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Comparison between *c*-cut and *a*-cut Nd:YVO_4 lasers passively Q-switched with a Cr^{4+}:YAG saturable absorber

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ABSTRACT Comparison between *c*-cut and *a*-cut Nd:YVO_4 microchip lasers passively Q-switched with a Cr^{4+}:YAG saturable absorber is experimentally made. The lower emission cross section of the *c*-cut Nd:YVO_4 crystal can enhance the passive Q-switching effect to produce a peak power 10 times higher than that obtained with the *a*-cut crystal. The experimental result further reveals that a *c*-cut Nd:YVO_4 crystal is a very convenient material for short-pulse (sub-nanosecond) and high-peak-power (> 10 kW) lasers.

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1 Introduction

Compact, all-solid-state pulse lasers are of potential interest for numerous applications such as ranging, remote sensing, and microsurgery [1]. Diode-pumped Q-switched microchip lasers are compact efficient solid-state lasers with a diffraction-limited output beam. Passive techniques that use saturable absorbers have the advantages of potentially lower cost and simplicity in fabrication and operation since they require no high-voltage or RF drivers. In recent years, Cr^{4+}:YAG crystals have been successfully used as passive Q-switches for a variety of gain media such as Nd:YAG [2], Nd:YVO_4 [3], and Nd:$GdVO_4$ crystals [4]. So far, only passively Q-switched Nd:YAG/Cr^{4+}:YAG lasers can generate extremely short (< 1 ns) high-peak-power (> 10 kW) pulses. The relatively narrow absorption band of a Nd:YAG crystal, however, sets stringent requirements on the spectrum of the pump diodes. Although microchip lasers passively Q-switched with a semiconductor saturable absorber mirror (SESAM) typically generate much shorter pulses compared to those using bulk-crystal absorbers, the pulse energy of Nd-doped microchip lasers was typically around 100 nJ [5].

YVO_4 and $GdVO_4$ crystals belong to the group of oxide compounds crystallizing in a zircon structure with a tetragonal space group. The four-fold-symmetry axis is the crystallographic *c* axis. Perpendicular to this axis are the two indistinguishable *a* and *b* axes. The uniaxial Nd:YVO_4 and $GdVO_4$ crystals show strong polarization-dependent fluorescence emission due to the anisotropic crystal field. In a Nd:YVO_4 crystal, for example, the stimulated emission cross section parallel to the *c* axis, $\sigma_\parallel = 25 \times 10^{-19}\,\mathrm{cm}^2$, is four times higher than that orthogonal to the *c* axis, $\sigma_\perp = 6.5 \times 10^{-19}\,\mathrm{cm}^2$, for the emission wavelength at 1064 nm [6]. A larger stimulated emission cross section normally results in a lower pumping threshold for cw or actively Q-switched laser operation. Therefore, the conventional Nd:YVO_4 or $GdVO_4$ crystals are cut along the *a* axis, i.e. so-called *a*-cut, to use the stimulated emission cross section of $\sigma_\parallel$ to dominate the laser oscillation.

On the contrary, the large stimulated emission cross section may be disadvantageous for a passively Q-switched laser. For good passive Q-switching, the saturation in the absorber must occur before the gain saturation in the laser crystal (the second threshold condition) [7]. From the analysis of the coupled rate equations, the criterion for good passive Q-switching is given by [8]:

$$\frac{\ln\left(\frac{1}{T_0^2}\right)}{\ln\left(\frac{1}{T_0^2}\right)+\ln\left(\frac{1}{R}\right)+L}\,\frac{\sigma_{\mathrm{gs}}}{\sigma}\,\frac{A}{A_{\mathrm{S}}} \gg \frac{\gamma}{1-\beta} \tag{1}$$

where T_0 is the initial transmission of the saturable absorber, A/A_{s} is the ratio of the effective area in the gain medium to that in the saturable absorber, R is the reflectivity of the output mirror, L is the nonsaturable intracavity round-trip dissipative optical loss, σ_{gs} is the ground-state absorption cross section of the saturable absorber, σ is the stimulated emission cross section of the gain medium, γ is the inversion reduction factor with a value between 0 and 2 as discussed in [9], and β is the ratio of the excited-state absorption cross section to that of the ground-state absorption in the saturable absorber. Since the $\sigma_\parallel$ value of the Nd:YVO_4 crystal is comparable to the σ_{gs} value of the Cr^{4+}:YAG crystal ($\sim (20 \pm 5) \times 10^{-18}\,\mathrm{cm}^2$ [7]), using a Cr^{4+}:YAG crystal as a saturable absorber in *a*-cut Nd:YVO_4 lasers generally produces a longer pulse width and a lower peak power, usually less than 1 kW [3, 4].

When a Nd:YVO_4 crystal is cut along the *c* axis, i.e. *c*-cut, the effective stimulated emission cross section is dominated by $\sigma_\perp$ instead of $\sigma_\parallel$. Since $\sigma_\perp$ is four times smaller than $\sigma_\parallel$, the *c*-cut Nd:YVO_4 crystal may be more appropri-

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ate than the *a*-cut Nd:YVO$_4$ crystal with a Cr^{4+}:YAG crystal as a saturable absorber, as indicated in the criterion of (1). In this work, we make an experimental comparison between *c*-cut and *a*-cut Nd:YVO$_4$ lasers passively Q-switched with a Cr^{4+}:YAG saturable absorber. The results reveal that a *c*-cut Nd:YVO$_4$ crystal is a very convenient material for short-pulse (< 2.5 ns) and high-peak-power (> 5 kW) lasers. Using a Cr^{4+}:YAG crystal with an initial transmission of 60%, more than 21-kW peak output power was obtained at the incident pump power of 2.4 W. The corresponding pulse width and the repetition rate were 0.85 ns and 13.5 kHz. Although the absorption bandwidth of the *c*-cut Nd:YVO$_4$ crystal is slightly narrower than that of the *a*-cut one with the same doping concentration, it is still three times wider than that of the standard Nd:YAG crystal and could be efficiently pumped by a laser diode without thermal regulation.

Figure 1a and b are schematics of the present resonators for cw and passively Q-switched lasers, respectively. The pump source is a 2.5-W fiber-coupled diode-laser array (Coherent) with a core size of 200 μm and a numerical aperture of 0.18. The output wavelength of the diode laser ranges from 807 to 810 nm at 25 °C. A focusing lens with 20-mm focal length is used to re-image the pump beam onto the laser crystal. The waist diameter of the pump beam was about 100 μm. The laser crystal is 5-mm long and doped with 1.0% Nd^{3+} concentration. One side of the Nd:YVO$_4$ crystal was coated so as to be nominally highly reflecting at 1064 nm ($R > 99.8\%$) and anti-reflection-coated at 808 nm ($T > 90\%$). The other side was anti-reflection-coated at 1064 nm ($R < 0.2\%$). The output coupler mirror used in the cw laser was a 1-m radius-of-curvature concave mirror with 85% reflectance at 1064 nm. In the passively Q-switched laser experiment, one side of the Cr^{4+}:YAG crystal was partial-reflection-coated at 1064 nm ($R = 75\%$) so as to be an output coupler. The other side of the Cr^{4+}:YAG crystal was anti-reflection-coated at 1064 nm ($R < 0.2\%$). Several Cr^{4+}:YAG crystals with different initial transmissions ($T_0 = 0.80$, $T_0 = 0.70$, and $T_0 = 0.60$) were used in the experiment. The final transmissions for Cr^{4+}:YAG crystals can be approximated as $(T_0)^{\beta}$, where the parameter β was measured to be around 0.23. The nonsaturable losses can be estimated to be $1-(T_0)^{\beta}$. The total cavity length was approximately 6–7 mm. The pulse temporal behavior was recorded by a LeCroy 9362 oscilloscope (500-MHz bandwidth) and a fast Si PIN photodiode with a rise time of ~ 0.35 ns. For all results shown the output was operating in a TEM$_{00}$ mode.

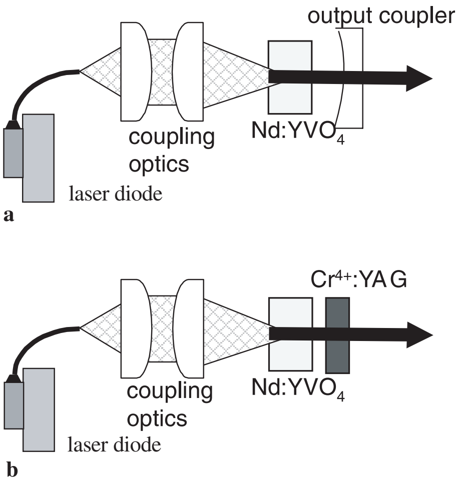

FIGURE 1 **a** Schematics for cw Nd:YVO$_4$ laser. **b** Schematics for passively Q-switched Nd:YVO$_4$/Cr^{4+}:YAG lasers

Figure 2 shows the cw output power of *a*-cut and *c*-cut Nd:YVO$_4$ lasers as a function of incident pump power. As is seen, thresholds of 0.28 W and 0.95 W and slope efficiencies of 63% and 73% were obtained for the *a*-cut and *c*-cut Nd:YVO$_4$ crystals, respectively. A higher threshold for the *c*-cut Nd:YVO$_4$ crystal was expected because of a lower stimulated emission cross section, compared with the *a*-cut crystal. Nevertheless, a higher slope efficiency for the *c*-cut Nd:YVO$_4$ crystal indicates that its intrinsic loss is distinctly smaller than that of the *a*-cut crystal. For the measurements at different output couplings the intrinsic losses were estimated to be 2.8% and 0.5% for the *a*-cut and *c*-cut Nd:YVO$_4$ crystals, respectively.

Figure 3 shows the average output power of *a*-cut and *c*-cut Nd:YVO$_4$ passively Q-switched lasers as a function of incident pump power with a saturable absorber of $T_0 = 0.80$. It can be seen that the threshold pump powers for passive Q-switched behavior are 1.0 and 1.6 W for the *a*-cut and *c*-cut Nd:YVO4 crystals, respectively. Although the threshold of the *c*-cut crystal is higher, the corresponding slope efficiency of 53.3% is significantly higher than 23.3% obtained in the *a*-cut Nd:YVO$_4$ passively Q-switched laser. Figure 4 shows the pulse-repetition rate versus the incident pump power for both lasers. It is seen that increasing the pump power increases the pulse-repetition rate in the *c*-cut Nd:YVO$_4$/Cr^{4+}:YAG passively Q-switched laser, whereas the repetition rate in the *a*-cut case is nearly independent of the pump power. Figures 5 and 6 illustrate the pulse energy and the pulse width, respectively, versus the incident pump power for both

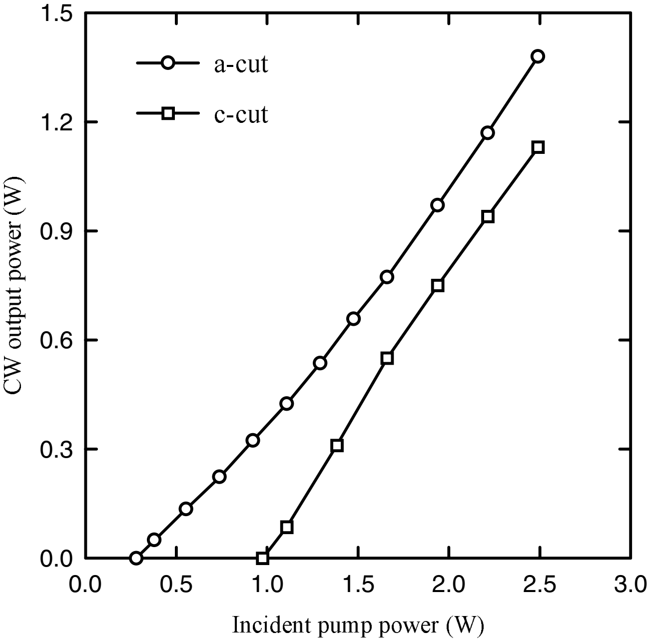

FIGURE 2 The cw output power of *a*-cut and *c*-cut Nd:YVO$_4$ lasers as a function of incident pump power

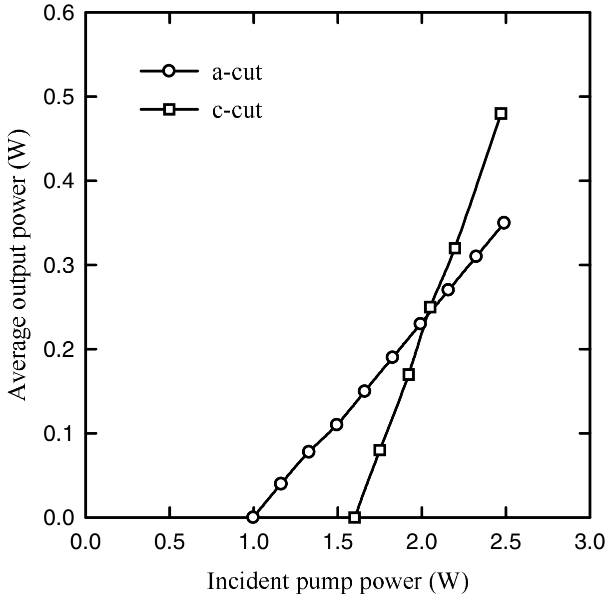

FIGURE 3 The average output power of *a*-cut and *c*-cut Nd:YVO_4 passively Q-switched lasers as a function of incident pump power with a saturable absorber of $T_0 = 0.80$

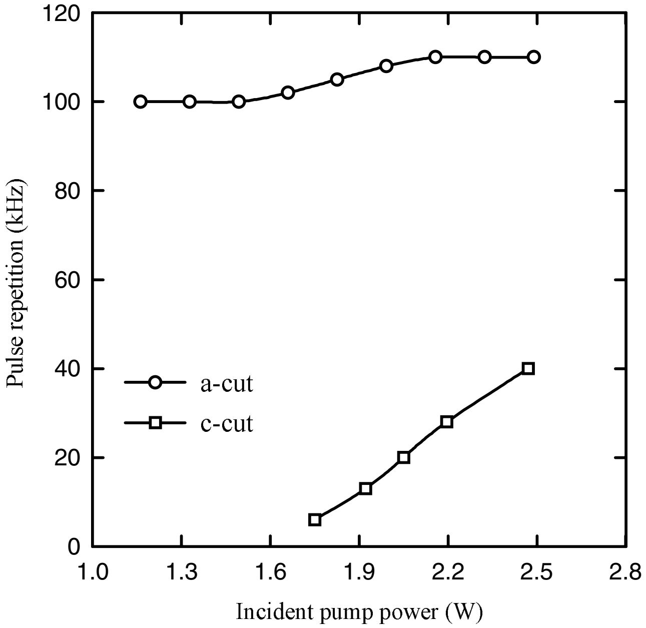

FIGURE 4 The pulse-repetition rate versus the incident pump power for *a*-cut and *c*-cut Nd:YVO_4 passively Q-switched lasers

lasers. Like typical systems, such as a Nd:YAG/Cr^{4+}:YAG passively Q-switched laser, both the pulse energy and the pulse width are insensitive to the pump power in the *c*-cut Nd:YVO_4/Cr^{4+}:YAG passively Q-switched laser. In contrast to this insensitivity, increasing the pump power substantially increases the pulse energy and decreases the pulse width in the *a*-cut Nd:YVO_4/Cr^{4+}:YAG passively Q-switched laser. This atypical behavior has been discussed in [10] and is attributed to the effect of the pumping rate. As estimated from Figs. 5 and 6, at a pump power of 2.4 W the peak powers are 0.57 and 5.8 kW for the *a*-cut and *c*-cut Nd:YVO_4 cases, respectively. This result confirms that the *c*-cut Nd:YVO_4 crystal is more appropriate than the *a*-cut crystal for the passively Q-switched microchip laser with a Cr^{4+}:YAG saturable absorber.

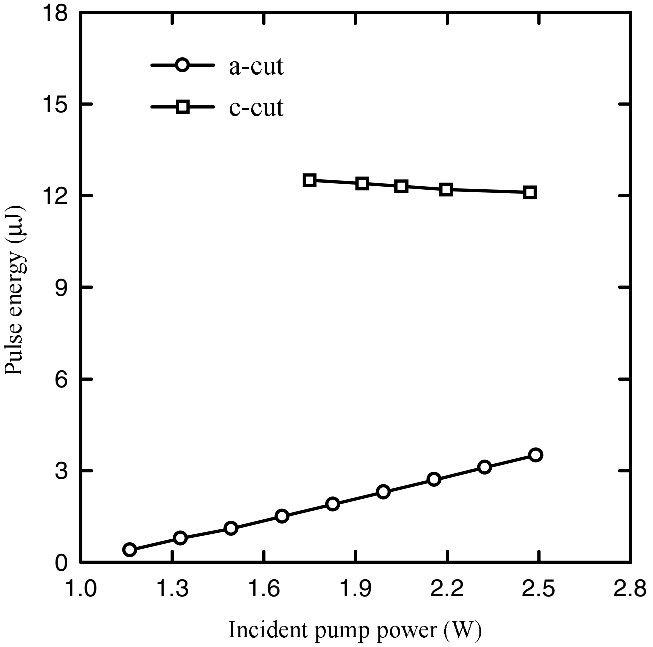

FIGURE 5 The pulse energy versus the incident pump power for *a*-cut and *c*-cut Nd:YVO_4 passively Q-switched lasers

In the *c*-cut Nd:YVO_4/Cr^{4+}:YAG passively Q-switched laser, a decrease in the initial transmission of the absorber resulted in an increase of the pulse energy and a decrease of the pulse width, thus leading to a higher peak power. When the Cr^{4+}:YAG crystal with an initial transmission of 60% was used, the pulse energies reach a level of 18 μJ with a pulse width of 0.85 ns at a pump power of 2.4 W. The correspond-

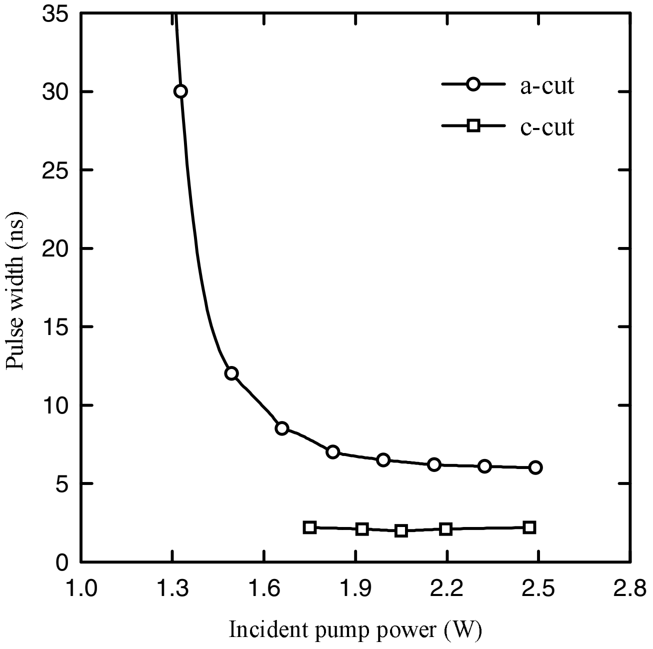

FIGURE 6 The pulse width versus the incident pump power for *a*-cut and *c*-cut Nd:YVO_4 passively Q-switched lasers

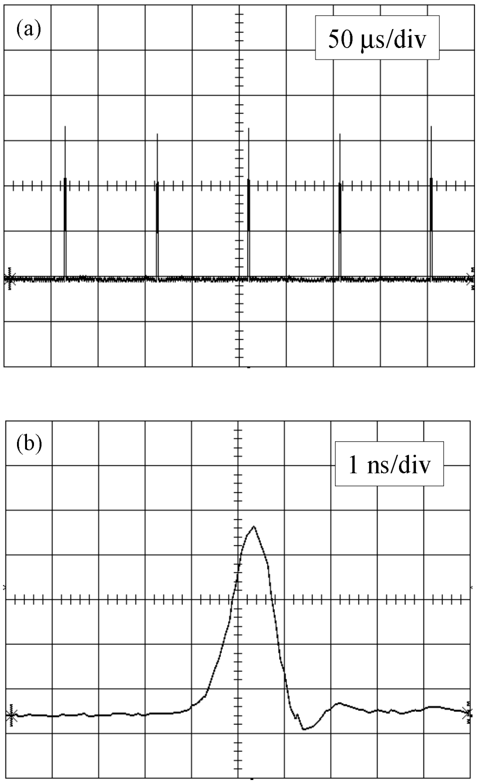

FIGURE 7 Oscilloscope traces of a train of output pulses; the *lower* trace is an expanded shape of a single pulse, showing a 0.85-ns width (FWHM)

ing peak power exceeds 21 kW at a pulse-repetition rate of 13.5 kHz and the conversion efficiency of the pump power into the average output power was about 10.1%. The inter-pulse time jittering is generally less than ±4%. A typical oscilloscope trace is presented in Fig. 7. The pulse-to-pulse amplitude fluctuation of the Q-switched pulse train was found to be less than ±5%. The output-beam quality was nearly the same for both laser cavities and the M^2 parameter has been estimated to be < 1.2 over the complete output power range with the algorithms of the knife-edge technique. Previously, Zayhowski and Dill [2] demonstrated a passively Q-switched Nd:YAG/Cr^{4+}:YAG microchip laser in which 11-µJ pulses of 0.337-ns duration at a pulse-repetition rate of 6 kHz were produced at a pump power of 1.2 W and the corresponding conversion efficiency was 5.5%. Compared with the Nd:YAG/Cr^{4+}:YAG microchip laser, the present results have a comparable peak output power and a higher optical conversion efficiency. This is mainly due to the fact that the *c*-cut 1% doped Nd:YVO_4 crystal has lower intrinsic losses [6] and its effective stimulated emission cross section is close to that of the Nd:YAG crystal in magnitude. Referring to the pulse duration, a two-fold pulse shortening should be feasible in our set-up using a cavity with a shorter *c*-cut 2% doped Nd:YVO_4 crystal.

In summary, the studies of the present performance indicate that a *c*-cut Nd:YVO_4 crystal is a very convenient material for short-pulse (sub-nanosecond) and high-peak-power (> 10 kW) lasers. It is demonstrated that 18-µJ pulses of 0.85-ns duration at a pulse-repetition rate of 13.5 kHz can be generated at a pump power of 2.4 W. The main advantages of the *c*-cut Nd:YVO_4 crystal are the combination of its high absorption cross section, wide absorption bandwidth, and low intrinsic losses. In addition to the *c*-cut Nd:YVO_4 crystal, we believe that the results presented here can be usefully applied to the *c*-cut Nd:$GdVO_4$ crystal for the design of reliable and simple sub-nanosecond (and even < 500 ps) lasers for various applications.

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