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Diode-pumped passively Q-switched $Nd{:}GdVO_4$ lasers operating at 1.06 μm wavelength

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Abstract. With a 10-W diode laser to pump $Nd{:}GdVO_4$ crystal in a folded cavity, we demonstrated Cr^{4+}:YAG passively Q-switched $Nd{:}GdVO_4$ lasers at 1.06 μm. The maximum average output power of 2.1 W and the highest peak power of 625 W were, respectively, obtained when the initial transmissions of the Cr^{4+}:YAG crystals were 90% and 80%.

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$Nd{:}GdVO_4$ crystal is a very efficient laser material for diode pumping and has been receiving considerable attention in recent years. Compared with Nd:YAG crystals, $Nd{:}GdVO_4$ has a 7-times higher absorption cross section at 808 nm ($\sigma_a = 5.2 \times 10^{-19}\,\mathrm{cm}^2$, $E \parallel c$) and a 3-times larger emission cross section at 1.06 μm ($\sigma_e = 7.6 \times 10^{-19}\,\mathrm{cm}^2$, $E \parallel c$) [1]. Compared with $Nd{:}YVO_4$ crystals, $Nd{:}GdVO_4$ has a much larger thermal conductivity along the direction of $\langle 110 \rangle$ (about $11.7\,\mathrm{W\,m^{-1}\,K^{-1}}$), which is more than a factor of two higher than that of $Nd{:}YVO_4$ and is even higher than that of Nd:YAG crystals [2, 3]. Such unique spectroscopic and thermal properties make $Nd{:}GdVO_4$ crystal a promising substitute for Nd:YAG and $Nd{:}YVO_4$ in diode-pumped compact solid-state lasers.

Since the early work on $Nd{:}GdVO_4$ lasers, considerable efforts have been made to increase the output power and the slope efficiency of diode-pumped cw $Nd{:}GdVO_4$ lasers [3–5]. Very recently, more than 14 W output power with a slope efficiency of 62% and an optical–optical conversion efficiency of 55% was obtained from these lasers [5]. However, the reported output powers of Q-switched $Nd{:}GdVO_4$ lasers are very small [6, 7]. In order to further investigate the properties of passively Q-switched $Nd{:}GdVO_4$ lasers, we used a 10-W diode laser to pump $Nd{:}GdVO_4$ crystal in a folded cavity and demonstrated the passively Q-switched $Nd{:}GdVO_4$ laser with Cr^{4+}:YAG crystals as the saturable absorber. The experimental configuration and the results for different Cr^{4+}:YAG crystals are described and discussed in this paper.

1 Experiments and results

Diode-pumped passively Q-switched $Nd{:}GdVO_4$ lasers using Cr^{4+}:YAG as the saturable absorber are not easy to operate successfully. The main difficulties stem from the fact that $Nd{:}GdVO_4$ crystals, having a very large emission cross section, thus need a special cavity to produce a large beam area in $Nd{:}GdVO_4$ crystal and a small beam area in Cr^{4+}:YAG crystal so that they can satisfy the passively Q-switching criteria. Considering the influence of the excited-state absorption of the saturable absorber, the passively Q-switching criteria for solid-state lasers can be written as [8]:

$$\frac{2\alpha_a L_a}{2\alpha_g L_g}\frac{\sigma_a}{\sigma_g}\frac{A_g}{A_a} > \frac{\gamma}{1-\beta}\,, \qquad (1)$$

where α_a, L_a, and σ_a are the small-signal absorption coefficient, the thickness, and the absorption cross section of the saturable absorber; A_a is the laser beam area in the saturable absorber. α_g, L_g, and σ_g are the small-signal gain coefficient, the thickness, and the emission cross section of the laser medium; A_g is the laser beam area in the laser medium. According to the theory of laser oscillation, α_g equals to $\Delta N \sigma_g$ for typical four-level systems. ΔN is the inversion population density, which depends on the dopant concentration, the emission cross section (σ_g), and the lifetime (τ) of the laser medium. γ is the population reduction factor, which equals to one for the ideal four-level laser and two for the three-level laser. β is the ratio of the excited-state absorption cross section to that of the ground-state absorption in the saturable absorber.

In our experiments, two pieces of Cr^{4+}:YAG crystals were used to test the properties of the passively Q-switched $Nd{:}GdVO_4$ lasers. One was 0.66 mm thick, with an initial transmission of 90% at 1.06 μm; the other one was 1.33 mm thick, with an initial transmission of 80% at 1.06 μm, corresponding to an absorption coefficient (α_a) of 1.65 cm^{-1}. The absorption cross section (σ_a) and the ratio of the excited- to ground-state absorption cross section (β) were reported as about 3.6×10^{-19}–7×10^{-18} cm^2 and 0.09 – 0.28, respectively [9–14]. The $Nd:GdVO_4$ crystal used in our experiment was 2.5 mm thick with a Nd concentration of 1.2 at. %. The emission cross section and the lifetime were reported as about 7.6×10^{-19} cm^2 ($E \parallel c$) and 90 μs, respectively [1]. Considering the output coupling and other dissipative losses of the laser cavity, the quantity $\alpha_a L_a / \alpha_g L_g$ in (1) is less than one. So, when the emission cross section of the laser crystal is relatively higher than, or close to, the absorption cross section of the saturable absorber, a large ratio of the mode area in the $Nd:GdVO_4$ to that in the Cr^{4+}:YAG crystal is required to satisfy the passively Q-switching criteria.

In the case of diode-pumped Cr^{4+}:YAG passively Q-switched $Nd:YVO_4$ lasers, the emission cross section of $Nd:YVO_4$ crystal is 24% less than that of $Nd:GdVO_4$ crystals [1] and the thermal lens effect of the $Nd:YVO_4$ crystal is as high as 14–19 m^{-1} W^{-1} [15]. When a conventional plane-parallel cavity is used, the thermal-induced lens effect can generate suitable beam areas in $Nd:YVO_4$ and Cr^{4+}:YAG crystals so that Cr^{4+}:YAG passively Q-switched $Nd:YVO_4$ lasers and the intracavity frequency-doubling were easily realized [16, 17]. However, with the same conventional plane-parallel cavity, we did not obtain the passively Q-switched $Nd:GdVO_4$ laser using Cr^{4+}:YAG crystal as the saturable absorber. It is probably because $Nd:GdVO_4$ crystal not only has a larger emission cross section, but also has a unexpectedly high thermal conductivity so that the passively Q-switching criteria cannot be satisfied. In this case, we designed a folded cavity to enlarge the ratio of A_g/A_a and finally demonstrated the passively Q-switched $Nd:GdVO_4$ laser.

Figure 1 shows the experimental setup. The pump source was a 10-W cw diode laser with an emission area of 1 μm × 10.5 mm. Its emission wavelength was temperature-tuned to 807.6 nm to match the absorption peak of the $Nd:GdVO_4$ crystal. The emission linewidth was about 1.5 nm at the output power of 10 W. The pump light from the diode laser was collimated and focused on the 2.5-mm-thick $Nd:GdVO_4$ crystal with a collimating lens ($L_1 : f = 8$ mm), two cylindrical lens ($L_2 : f = 50$ mm and $L_3 : f = 80$ mm) and a spherical lens ($L_4 : f = 10$ mm). The spot size of the pump light in the $Nd:GdVO_4$ crystal was estimated to be about 350 μm. The $Nd:GdVO_4$ crystal doped with 1.2 at. % Nd^{3+} was cut along the *a* axis and its absorption coefficient at pump wavelength was measured to be about 18.2 cm^{-1} when the pump radiation is polarized parallel to the *c* axis of the crystal. The $Nd:GdVO_4$ crystal was simply attached on a copper holder without special cooling. One side of it was high-reflectively coated for 1.06-μm light and anti-reflectively coated for 808-nm light; the other side was anti-reflectively coated for 1.06-μm light. The 140-mm-long laser cavity was formed by the high-reflection coating on $Nd:GdVO_4$ crystal, the high-reflectively concave mirror (M, $R = 100$ mm) and the plane output coupler with a transmission of 5% at 1.06 μm. In the passively Q-switched operation, two Cr^{4+}:YAG crystals with different initial transmissions were respectively inserted near the output coupler. In such a configuration, the diameters of the TEM_{00} laser mode in the $Nd:GdVO_4$ and Cr^{4+}:YAG crystals were calculated as about 430 μm and 150 μm, respectively. We found in our experiments that such a folded cavity could satisfy the Q-switching criteria and the mode-matching condition.

Figure 2 shows the average output power of the passively Q-switched $Nd:GdVO_4$ lasers with different Cr^{4+}:YAG crystals. When the Cr^{4+}:YAG crystal with an initial transmission of 80% was used, the average output power at the wavelength of 1.06 μm was measured to be about 1.4 W at the incident pump power of 8.1 W. The threshold power and the slope efficiency were 1.6 W and 20.3%, respectively. While the Cr^{4+}:YAG crystal with an initial transmission of 90% was used, the average output power increased to 2.1 W at the same pump power. The laser threshold power and the slope efficiency became 1.2 W and 31.6%, respectively. These indicate that the decrease of the initial transmission of the Cr^{4+}:YAG crystal will not only increase the threshold power, but also decrease the slope efficiency of the passively Q-switched lasers.

Figure 3 shows the pulse width, the repetition frequency, and the corresponding pulse energy and peak power of the Q-switched $Nd:GdVO_4$ lasers with the different Cr^{4+}:YAG crystals. We can find that the maximum pulse energy of 20 μJ and the highest peak power of 625 W were obtained when the Cr^{4+}:YAG crystal with the initial transmission of 80% was used, in spite of its lower average output power. The corresponding pulse width and the repetition frequency were 32 ns and 69 kHz, respectively, which are much narrower and less than that when the 90% Cr^{4+}:YAG crystal was used. In that case, the pulse width and the repetition frequency were 45 ns and 125 kHz when the incident pump power was 8.1 W. The

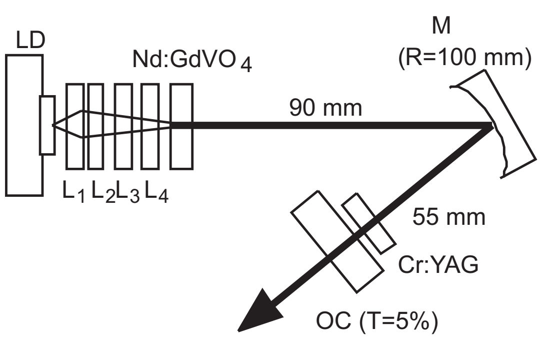

Fig. 1. Experimental setup

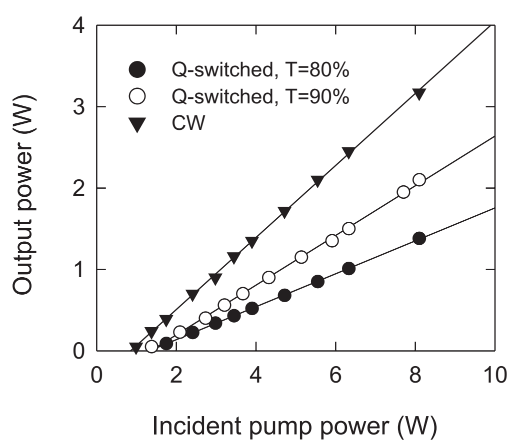

Fig. 2. Output power of cw and passively Q-switched $Nd:GdVO_4$ lasers with different Cr^{4+}:YAG crystals and at different incident pump power

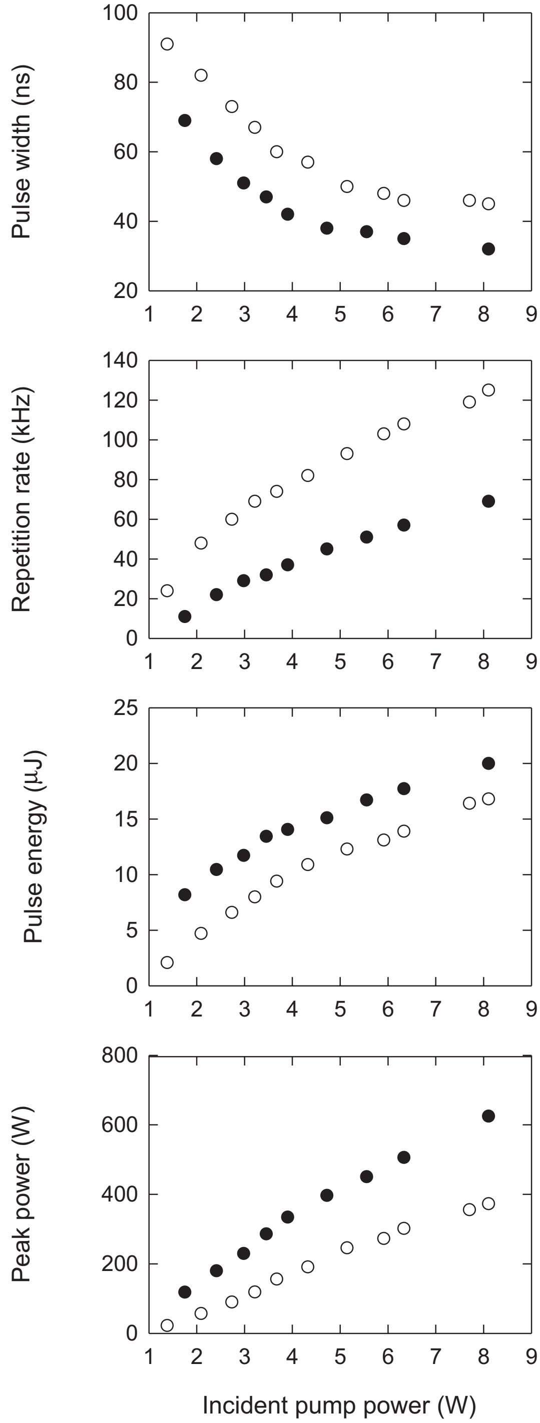

Fig. 3a–d. Output parameters of the passively Q-switched Nd:$GdVO_4$ lasers with different Cr^{4+}:YAG crystals. **a** pulse width; **b** repetition frequency; **c** pulse energy, and **d** peak power. • – Cr^{4+}:YAG crystal with 80% initial transmission; ◦ – Cr^{4+}:YAG crystal with 90% initial transmission

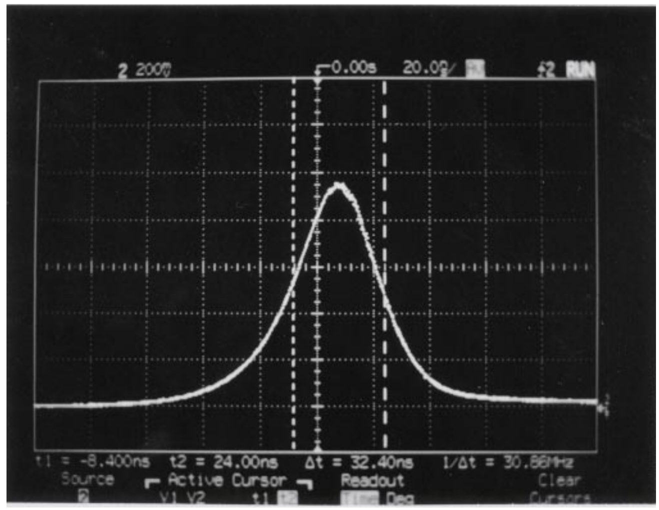

Fig. 4. The pulse profile of the passively Q-switched Nd:$GdVO_4$ lasers using 80% Cr^{4+}:YAG crystal as the saturable absorber. The pulse width was 32 ns (20 ns/div.)

corresponding pulse energy and peak power were only 17 μJ and 373 W, respectively. Figure 4 shows the profile of the laser pulses with 32-ns pulse width. The pulse-to-pulse amplitude fluctuations were measured to be less than 3%.

Compared with the passively Q-switched Nd:YAG, Nd:$LaSc_3(BO)_4$, Nd:S-FAP, and Nd:S-VAP lasers [18–21], Cr^{4+}:YAG passively Q-switched Nd:$GdVO_4$ lasers have higher repetition frequency and therefore produce lower pulse energy and lower peak power just like Nd:YVO_4 lasers [8, 16]. This is probably because Nd:$GdVO_4$ and Nd:YVO_4 crystals have much shorter lifetimes (≈ 90 μs) [1] and larger emission cross sections than those of Nd:YAG, Nd:$LaSc_3(BO)_4$, Nd:S-FAP, and Nd:S-VAP crystals. Under considerable excitation, the gain ($\Delta N\sigma_e$) of the lasers with a large emission cross section will be so high that the metastable state will be effectively deactivated through the channels of amplified spontaneous emission and the energy storage in the upper-state level will become difficult.

From Fig. 3, we can also find that the slopes of the peak power and the pulse energy tend to decrease when the incident pump power increases. Such a phenomenon can also be ascribed to the amplified spontaneous emission that occurred in the Nd:$GdVO_4$ laser under intense pumping.

Besides the Cr^{4+}:YAG passively Q-switched Nd:$GdVO_4$ laser, we also demonstrated the cw operation of the Nd:$GdVO_4$ laser and measured its output power in the same configuration (without the Cr^{4+}:YAG crystal). The experimental results are presented in Fig. 2. When the incident pump power was 8.1 W, we obtained more than 3.2 W output power at the wavelength of 1.06 μm. The corresponding threshold power and the slope efficiency were 0.65 W and 43.8%, respectively. Compared with the reported results in [4, 5], the higher threshold power and the lower slope efficiency in our experiments may come from the longer and folded cavity.

2 Summary

We demonstrated a diode-pumped passively Q-switched Nd:$GdVO_4$ laser using Cr^{4+}:YAG crystals as the saturable absorber. When a Cr^{4+}:YAG crystal with an initial transmission of 90% was used, we obtained more than 2.1 W average output power at the incident pump power of 8.1 W. The corresponding pulse width and the repetition frequency were 45 ns and 125 kHz, respectively. When a Cr^{4+}:YAG crystal with an initial transmission of 80% was used, the average output power decreased to 1.4 W at the same pump power and the corresponding pulse width and the repetition frequency became 32 ns and 69 kHz, respectively.

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