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Efficient sub-nanosecond intracavity optical parametric oscillator pumped with a passively Q-switched Nd:GdVO$_4$ laser

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ABSTRACT An efficient diode-pumped passively Q-switched Nd:GdVO$_4$/Cr^{4+}:YAG laser was employed to generate a high-repetition-rate, high-peak-power eye-safe laser beam with an intracavity optical parametric oscillator (OPO) based on a KTP crystal. The conversion efficiency for the average power is 8.3% from pump diode input to OPO signal output and the slope efficiency is up to 10%. At an incident pump power of 14.5 W, the compact intracavity OPO cavity, operating at 46 kHz, produces average powers at 1571 nm up to 1.2 W with a pulse width as short as 700 ps.

PACS 42.60.Gd; 42.65.Yj; 42.55.X

1 Introduction

Recently, neodymium-doped gadolinium orthovanadate (Nd:GdVO$_4$) has proved to be an excellent gain medium due to its high absorption coefficient and large thermal conductivity [1–4]. Up to now, the output wavelengths of the researches involving Nd:GdVO$_4$ crystals were mostly focused on 1.06, 1.34, 0.53, and 0.67 μm [5–9]. One area that demands particular attention is the so-called eye-safe region of the spectrum near 1.5–1.6 μm. Extremely short (< 1 ns) high-peak-power (> 10 kW) pulses of lasers at the eye-safe wavelength region are practically valuable for applications such as telemetry and range finders. One approach for high-peak-power eye-safe laser sources is based on intracavity optical parametric oscillators (OPOs) [10]. The advent of high-damage-threshold nonlinear crystals and diode-pumped Nd-doped lasers has led to a renaissance of interest in intracavity OPOs [11–13]. Recently, we demonstrated a compact efficient eye-safe OPO pumped by a diode-pumped passively Q-switched Nd:YVO$_4$ laser to produce peak powers at 1573 nm higher than 1 kW with pulse widths of 2.5 ns [14]. Compared with Nd:YVO$_4$ lasers, all the experimental results to date have revealed that Nd:GdVO$_4$ crystals may be potentially more competent than Nd:YVO$_4$ crystals in diode-pumped solid-state lasers. Even so, diode-pumped Nd:GdVO$_4$ lasers have never been used to pump intracavity OPOs for generation of an eye-safe laser beam.

In this work we report, for the first time to our knowledge, the generation of a laser beam from an efficient sub-nanosecond intracavity OPO based on a diode-pumped passively Q-switched Nd:GdVO$_4$ laser. With an incident pump power of 14.5 W, the compact intracavity OPO cavity, operating at 46 kHz, produces average powers at 1571 nm up to 1.2 W with pulse widths shorter than 700 ps and peak powers higher than 20 kW.

2 Experimental setup

A schematic of the passively Q-switched intracavity OPO laser is shown in Fig. 1. Here a saturable absorber Cr^{4+}:YAG crystal is coated as an output coupler of the OPO cavity and a nearly hemispherical cavity is used to enhance the performance of passive Q-switching. The OPO cavity was formed by a coated KTP crystal and a coated Cr^{4+}:YAG crystal. The 20-mm-long KTP crystal was used in type II noncritical phase-matching configuration along the x axis ($\theta = 90°$ and $\phi = 0°$) to have both a maximum effective nonlinear coefficient and no walk-off between the pump, signal, and idler beams. The KTP crystal was coated to have high reflectivity at the signal wavelength of 1571 nm ($R > 99.8\%$) and high transmission at the pump wavelength of 1063 nm ($T > 95\%$). The other face of the KTP crystal was antireflection coated at 1571 nm and 1063 nm. The Cr^{4+}:YAG crystal has a thick-

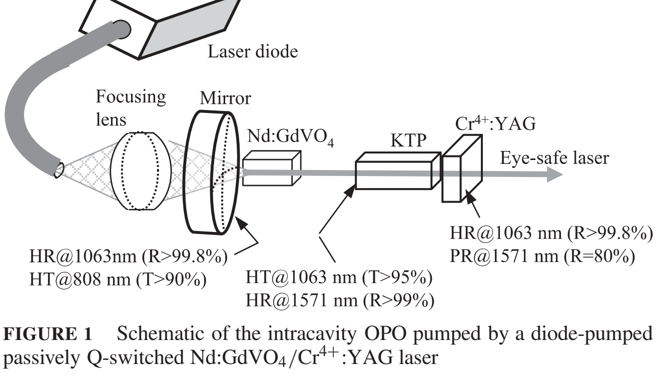

FIGURE 1 Schematic of the intracavity OPO pumped by a diode-pumped passively Q-switched Nd:GdVO$_4$/Cr^{4+}:YAG laser

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ness of 3 mm with 80% initial transmission at 1063 nm. One side of the Cr^{4+}:YAG crystal was coated so that it was nominally highly reflecting at 1063 nm ($R > 99.8\%$) and partially reflecting at 1571 nm ($R = 80\%$). The remaining side was antireflection coated at 1063 and 1571 nm. The active medium was an *a*-cut 0.25 at. % Nd^{3+}, 8-mm-long $Nd:GdVO_4$ crystal. Both sides of the laser crystal were coated for antireflection at 1063 nm ($R < 0.2\%$). A $Nd:GdVO_4$ crystal with low doping concentration was used to avoid the thermally induced fracture [15]. All crystals were wrapped with indium foil and mounted in water-cooled copper blocks. The water temperature was maintained at 25 °C. The pump source was a 16-W, 808-nm fiber-coupled laser diode with a core diameter of 800 μm and a numerical aperture of 0.2. A focusing lens with 12.5-mm focal length and 92% coupling efficiency was used to re-image the pump beam into the laser crystal. The pump spot radius was around 350 μm. The input mirror was a 50-mm radius-of-curvature concave mirror with an antireflection coating at the diode wavelength on the entrance face ($R < 0.2\%$), a high-reflection coating at lasing wavelength ($R > 99.8\%$) and a high-transmission coating at the diode wavelength on the other surface ($T > 95\%$). The overall $Nd:GdVO_4$ laser cavity length was approximately 59 mm and the OPO cavity length was about 25 mm.

From the analysis of the coupled rate equations, the criterion for good passive Q-switching is given by [16–18]

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

where T_0 is the initial transmission of the saturable absorber, A/A_{s} is the ratio of the effective areas in the gain medium and 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 [19], 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 ratio A/A_{s} in the present cavity is generally greater than 10, the criterion for good passive Q-switching can be satisfied under the circumstance that the σ value of the $Nd:GdVO_4$ crystal is comparable to the σ_{gs} value of the Cr^{4+}:YAG crystal.

3 Experimental results

Figure 2 shows the average output power at 1571 nm with respect to the incident pump power. For all pump powers the beam quality M^2 factor was found to be less than 2.0. The average output power reached 1.2 W at an incident pump power of 14.5 W. The conversion efficiency from diode laser input power to OPO signal output power was 8.3%. The pulse temporal behavior at 1063 nm and 1571 nm was recorded by a LeCroy 9362 digital oscilloscope (500-MHz bandwidth) with a fast InGaAs photodiode. The pulse-to-pulse amplitude fluctuation was found to be within ±10%.

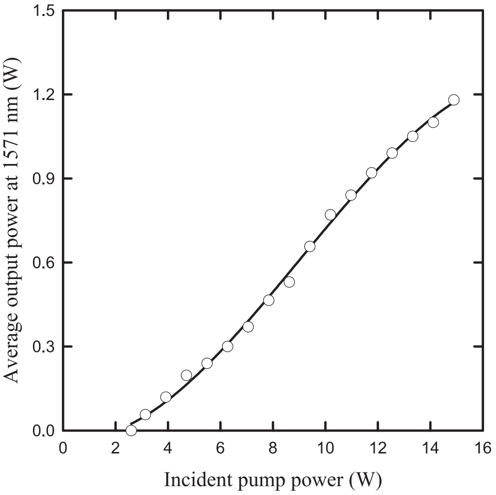

FIGURE 2 The average output power at 1571 nm with respect to the incident pump power

Figure 3 depicts the pulse-repetition rate and the pulse energy at 1571 nm versus the incident pump power. It is seen that the pulse-repetition rate initially increases with the pump power, and begins to saturate at 40–46 kHz for an incident pump power greater than 10 W. A typical temporal shape for the laser and signal pulses is shown in the inset of Fig. 4. As seen (Fig. 3), the pulse energy is nearly constant for a pump power less than 10 W. Figure 4 shows a typical temporal trace for the laser and signal pulses for a pump power less than 10 W. It can be seen that the pulse duration of the signal output was as short as 600–700 ps. As a consequence, the peak power was found to be higher than 20 kW. On the other hand, the stored energy is not fully extracted in a single output pulse for a pump power higher than 10 W. Since the remaining energy is sufficient to evolve the pump field, the OPO threshold can be reached again and a second signal pulse is produced, as shown in Fig. 5. The multiple-pulse output makes the pulse energy to linearly increase with the pump power beyond 10 W of the incident pump power, as seen in

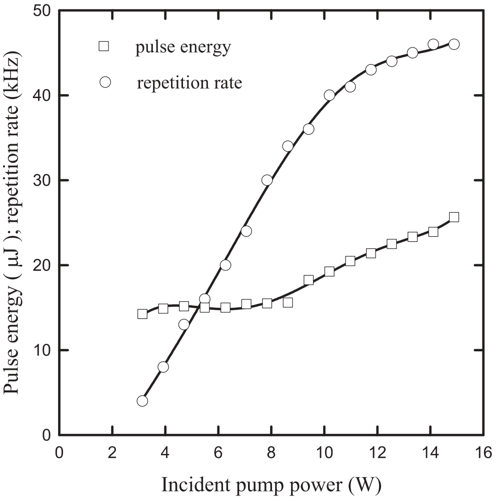

FIGURE 3 Dependence of the pulse-repetition rate and the pulse energy at 1571 nm on the incident pump power

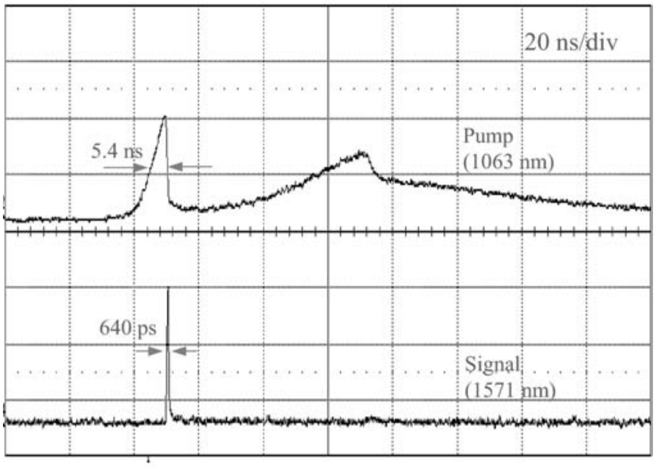

FIGURE 4 Typical temporal traces for the laser and signal pulses for pump power less than 10 W

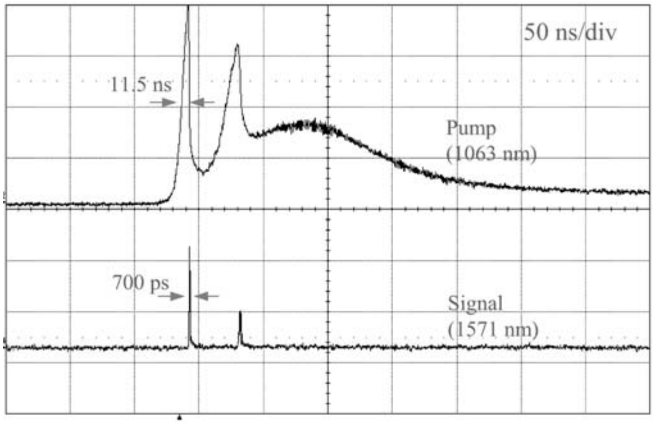

FIGURE 5 Typical temporal traces for the laser and signal pulses for pump power higher than 10 W

Fig. 3. The output energy of the main pulse for high pump power is found to be approximately 15 μJ, nearly the same as the value of the pulse energy at a pump power less than 10 W. Since the pulse duration of the main pulse is typically shorter than 700 ps, the overall peak power can still be higher than 20 kW.

4 Summary

An efficient sub-nanosecond diode-pumped passively Q-switched eye-safe laser has been demonstrated by using Nd:GdVO$_4$, Cr^{4+}:YAG, and KTP crystals to be a gain medium, a saturable absorber, and a nonlinear crystal for an intracavity OPO, respectively. A nearly hemispherical cavity was employed to enhance the performance of passive Q-switching. At an incident pump power of 14.5 W, the average output power at 1571 nm can amount to 1.2 W with a pulse-repetition rate of 46 kHz and a peak power > 20 kW.

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