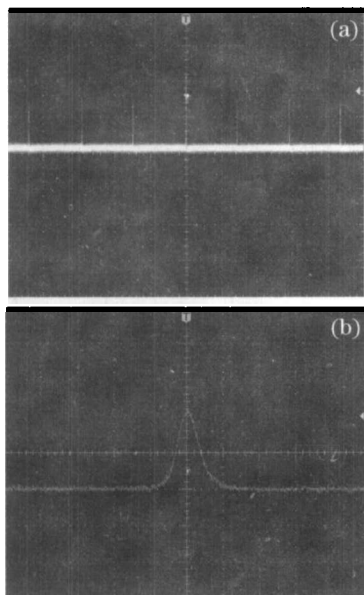


Fig. 7. Profiles of pulse repetition frequency (a) and pulse width (b).

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:GdVO₄/KTP laser is reported. We studied the optimum coupling at end-pump and optimum design of resonator. The maximum output power of TEM₀₀ 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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