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Efficient pulse operation of $Nd:GdVO_4$ laser with AO Q-switch

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ABSTRACT We realized an efficient laser diode-pumped $Nd:GdVO_4$ laser with crystals grown by the floating zone method. In the lasing experiment, a slope efficiency of 78% was achieved with a 1 at.% Nd-doped crystal by pumping at 879 nm. Furthermore, excellent pulsed laser operation was demonstrated with the $Nd:GdVO_4$ crystal by using an acousto-optical (AO) Q-switch. A pulse width of 7 ns was observed when the pulse-repetition frequency was 40 kHz. It is the shortest pulse width recorded in the case of the AO Q-switched $Nd:GdVO_4$ laser.

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1 Introduction

Laser diode (LD)-pumped solid-state lasers are attracting much attention in various fields. Particularly, 1-µm lasers such as Nd:YAG or $Nd:YVO_4$ are widely used in various fields as basic tools. Considering the high-power operation, the generation of short wavelengths with nonlinear crystals, and various other applications, efficient and thermally stable laser crystals are required. The $Nd:GdVO_4$ crystal is a promising 1-µm laser medium for realizing an efficient laser with sufficient thermal stability because of its large emission cross section, which is the same as that of YVO_4, and high thermal conductivity, which is the same as that of YAG [1–6]. However, $Nd:GdVO_4$ crystals have not become widely used because $Nd:GdVO_4$ crystal is difficult to grow because of its high melting point. The conventional technique used to grow $Nd:GdVO_4$ single crystals is the Czochralski (CZ) method [7–9]. The melting point of this crystal is 1780°C. The high melting point of orthovanadate limits the material of the crucible. Iridium crucibles, which can be used at high temperature, tend to be oxidized at high oxygen partial pressure. Therefore, oxygen partial pressure in the furnace must be reduced. However, the orthovanadate in the crystalline material evaporates at low oxygen partial pressure in the furnace. As a result, we have not obtained high-quality crystals without defects by means of strict control of the atmospheric conditions in the furnace for growing $Nd:GdVO_4$.

In our previous work, we succeeded in growing high-optical-quality $Nd:GdVO_4$ single crystals by the floating zone (FZ) method [10–12]. The FZ method does not require a crucible; thus, it is highly advantageous for growing $Nd:GdVO_4$ crystals without inclusions under high oxygen partial pressure. The obtained crystals exhibit favorable optical properties for use as a laser medium. The absorption characteristics of $Nd:GdVO_4$ have polarization dependence. Two large absorption peaks at 808 nm and 879 nm with π polarization are stronger than those with σ polarization. 808 nm is a conventional pumping wavelength for Nd-doped lasers. On the other hand, in the case of pumping at 879 nm, since Nd ions are pumped directly to the start level of laser oscillation, it has been expected that the quantum defect would be markedly reduced in order to perform 879-nm pumping [13, 14]. If it is achieved, efficient and high thermal stability of the laser oscillation can be obtained. Therefore, we have demonstrated basic lasing experiments with pumping at 879 nm using a pulsed Ti:sapphire laser [15]. As a result, excellent laser performance with a slope efficiency of 78% was obtained with a 2 at.% Nd-doped $GdVO_4$ crystal by pumping at 879 nm.

In this work, we realized an efficient LD-pumped $Nd:GdVO_4$ laser with crystals grown by the FZ method. In the case of continuous-wave (CW) operation, a high slope efficiency of 78% was achieved with a 1 at.% Nd-doped crystal by pumping at 879 nm. Furthermore, we attempted to develop a high pulse repetition rate laser which can be used to obtain high peak power using an acousto-optical (AO) Q-switch. As a result, excellent pulsed laser operation was demonstrated with the $Nd:GdVO_4$ crystal by using the AO Q-switch. A pulse width of 7 ns was observed when the pulse-repetition frequency was 40 kHz. To the best of our knowledge, this is the shortest pulse width recorded in the case of the AO Q-switched $Nd:GdVO_4$ laser.

2 Experimental setup

First, we attempted basic experiments on CW laser oscillation at 1063 nm. The experimental setup for the laser oscillation is simply shown in Fig. 1. Fiber-coupled CW LDs at 808 nm (THALES, TH-C1725-F4) and 879 nm

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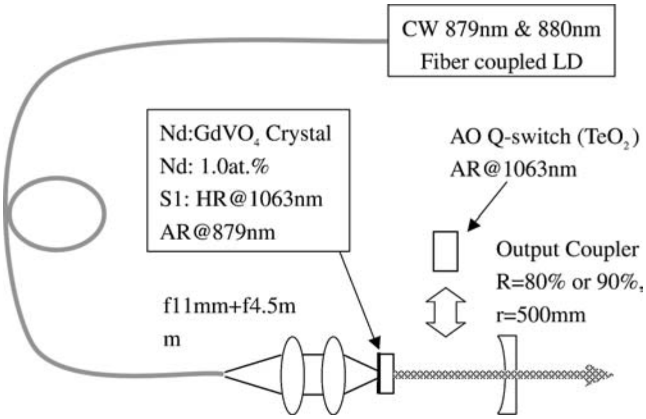

FIGURE 1 Schematic of the laser setup

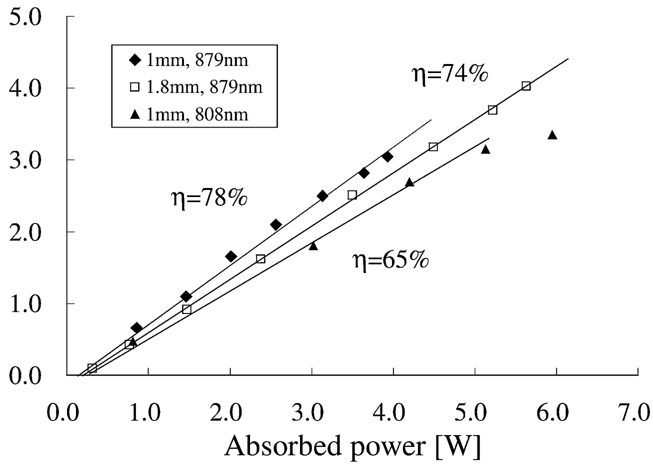

FIGURE 2 Lasing characteristics with CW LD pumping

(Hamamatsu Photonics, LA0319-880CWF) were used for pumping the Nd:GdVO$_4$ crystals. The diameter of the fiber core and the numerical aperture of the 808-nm LD were 400 µm and 0.22, and those of the 879-nm LD were 400 µm and 0.20, respectively. Maximum available power of these LDs was 15 W. The output beam from the fiber was focused into the Nd:GdVO$_4$ crystals with a spot size of about 200 µm using focusing lenses. The crystals used in the experiment were a-cut. The dimensions of the crystals were 4 mm × 4 mm × 1 mm and 4 mm × 4 mm × 1.8 mm. Crystal growth, fabrication, and coating of Nd:GdVO$_4$ were performed by NEC-Tokin Corporation. A plano-concave-type laser cavity was used in the experiments. The cavity consisted of one flat crystal surface with a high-reflectivity coating and an output coupler with 90% reflectivity. The resonator length of the laser was set to 10 mm. Furthermore, we developed a compact laser system with a TEM$_{00}$ mode and measured its lasing characteristics to estimate the optical–optical efficiency of the entire system including the losses. Next, we attempted pulse operation with the Nd:GdVO$_4$ crystal using the AO Q-switch (Gooch & Housego, QS041-4G-AE5). In the case of pulsed operation, we use the same pumping setup of the CW operation but an output coupler with 80% reflectivity. Also, the dimensions of the crystal were changed to 3 mm × 3 mm × 5 mm (a-cut) in order to increase the absorbed pump power. The AO Q-switch was inserted into the resonator. The resonator length of the laser was set to 40 mm. The laser pulse was detected by means of a high-speed photodetector (Thorlabs, DET410) and was observed using a digitizing oscilloscope (Tektronix, TDS3054B).

3 Results and discussion

Figure 2 shows the output power at 1063 nm depending on the absorbed pump power. A slope efficiency of 78% was achieved with the 1 at.% Nd-doped crystal pumped at 879 nm. The optical–optical conversion efficiency reached 70%. The principal limit of the energy-conversion efficiency is 82.3% in the case of 879-nm pumping. In our previous work, we also obtained 78% for the slope efficiency when pumping with a pulsed Ti:sapphire laser [15]. The conditions of the mode matching between pumping geometry and cavity mode were different. However, we achieved high slope efficiencies close to the principal limit in the case of CW operations with LD pumping by optimizing the pumping conditions. On the other hand, in the case of pumping at 808 nm, the output power tended to saturate at higher than 5 W of absorbed pump power. This was caused by the thermal effect. The mismatching of the resonator mode depending on the thermal lens causes the saturation of the output power. The difference between 808-nm and 879-nm pumping is the thermal load caused by non-radiative transitions from the upper state ($^4F_{5/2}$) to the start level ($^4F_{3/2}$) of the laser emission. By 879-nm pumping, a 50% reduction in thermal load is expected. These results show that this crystal is of sufficiently high quality for application in lasers, and that LD pumping at 879 nm is effective for Nd:GdVO$_4$ lasers.

We have developed a compact CW laser system with a TEM$_{00}$ mode. The dimensions of the laser head are 100 mm × 50 mm × 60-mm high. Figure 3a shows the output power at 1063 nm vs pump power from the CW LD at 879 nm. The horizontal and vertical axes show the power of the pump beam at the fiber end and the output power, respectively. Efficient laser performance was demonstrated. A high slope efficiency of 65% was achieved with this laser system including all losses. The optical–optical conversion efficiency is 54%. The maximum output power reached 7 W. The typical beam profile of this laser at 7 W is shown in Fig. 3b. The TEM$_{00}$ mode was obtained, and M^2 of the output beam was 1.1. To obtain high beam quality, we extended the resonator length to 40 mm and increased the gain volume for cavity-mode matching. Under these conditions, we did not observe the saturation of the output power although slope efficiency and optical–optical conversion efficiency slightly decreased compared with results of basic experiments shown in Fig. 2.

Figure 4a shows the result of the pulsed operation by pumping with 11.7 W of the CW LD at 879 nm. The horizontal axis shows the repetition rate and the vertical axis shows the average power and the pulse width. White and black dots indicate the average power at 1063 nm and the pulse width, respectively. The averaged output power increased with the pulse-repetition rate. The maximum averaged output power of over 4 W was obtained when the pulse-repetition rate was 100 kHz. Furthermore, in the case of decreasing the pulse-repetition rate, the pulse width tended to be narrow.

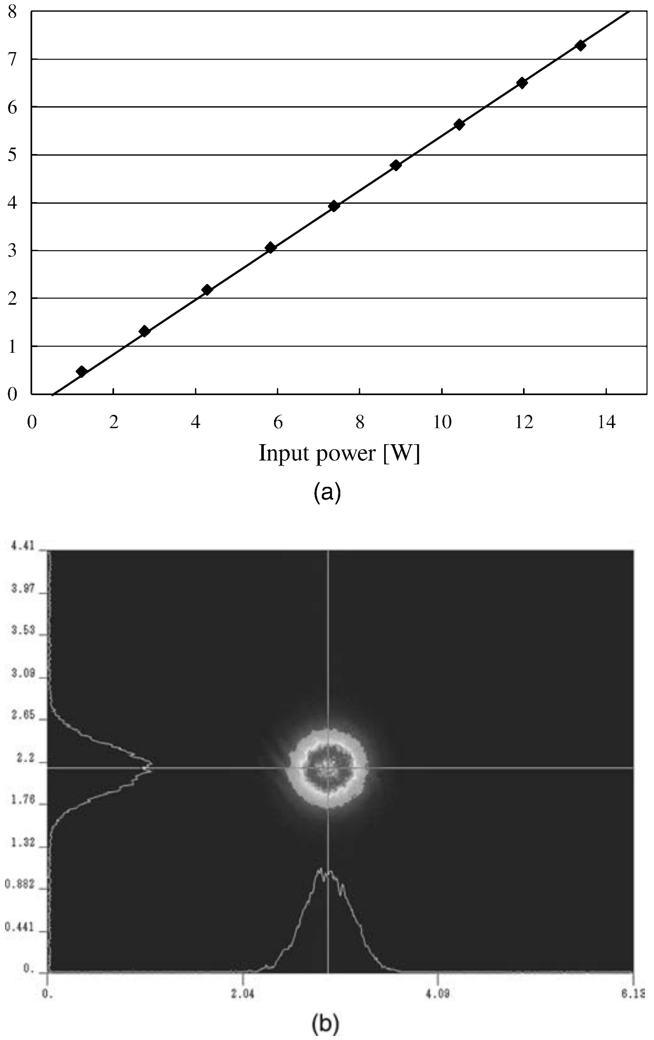

FIGURE 3 Prototype of laser system: **a** lasing characteristics, **b** beam profile

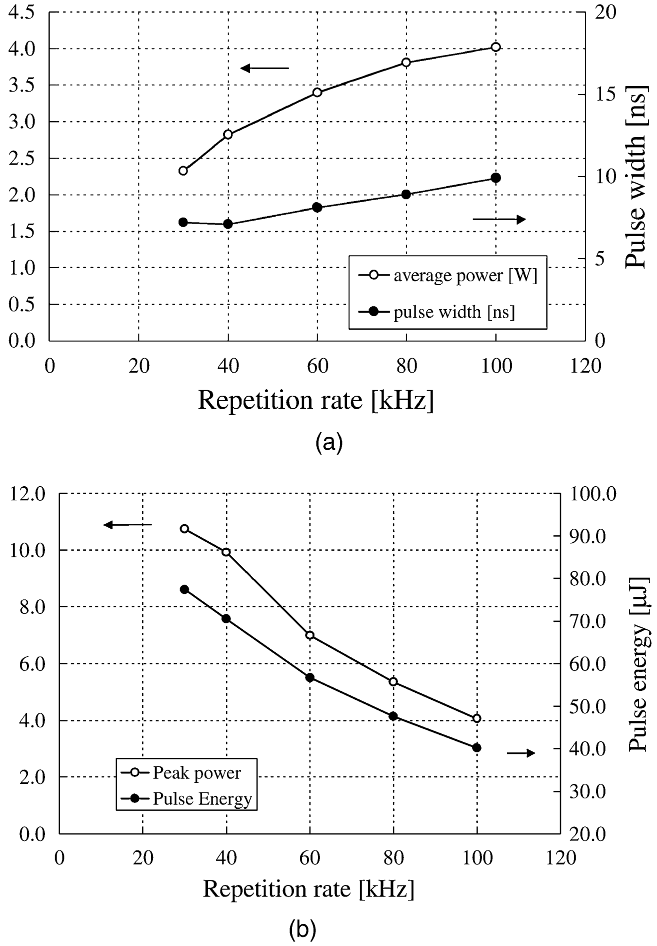

FIGURE 4 Average power and pulse width (**a**) as well as peak power and pulse energy (**b**), vs pulse-repetition rate

The shortest pulse width of 7 ns was achieved when the pulse-repetition rate was 40 kHz. It is a very short pulse width in the case of applying the AO Q-switch to the $Nd:GdVO_4$ laser.

Figure 4b shows the peak power and the pulse energy we calculated from the experimental results. The horizontal axis shows the repetition rate and the vertical axis shows the peak power and the pulse energy. White and black dots represent the peak power and the pulse energy, respectively. The maximum peak power of 10.7 kW was observed with the pulse width of 7.2 ns at the pulse-repetition rate of 30 kHz.

The pulse width of the laser depends on the cavity lifetime of the photons. The pulse width of the Q-switched laser can be written as

$$\Delta t_p = \tau_c \frac{n_i - n_f}{n_i - n_t\,[1 + \ln(n_i/n_t)]}, \quad (1)$$

$$\tau_c = \frac{1}{c\sigma n_t}, \quad (2)$$

where Δt_p is the pulse width of the laser, τ_c is the cavity lifetime, σ is the emission cross section, and c is the velocity of light. n_i, n_f, and n_t represent the initial population inversion density, the final population inversion density, and the population inversion density at threshold [16]. Vanadate crystals such as $Nd:GdVO_4$, $Nd:YVO_4$, and $Nd:LuVO_4$ tend to have a large emission cross section. For example, an emission cross section of the $Nd:GdVO_4$ to π polarization is three times larger than that of Nd:YAG [2]. Therefore, it is considered that a short pulse width can be realized at a high repetition rate by using the vanadate lasers [17, 18]. In this work, we confirmed that a short pulse width at a high repetition rate can be obtained with $Nd:GdVO_4$ lasers with the AO Q-switch.

Generally, the short-pulse generation less than 10 ns is difficult in the case of using the AO Q-switch, although it can realize a higher pulse-repetition rate and a lower cost than the electro-optical (EO) Q-switch. However, the results show that the AO Q-switched $Nd:GdVO_4$ laser can obtain a short pulse width similar to that of the EO Q-switched laser, despite its high pulse-repetition rate. To our knowledge, this is the first report demonstrating a short-pulse generation of less than 10 ns with the AO Q-switched $Nd:GdVO_4$.

4 Summary

We developed a compact, efficient laser system using the $Nd:GdVO_4$ crystal. In the case of CW operation, an efficient laser performance was demonstrated by pumping at 879 nm. A maximum slope efficiency of 78% was achieved with the 1 at.% Nd-doped crystal. Furthermore, a high pulse-repetition rate was observed with an AO Q-switch. The pulse-repetition rate reached 100 kHz and the peak power was over 10 kW. The shortest pulse width of 7 ns was observed when the pulse-repetition rate was 40 kHz. The pulse width of the laser depends on the cavity lifetime of the crystal. This is an advantage of vanadate crystals such as $Nd:GdVO_4$, $Nd:YVO_4$, and $Nd:LuVO_4$. These results show that the $Nd:GdVO_4$ crystal is suitable for high-power, high pulse repetition rate lasers that can be put to practical use.

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