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Output properties of diode-pumped passively Q-switched 1.06 μm $Nd:GdVO_4$ laser using a [100]-cut Cr^{4+}:YAG crystal

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Abstract A passively Q-switched 1.06 μm $Nd:GdVO_4$ laser with a [100]-cut Cr^{4+}:YAG saturable absorber was demonstrated. The output characteristics were investigated when the anisotropic transmission of Cr^{4+}:YAG crystal and the incident pump power level were considered. The experimental results showed that it was feasible to generate laser with narrower pulse width (τ_p), higher pulse energy and peak power when the polarization direction of laser was parallel to the [001], [010], $[00\bar{1}]$, and $[0\bar{1}0]$ orientations of the Cr^{4+}:YAG crystal. The different changes of τ_p as a function of incident pump power was observed due to the anisotropy of transmission of Cr^{4+}:YAG and the different gain levels (pump power levels). If the Cr^{4+}:YAG was fully bleached as a result of high cavity gain or due to the laser polarization direction was parallel to the [001], [010], $[00\bar{1}]$, and $[0\bar{1}0]$ orientations, τ_p was constant, otherwise τ_p decreased when the gain increased.

1 Introduction

Q-switched lasers are used in many applications, such as laser lidar, remote sensing, micro-machining, and microsurgery [1, 2]. Compared with active Q-switching, the passive techniques have advantages such as lower cost, compactness, simplicity in set-up, and operation since they do not require external control. Cr^{4+}:YAG crystal as a saturable absorber has advantages of improved thermo-mechanical properties, large absorption cross section, low saturable intensity, and high damage threshold [3, 4].

The output performance, such as output energy, E_p, pulse duration, τ_p, pulse peak power, P_p, and pulse repetition rate, f, are important for passively Q-switched lasers. Many theoretical models and experimental results about passively Q-switched lasers have appeared in the literature [5–12]. But some of the theoretical opinions and experimental observations differed in these publications. For example, Degnan [5] reported that τ_p was not affected by the pump power level, but was determined by other parameters, such as the cavity length. This was confirmed by experimental results reported in [6–8]. However, Lu et al. [9] reported that τ_p decreases when the incident pump power increases, which was supported by experimental investigations [10–12]. In our characterization studies of a Cr^{4+}:YAG passively Q-switched $Nd:GdVO_4$ laser, both these two different experimental phenomenon were observed for the first time in the same experimental configuration, which we attributed them to the anisotropy of the Cr^{4+}:YAG transmission and the different laser cavity gain. The anisotropic transmission of Cr^{4+}:YAG crystal was previously reported in [13, 14], but to the best of our knowledge, there was no researcher to report the above two changes of τ_p simultaneously, not to mention giving an explanation.

In this paper, we demonstrated a passively Q-switched 1.06 μm $Nd:GdVO_4$ laser with a [100]-cut Cr^{4+}:YAG crystal by 808 nm laser diode pumping. The output characteristics were investigated when the anisotropic transmission of Cr^{4+}:YAG crystal and the different gain levels were considered. The experimental results showed that we could obtain a pulsed laser output with narrower τ_p, higher E_p and P_p when the polarization direction of laser was paral-

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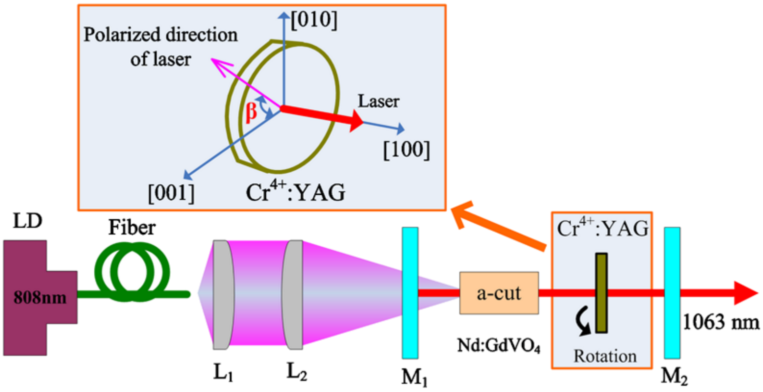

Fig. 1 Experimental setup of a passively Q-switched Nd:GdVO$_4$ laser and the schematic of crystallographic axis of the Cr^{4+}:YAG, polarized laser, and a rotation angle β

lel to the [001], [010], $[00\bar{1}]$, and $[0\bar{1}0]$ orientations of the Cr^{4+}:YAG crystal, respectively. The different changes of τ_p as a function of incident pump power were observed due to the anisotropic transmission of Cr^{4+}:YAG crystal and the different cavity gain levels.

2 Experimental setup

The experimental configurations of a [100]-cut Cr^{4+}:YAG passively Q-switched Nd:GdVO$_4$ laser using 808 nm laser-diode end-pumping is shown in Fig. 1.

The 808 nm pump source was a fiber coupled laser diode. L$_1$ and L$_2$ were a set of collimating and focusing lenses. The a-cut Nd:GdVO$_4$ crystal with a 0.3 at.% Nd^{3+} concentration had dimensions of $3 \times 3 \times 8$ mm^3. The crystal was wrapped with indium foil and placed into water-cooled copper heat sink. The input mirror M$_1$ was a flat mirror with an antireflection coating at 808 nm and a high reflectivity at 1063 nm. The output coupler M$_2$ had a transmission of 30 % at 1063 nm. The [100]-cut Cr^{4+}:YAG crystal with initial transmission T_0 of 90 % acted as a saturable absorber. The cavity length was about 160 mm.

3 Experimental results and discussions

The dependence of energy transmission T_i of the Cr^{4+}:YAG crystal with the angle between the crystallographic axis and the polarization direction of laser was investigated firstly. The crystal was excited with a linearly polarized, AO Q-switched 1063 nm Nd:GdVO$_4$ laser propagating along its growth direction. The schematic of crystallographic axis of Cr^{4+}:YAG, polarized laser and rotation angle β is same as shown in Fig. 1. The laser was focused by a lens to increase the power density I_L. The crystal was fixed on a precise rotatable mount in order to measure the rotation dependent T_i. The experimental results are shown in Fig. 2.

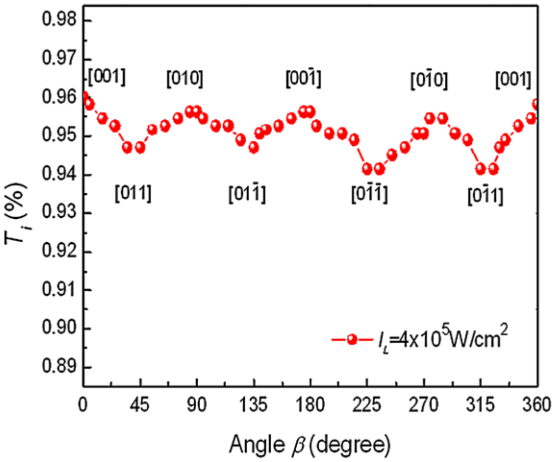

Fig. 2 T_i of the [100]-cut Cr^{4+}:YAG crystal as a function of rotation angle

From Fig. 2, we can see that at a power density of $I_L = 4 \times 10^5$ W/cm^2, there is an obvious anisotropic energy transmission. T_i varied with the angle β, and the almost same T_i peaks appeared every 90°. When β was 0°, 90°, 180°, and 270°, the polarization direction of laser was parallel to the [001], [010], $[00\bar{1}]$, and $[0\bar{1}0]$ orientations of Cr^{4+}:YAG, respectively, and T_i had the maximum value. When the polarization direction of laser was parallel to the [011], $[01\bar{1}]$, $[0\bar{1}\bar{1}]$, $[0\bar{1}1]$, orientations ($\beta = 45°$, 135°, 225°, and 275°, respectively), T_i was minimum.

The output characteristics of passively Q-switched Nd:GdVO$_4$ laser with the [100]-cut Cr^{4+}:YAG crystal were investigated. The experimental configuration is shown in Fig. 1. The incident pump power was 7.5 W and the Cr^{4+}:YAG crystal was rotated in a full 360°. The measured results are shown in Figs. 3–7.

From Fig. 3, we can see that the maximum average output power was obtained when β was 0°, 90°, 180°, and 270°, respectively. This is because of when the polarization direction of laser was parallel to the [001], [010], $[00\bar{1}]$, and $[0\bar{1}0]$ orientations, the T_i of Cr^{4+}:YAG crystal had a maximum value. The loss was smaller and the laser was easier to oscillate compared with the directions of [011], $[01\bar{1}]$, $[0\bar{1}\bar{1}]$, and $[0\bar{1}1]$.

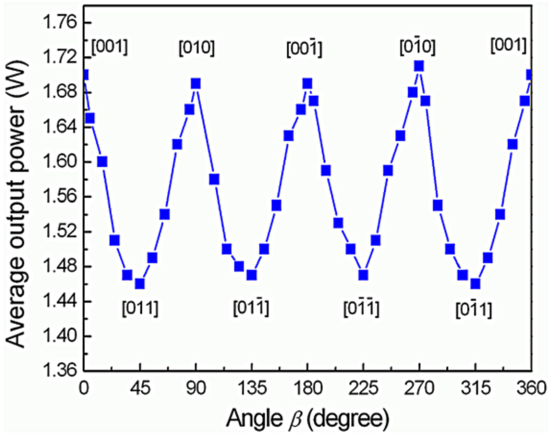

Fig. 3 Relation between the average output power and the rotation angle β

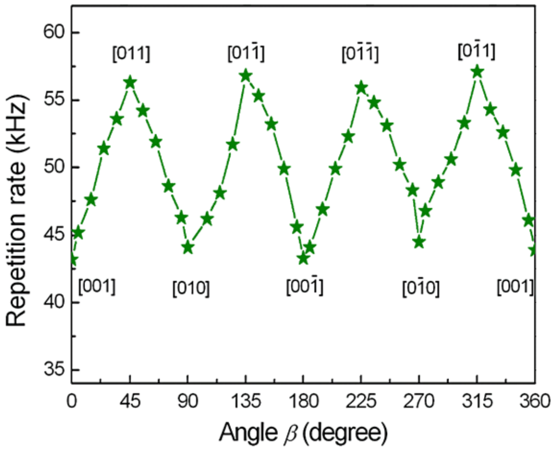

Fig. 4 Relation between the repetition rate and the rotation angle β

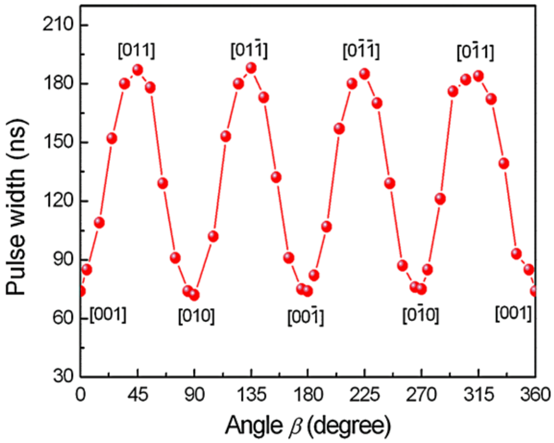

Fig. 5 Relation between the pulse width and the rotation angle β

The modulation depth Q_o of Cr^{4+}:YAG crystal is approximately directly proportional to the difference of T_i and T_0. Q_o peaks emerged when β was 0°, 90°, 180°, and 270°, respectively. Therefore, at these β values, the repetition rate and the pulse width were at a minimum and the pulse energy and the pulse peak power were maximum, as shown in Figs. 4, 5, 6 and 7.

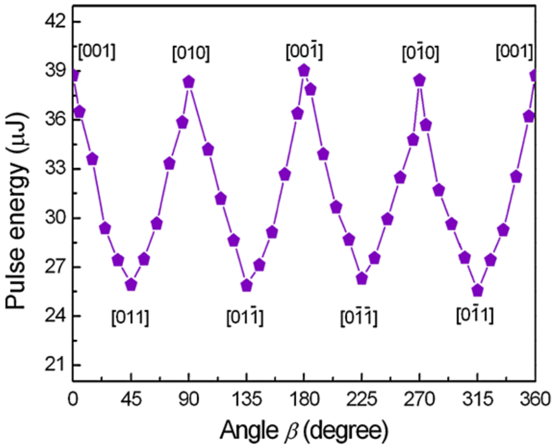

Fig. 6 Relation between the pulse energy and the rotation angle β

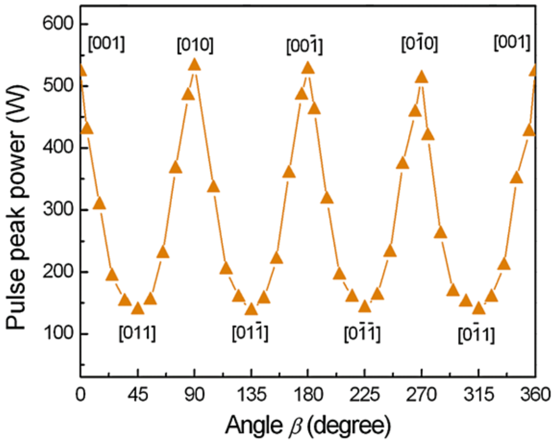

Fig. 7 Relation between the pulse peak power and the rotation angle β

There are four sinusoidal modulations of T_i in a full 360°. We studied the pulse width as a function of incident pump power at different rotation degree within 45° to illustrate the law of the full 360°. The measured results are depicted in Fig. 8.

From Fig. 8, we can see that at the same incident pump power, the narrowest τ_p was achieved when β was 0° and the largest could be obtained when β was 45°. Due to the anisotropic transmission, at β of 0° and in the investigated pump power range (from 7.5 W to 13.7 W), the Cr^{4+}:YAG crystal was fully bleached, and the pulse width was constant and $\sim$76 ns. At other angles ($\beta = 10°$, 22.5°, 35°, and 45°, respectively), τ_p was a decreasing function of the incident pump power, and it would decrease to a constant value of 76 ns ($\beta = 0°$) when the incident pump power increased. Because the gain of the laser oscillator is a function of the incident pump power level, as shown in Fig. 8, the gain impacts

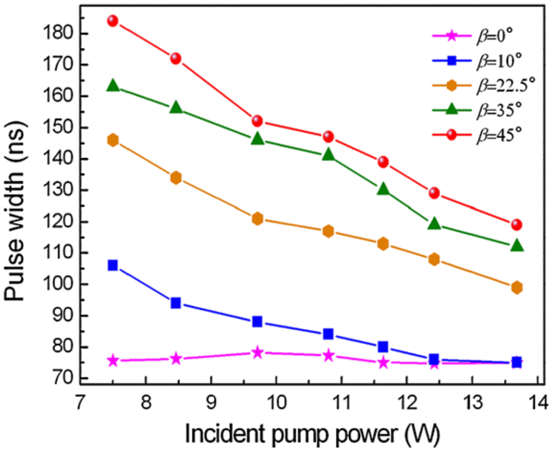

Fig. 8 Pulse width as a function of incident pump power at different rotation degree

the pulse duration. If the Cr^{4+}:YAG was fully bleached as the result of high gain or due to the laser polarization direction was parallel to the [001], [010], [00$\bar{1}$], and [0$\bar{1}$0] orientations, τ_p was constant, otherwise τ_p decreased when the gain increased.

4 Conclusions

In conclusion, we have demonstrated a passively Q-switched 1.06 µm Nd:$GdVO_4$ laser with a [100]-cut Cr^{4+}:YAG saturable absorber by 808 nm laser diode pumping. The output characteristics were investigated when the anisotropic transmission of Cr^{4+}:YAG crystal and the different gain levels were considered. The experimental results showed that a pulsed laser output with narrower τ_p, higher E_p and P_p can be achieved when the laser polarization direction was parallel to the [001], [010], [00$\bar{1}$], and [0$\bar{1}$0] orientations of Cr^{4+}:YAG, respectively. Two different effects of constant τ_p and varying τ_p were observed due to the anisotropy of transmission of Cr^{4+}:YAG crystal and the gain level. If the Cr^{4+}:YAG was fully bleached as the result of high gain or due to the laser polarization direction was parallel to the [001], [010], [00$\bar{1}$], and [0$\bar{1}$0] orientations of Cr^{4+}:YAG, which was more easily to be complete bleached, τ_p was constant, otherwise τ_p decreased when the gain increased.

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