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Efficient and compact intracavity-frequency-doubled Nd:$GdVO_4$/KTP laser end-pumped by a fiber-coupled laser diode

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Abstract. A compact and efficient diode-pumped intracavity-frequency-doubled Nd:$GdVO_4$/KTP green laser is demonstrated with a flat–flat cavity design. With a 1.3 at. % Nd^{3+}-doped $GdVO_4$ crystal and pumped at the weak-absorption peak of 806 nm, the second-harmonic output power at 532 nm was measured to be 1.95 W at an incident pump power of 8.4 W, corresponding to an optical conversion efficiency of 23.2%. The output characteristic at the fundamental wavelength of 1.063 μm was investigated with two different pump wavelengths. More than 4.5-W output power was generated when the laser was pumped at 806.2 nm.

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Compared with Nd:YAG and Nd:YVO_4, neodymium-doped gadolinium vanadate (Nd:$GdVO_4$) is an attractive and very efficient laser material for diode pumping and has been receiving considerable attention in recent years [1–4]. Nd:$GdVO_4$ has a large emission cross section at 1.06 μm ($7.6\times10^{-19}\,cm^2$) and high absorption cross section ($5.2\times10^{-19}\,cm^2$), and a wide absorption bandwidth at a pump wavelength of 808 nm [2]. More important, the thermal conductivity of $GdVO_4$ (12.3 W/mK along the ⟨001⟩ direction) is more than a factor of two higher than that of YVO_4 and is even higher than that of YAG [5, 6]. Such unique spectroscopic and thermal properties make a Nd:$GdVO_4$ crystal a promising substitute for Nd:YAG and Nd:YVO_4 in diode-pumped compact solid-state lasers.

Since the first demonstration of laser oscillation in a Nd:$GdVO_4$ crystal [1], considerable efforts have been made on power scaling of both cw and pulsed Nd:$GdVO_4$ lasers at 1.06 μm [7–10]. However, it was not until recently that efficient intracavity-frequency-doubled Nd:$GdVO_4$ lasers were reported [11, 12]. A comparative study shows that not only the fundamental wavelength but also the intracavity-frequency-doubled Nd:$GdVO_4$ lasers are more efficient than Nd:YVO_4 lasers [11]. An intracavity-doubled 3.6-W Nd:$GdVO_4$ laser was reported using a lightly Nd-doped crystal (0.5 at. %) and a folded-cavity design [12]. Low Nd-doping avoids severe thermal deposition in the crystal and hence helps the power scaling of the laser; with a folded-cavity design, the laser mode size in the laser and nonlinear crystals can be optimized separately, which ensures the efficient operation of the laser. In this paper, we report on a compact and highly efficient intracavity-doubled Nd:$GdVO_4$/KTP green laser with a 1.3 at. % Nd-doped crystal and a compact flat–flat cavity design. The thermally induced lens provides the cavity stability and ensures a good mode matching between the laser mode and the pump beam. The optimum cavity-length condition is discussed taking into account the thermal focal length of the laser crystal. Because the Nd:$GdVO_4$ crystal was not a lightly Nd-doped one, the weak-absorption peak at 806.2 nm was selected as the pump wavelength to increase the absorption depth and avoid severe thermal deposition. At an incident pump power of 8.4 W, a green output power of 1.95 W was generated, corresponding to an optical conversion efficiency of 23.2%.

1 Experimental setup

The experimental setup is shown schematically in Fig. 1. The 1.3 at. % neodymium-doped $GdVO_4$ crystal was *a*-axis cut with a cross-sectional area of $3\times3\,mm^2$ and a thickness of 3 mm. One side of the laser crystal was anti-reflection coated at the pump wavelength of 808 nm ($R < 5\%$) and high-reflection coated at both the fundamental wavelength of 1.06 μm ($R > 99.8\%$) and the second-harmonic wavelength ($R > 99\%$) to act as a cavity mirror of the laser (input mirror). The other side was anti-reflection coated at 1.06 μm. The nonlinear crystal used in this research was a type-II phase-matched 7-mm-long KTP crystal which was located close to the output coupler. The two ends of the KTP crystal were anti-reflection coated at both 1.06 and 0.53 μm to reduce the cavity loss. The absorption coefficient of KTP at 1.06 μm is $\sim 5\times10^{-3}\,cm^{-1}$ [13]. $GdVO_4$ and KTP crystals were wrapped with indium foil and mounted on separate copper holders and could be temperature-controlled independently using Peltier devices. The flat output mir-

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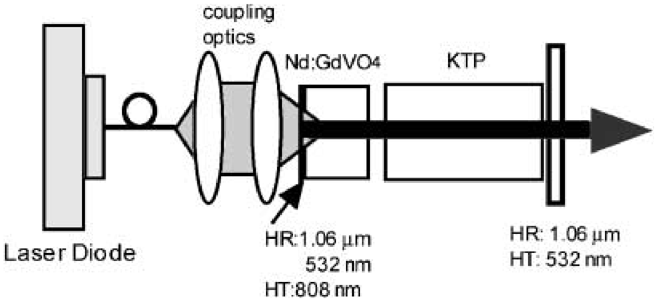

Fig. 1. Experimental setup of the intracavity-frequency-doubled $Nd{:}GdVO_4$ /KTP laser

ror was highly reflective coated at the fundamental wavelength ($R > 99.9\%$) and anti-reflective coated at the green wavelength ($T > 95\%$). The pump source is a fiber-coupled 10-W cw laser diode (SDL-2450) with a core diameter of 400 μm and a numerical aperture of 0.4. For pumping, the light from the fiber end was collimated and focused to a spot size of approximately 380 μm in diameter. It should be noted that although the input mirror of the laser had a high-reflection coating of $R > 99\%$ at the 532-nm wavelength, the reflectivity was measured to be about 60% for the green light incident on the $Nd{:}GdVO_4$ crystal from the right-hand side because of the absorption of the crystal.

2 Results and discussion

Figure 2 shows the unpolarized absorption spectrum of $Nd{:}GdVO_4$ which was measured with an ANDO AQ-6315A optical spectrum analyzer at a resolution of 0.05 nm. Except for the strong-absorption peak at 808.2 nm, there is also an adjacent weak-absorption peak at 806.2 nm. For the light from the fiber-coupled laser diode, the absorption coefficients at the two peaks are measured to be 18.0 and 10.2 cm^{-1}, respectively. Including the weak-absorption peak, $Nd{:}GdVO_4$ has an absorption bandwidth of ∼ 4 nm. For comparison, the absorption spectrum of a 2 at. % Nd-doped $Nd{:}YVO_4$ crystal was also measured and shown in Fig. 2. Apart from the strong-absorption peak, the two crystals both have a weak-absorption peak at ∼ 806.2 nm. The weak-to-strong absorption ratio of $Nd{:}GdVO_4$ (∼ 0.51) is higher than that of the $Nd{:}YVO_4$ crystal (∼ 0.34).

We investigated the output characteristics at the fundamental wavelength with the laser pumped at 808.2 and 806.2 nm. The output coupler was a $T = 10\%$ flat mirror, and the cavity length was ∼ 15 mm. Figure 3 shows the output power as a function of the incident pump power. When pumped at 806.2 nm, an output power of 4.5 W at 1.063 μm was obtained at an incident pump power of 8.4 W, giving an optical conversion efficiency of 53.6%. When the pump wavelength was tuned to center at 808.2 nm, the output power began to saturate at pump powers exceeding 6 W. The saturation behavior was attributed to the severe thermal effects induced by the strong absorption of the crystal. At a pump wavelength of 808.2 nm, about 85% incident pump power (∼ 7 W) was absorbed within 1 mm. When the pump wavelength was tuned to 806.2 nm, the pump power absorbed within the first 1 mm of the crystal was estimated to be only about 60% of the incident pump power. It worth to note that the pump-wavelength shift affected only the pump power's distribution in the laser crystal. The total absorbed pump power, however, was not reduced. The large absorption coefficients of $Nd{:}GdVO_4$ are favorable for the construction of microchip lasers that use very short laser crystals. For high-power end-pumped lasers, however, low Nd-doped crystals are preferable because high absorption will result in severe thermal lensing and thermally induced fracture that hinder the power scaling [9, 14]. Figure 3 shows that pumping the laser at the weak-absorption peak of $Nd{:}GdVO_4$ can, to some extent, avoid thermally induced power reduction. For experiments on the intracavity-doubled $Nd{:}GdVO_4$/KTP lasers, the weak-absorption peak of 806.2 nm was selected as the pump wavelength.

In an end-pumped intracavity-doubled laser, the generated second-harmonic power can be estimated by $P_{SHG} = KP_c^2/\pi w_c^2$ [13]. Here P_c, the fundamental circulating power

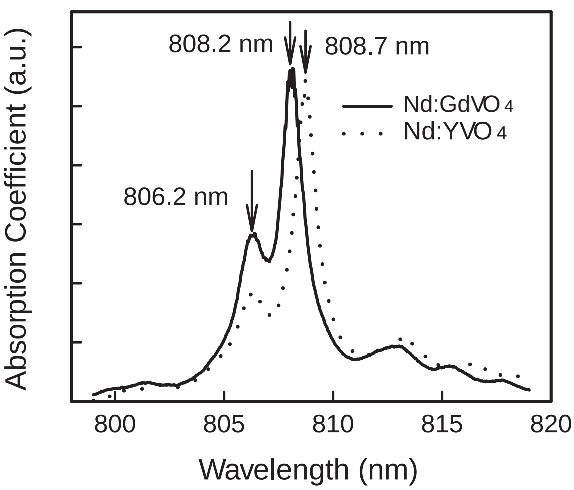

Fig. 2. Room-temperature nonpolarized absorption spectra of $Nd{:}GdVO_4$ and $Nd{:}YVO_4$

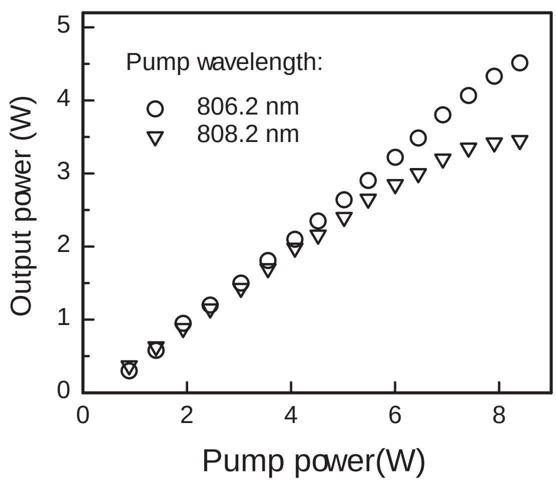

Fig. 3. Output power at 1.06 μm as a function of incident pump power for pumping at the strong- and weak-absorption peaks of 808.2 and 806.2 nm

within the laser cavity, is determined by

$$4K\xi\left(\frac{P_c}{\pi w_c^2}\right)^2 + (4\delta\xi + KS_0)\,\frac{P_c}{\pi w_c^2} + (\delta - 2G)S_0 = 0, \qquad (1)$$

where

$$K = 4\frac{w_c^2}{w_n^2}\left(\frac{\mu_0}{\varepsilon_0}\right)^{\frac{1}{2}}\frac{\omega^2 d_{\mathrm{eff}}^2 l_n^2}{n^3 c^2}\eta_a, \qquad (2)$$

$$G = \frac{2\sigma\tau\lambda_p P_{p0}(1 - e^{-\alpha_p l})}{\pi hc(w_p^2 + w_c^2)}; \qquad (3)$$

$S_0 = \hbar\omega/\sigma\tau$ is the saturation intensity. w_p and w_c are the pump and cavity mode radii, respectively, in the laser crystal. δ is the round-trip loss of the cavity that can be written in terms of $\delta_0 + \delta_d$, where δ_d is the diffraction loss induced by thermal spherical aberration; δ_0 is the nondiffraction loss which includes the absorption loss of Nd:$GdVO_4$ and KTP, transmission losses at the two cavity mirrors and scattering losses at all the interfaces. d_{eff} is the effective nonlinear coefficient of KTP; l_n and n are the KTP crystal's length and refractive index, respectively. w_n is the beam radius in the nonlinear crystal. η_a accounts for the efficiency reduction induced by the walk-off effect of KTP. P_{p0} is the incident pump power at the input mirror of the laser; ξ is a numerical simulating factor ~0.5 [13].

For thermally stabilized flat–flat cavity lasers, the cavity mode sizes are determined by the thermal focal length and cavity length. The thermal lensing in the Nd:$GdVO_4$ crystal was measured with a 10% transmission flat coupler so that thermal focusing alone defined the cavity. The actual beam radii were measured with the well-known scanning slit technique [2]. The thermal focal lengths were estimated according to the measured divergence data and shown in Fig. 4. At the maximum incident pump power of 8.4 W, the thermal focal length was ~ 20.2 cm.

In intracavity-doubled lasers, the cavity beam size in the nonlinear crystal should be small to enhance the fundamental power intensity and SHG (second-harmonic generation) conversion efficiency. At the same time, however, the cavity mode size in the laser crystal should be best matched to the pump-beam size for increasing the conversion efficiency from the pump to the fundamental power. Therefore, the optimum mode size for the high-efficiency operation of a laser is expected when the two effects are balanced. The cavity mode radii in both Nd:$GdVO_4$ (w_c) and KTP (w_n) are determined by the thermal focal length and cavity length. For a focal length of 20.2 cm, w_c, w_n and the second-harmonic optical conversion efficiency as a function of cavity length were calculated and shown in Fig. 5. Other parameters used in the calculation are as follows: the effective nonlinear coefficient of KTP $d_{\mathrm{eff}} = 3.2 \times 10^{-12}\,\mathrm{mV}^{-1}$, the refractive index $n = 1.83$ and $\omega = 1.78 \times 10^{15}\,\mathrm{s}^{-1}$; the fluorescence lifetime and stimulated-emission cross section of Nd:$GdVO_4$ are $\tau = 90\,\mu\mathrm{s}$ and $\sigma = 7.6 \times 10^{-19}\,\mathrm{cm}^2$, respectively. The nondiffraction loss of the cavity, δ_0, was measured at approximately 0.005 using three output couplers of different transmissions at 1.06 μm [13]. The diffraction loss was estimated according to the pump power and cavity parameters [15]. It can be seen from Fig. 5 that the suitable cavity length for efficient operation was around 20 mm. Although w_n is small and preferable for second-harmonic generation at short cavity lengths (< 20 mm), the laser efficiency is, however, limited by the small w_c. At cavity lengths longer than 25 mm, the green output decreases because of the rapidly increasing w_c and the thermally induced diffraction loss, which is a rapidly increasing function of the mode-to-pump ratio when $w_c > w_p$ [14, 15].

The experimental and theoretical green output powers as a function of the incident pump power are shown in Fig. 6. The best result was obtained at a cavity length of ~23 mm at the maximum pump power. A stable green output power of 1.95 W was generated at an incident pump power of 8.4 W, corresponding to an 'optical-to-optical' efficiency of 23.2%. For the cavity length of 23 mm, the theoretical results are shown in Fig. 6. The experimental results are in close agreement with the calculated ones. At the maximum pump power of 8.4 W, the intracavity circulating power, P_c, was estimated

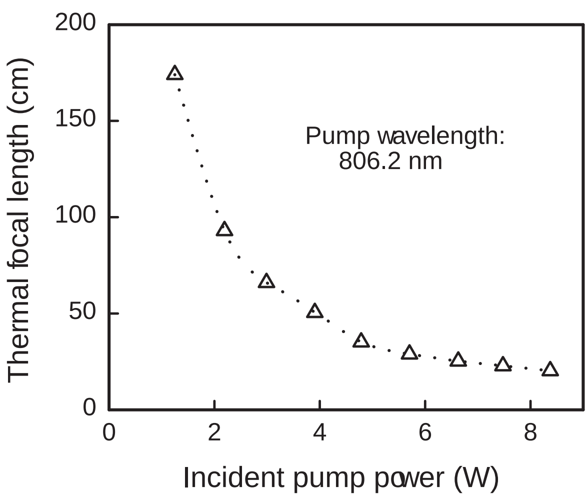

Fig. 4. Effective focal length of the thermally generated lens in Nd:$GdVO_4$ as a function of the incident pump power

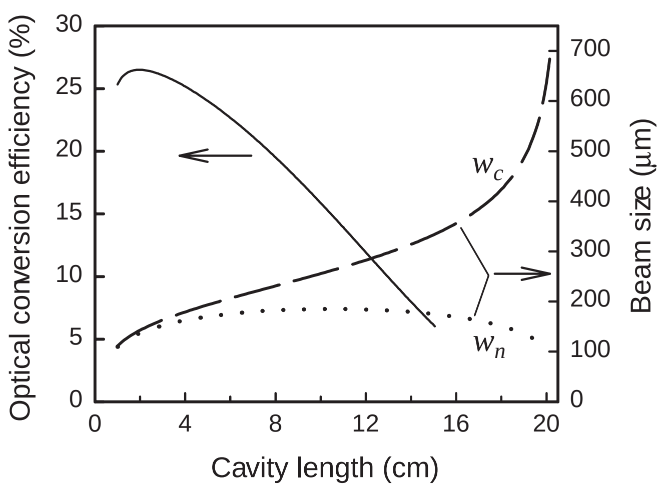

Fig. 5. The cavity mode radii in Nd:$GdVO_4$ (w_c) and KTP (w_n) as well as the second-harmonic optical conversion efficiency as a function of the cavity length for a thermal focal length of 20.2 cm

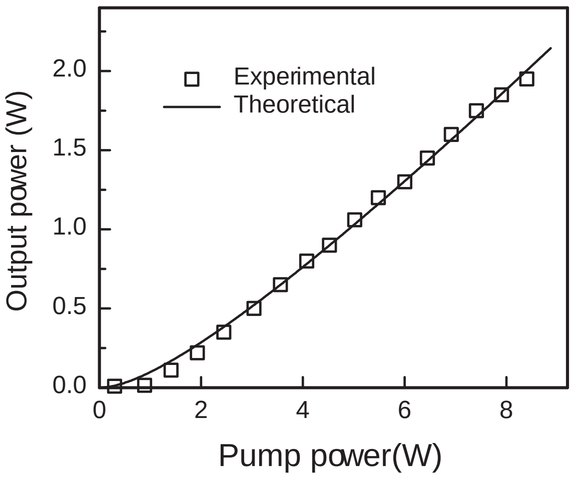

Fig. 6. Green output power as a function of the incident pump power

to be ∼ 207 W. The 1.06-μm power leakage of the laser due to the nonzero transmission of the output mirror was measured to be ∼ 21 mW at the maximum pump power. Because both Nd:$GdVO_4$ and KTP are birefringent crystals and have phase-retardation effects, it is necessary to select suitable crystal temperatures to ensure the efficient operation of an intracavity-doubled laser [13, 16, 17]. In this experiment, the temperatures of Nd:$GdVO_4$ and KTP were controlled at 18 and 21 °C, respectively. At the optimum cavity length of 23 mm, the mode-to-pump ratio was estimated to be smaller than 1 for pump powers greater than 4 W and ∼0.8 at the maximum pump power of 8.4 W. The beam-quality parameter M^2 of the green light was measured to be $M^2 = 1.3$ perpendicular and $M^2 = 1.4$ parallel to the *c*-axis of Nd:$GdVO_4$. The difference of M^2 in the two directions is probably caused by a nonperfect thermal lens of the laser crystal. The output power stability was measured to be better than 3% with a power meter over 1 h of operation. The short-term amplitude fluctuations of the green output were found to vary with the temperature of Nd:$GdVO_4$ and KTP. This may be due to a mode-selection process within the cavity, because both the laser and nonlinear crystal are birefringent and have phase-retardation effects. An amplitude fluctuation of better than 5% (RMS) was measured with the optimized crystal temperatures.

3 Conclusions

We have demonstrated a compact and efficient diode-pumped intracavity-frequency-doubled Nd:$GdVO_4$/KTP green laser with a 1.3 at. % Nd^{3+}-doped $GdVO_4$ crystal and pumped at the weak-absorption peak of 806.2 nm. A green output power of 1.95 W was generated at an incident pump power of 8.4 W, corresponding to an optical conversion efficiency of 23.2%. When operated at the fundamental wavelength of 1.063 μm, greater than 4.5-W output power was generated with an optical conversion efficiency of 54%. The results suggest that an off-peak pump method can be helpful for the power scaling of non-lightly-doped Nd:$GdVO_4$ crystals.

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