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# Compact efficient intracavity optical parametric oscillator with a passively Q-switched $Nd:YVO_4/Cr^{4+}:YAG$ laser in a hemispherical cavity

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**ABSTRACT** A compact eye-safe optical parametric oscillator (OPO) using a noncritically phase-matched KTP crystal intracavity pumped by a passively Q-switched $Nd:YVO_4$ laser is experimentally demonstrated. To enhance the performance of passive Q-switching, a $Cr^{4+}:YAG$ saturable absorber crystal is coated as an OPO output coupler in a nearly hemispherical cavity. With an incident pump power of 2.5 W, the compact intracavity OPO cavity, operating at 62.5 kHz, produces average powers at 1573 nm up to 255 mW and peak powers higher than 1 kW.

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## 1 Introduction

Compact pulsed lasers with emission at the eyesafe wavelength region (1.5–1.6 μm) are of great interest for many applications such as telemetry and range finders [1]. The need for high-peak-power eyesafe laser sources has stimulated much interest in intracavity optical parametric oscillators (OPO's). Although intracavity OPO's have been proposed for over 30 years [2–4], only recently have their merits been appreciated, with the advent of high-damage-threshold nonlinear crystals and diode-pumped Nd-doped lasers [1, 5–7].

Diode-pumped Q-switched microchip lasers are compact efficient solid-state lasers with a diffraction-limited output beam. Saturable-absorber Q-switching has the advantages of potentially lower cost and simplicity in fabrication and operation. In recent year, $Cr^{4+}:YAG$ crystals have been successfully used as passive Q-switches for a variety of gain media such as $Nd:YAG$ [8], $Nd:YVO_4$ [9–11], and $Nd:GdVO_4$ crystals [12], etc. $Nd:YVO_4$ and $Nd:GdVO_4$ crystals have several advantages over $Nd:YAG$ crystals, including higher absorption cross section, wider absorption bandwidth, and a polarized output. The linearly polarized laser output is beneficial not only to non-linear wavelength conversion, but also to avoiding of undesired birefringent effects. It is, however, usually difficult to operate a diode-pumped passively Q-switched $Nd:YVO_4$ and $Nd:GdVO_4$ lasers with $Cr^{4+}:YAG$ saturable absorbers because of their large emission cross-sections. For good passive Q-switching, absorption saturation in the absorber must occur before gain saturation in the laser crystal (the second threshold condition) [13, 14]. Even though passively Q-switched $Nd:YVO_4$ and $Nd:GdVO_4$ lasers have been demonstrated [9–12], the output pulse energy and peak power are obviously lower than those of $Nd:YAG$ laser. Therefore, so far the pumped sources for passively Q-switched intracavity OPO's are mostly composed of $Nd:YAG$ and $Cr^{4+}:YAG$ crystals. The relatively narrow absorption band of $Nd:YAG$ crystal, however, sets stringent requirements on the spectrum of the pump diodes.

In this work we report a compact, efficient scheme for generating 1573-nm laser based on intracavity OPO of a diode-pumped passively Q-switched $Nd:YVO_4/Cr^{4+}:YAG$ laser. With an incident pump power of 2.5 W, the compact intracavity OPO cavity, operating at 62.5 kHz, produces average powers at 1573 nm up to 255 mW and peak powers higher than 1 kW.

## 2 Experimental setup

Figure 1 is a schematic of the passively Q-switched intracavity OPO laser. The novelty is that a saturable absorber $Cr^{4+}:YAG$ 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 active medium was an *a*-cut 1.0 at. % $Nd^{3+}$, 2-mm-long $Nd:YVO_4$ crystal. Both sides of the laser crystal were coated for antireflection at 1064 nm ($R < 0.2\%$). The pump source was a 2.5-W 808-nm fiber-coupled laser diode with a core diameter of 200 μm and a numerical aperture of 0.16. Focusing

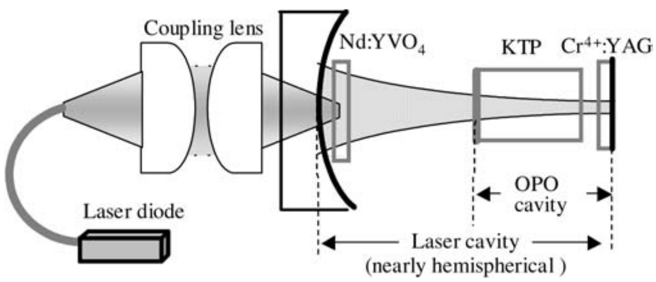


**FIGURE 1** Schematic of the intracavity OPO pumped by a diode-pumped passively Q-switched $Nd:YVO_4/Cr^{4+}:YAG$ laser

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lens with 12.5 mm focal length and 95% coupling efficiency was used to re-image the pump beam into the laser crystal. The average pump-spot radius, $\omega_p$, was around 150 μm. The input mirror, $M_1$, was a 50 mm radius-of-curvature concave mirror with antireflection coating at the diode wavelength on the entrance face ($R < 0.2\%$), high-reflection coating at lasing wavelength ($R > 99.8\%$) and high-transmission coating at the diode wavelength on the other surface ($T > 95\%$). Note that the laser crystal was placed very near ($0.5 \sim 1$ mm) the input mirror. 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 $\varphi = 0°$) to have both a maximum effective nonlinear coefficient and no walk-off between the pump, signal, and idler beams [15–18]. The KTP crystal was coated to have high reflectivity at the signal wavelength of 1573 nm ($R > 99.8\%$) and high transmission at the pump wavelength of 1064 nm ($T > 95\%$). The other face of the KTP crystal was antireflection coated at 1573 nm and 1064 nm. The $Cr^{4+}$ : YAG crystal has a thickness of 2 mm with 80% initial transmission at 1064 nm. One side of the $Cr^{4+}$ : YAG crystal was coated so that it was nominally highly reflecting at 1064 nm ($R > 99.8\%$) and partially reflecting at 1573 nm ($R_s = 80\%$). The remaining side was antireflection coated at 1064 and 1573 nm. The overall Nd : $YVO_4$ laser cavity length was approximately 55 mm and the OPO cavity length was about 23 mm.

The mode beam radii $\omega_1$ on the laser crystal and $\omega_2$ on the saturable absorber can be given by

$$\omega_1 = \sqrt{\frac{\lambda L_c}{\pi}\sqrt{\frac{L_c}{R_c - L_c}}}\,, \quad \omega_2 = \sqrt{\frac{\lambda L_c}{\pi}\sqrt{\frac{R_c - L_c}{L_c}}}\,, \tag{1}$$

where $\lambda$ is the lasing wavelength, $L_c$ is the effective cavity length, and $R_c$ is the radius of curvature of the input mirror. The effective cavity length is given by $L_c = L_c^* + l(1/n - 1) + l_{KTP}(1/n_{KTP} - 1)$, $L_c^*$ is the cavity length, $n$ is the refractive indices along the $c$ axis of the Nd : $YVO_4$ crystal, $l$ is the length of the Nd : $YVO_4$ crystal, $l_{KTP}$ is the length of the KTP crystal, and $n_{KTP}$ is the KTP refractive index for the output laser beam. For the present cavity length of $L_c^* = 55$ mm, $\omega_1$ and $\omega_2$ can be calculated to be 225 μm and 71 μm, respectively. With $\omega_1 = 225$ μm and $\omega_p = 150$ μm, the ratio between the mode and pump area, $\alpha = (\omega_1/\omega_p)^2 = 2.25$, satisfies the design criterion of mode-matching optimization [19]. On the other hand, the ratio of the mode area in the gain medium and in the saturable absorber, $A/A_s = (\omega_1/\omega_p)^2 = 10$, satisfies the criterion for good passively Q-switching [13, 14].

## 3 Result and discussion

Figure 2 shows the average output power and the pulse repetition rate at 1573 nm with respect to the absorbed pump power. For all pump powers the beam quality $M^2$ factor was found to be less than 1.3. The average output power reached 255 mW, and the pulse repetition rate was 62.5 kHz at an incident pump power of 2.5 W. The threshold power and the slope efficiency were 1.1 W and 18.3%, respectively. The conversion efficient from diode laser input power to OPO signal output power was 10.2%. To the best of our knowledge, this is highest efficiency for average power conversion reported to date.

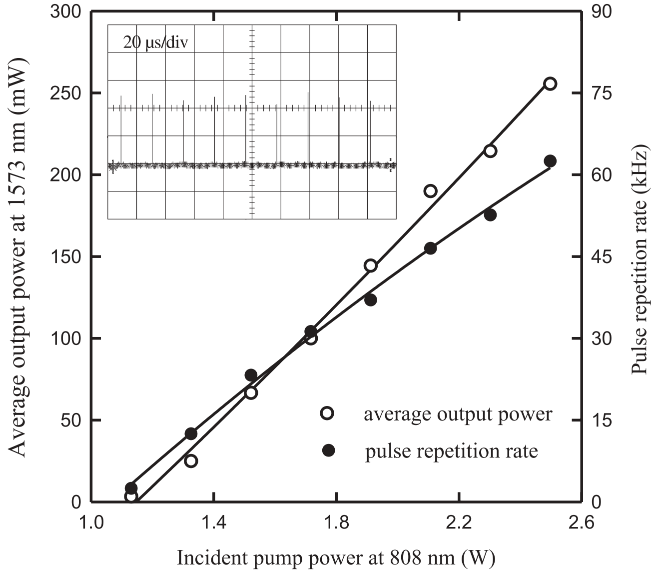


**FIGURE 2** Dependence of the average output power and the pulse repetition rate at 1573 nm on the absorbed pump power. An oscilloscope trace of a train of the signal pulses is shown in the *inset*

The pulse temporal behavior at 1573 nm was recorded by a LeCroy 9362 digital oscilloscope (500 MHz bandwidth) with a fast germanium photodiode. An oscilloscope trace of a train of the signal pulses is shown in the inset of Fig. 2. The pulse-to-pulse amplitude fluctuation was found to be within ±10%. Figure 3 shows typical temporal shapes for the laser and signal pulses. The relatively short signal pulse indicates that the OPO effectively cavity dumps the laser energy. Experimental results reveal that the signal pulse width decreases from 6.0 ns at threshold to 3.8 ns at 2.5 W of incident pump power. Figure 4 depicts the peak power and the pulse energy at 1573 nm versus the absorbed pump power. It is seen that the pulse energy initially increases with pump power, and is almost saturated

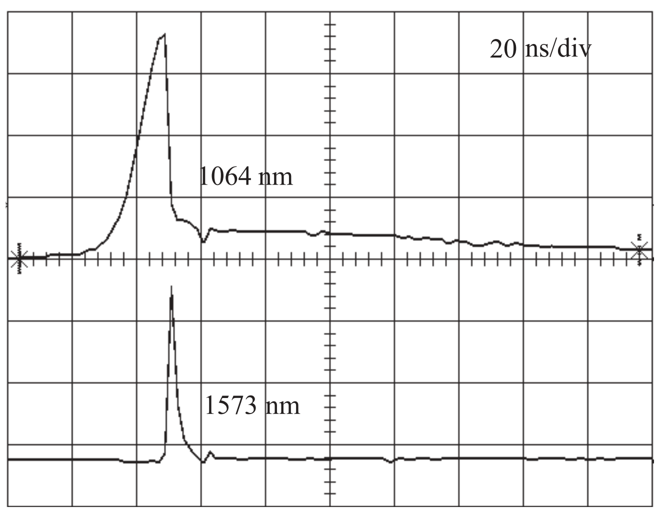


**FIGURE 3** Typical temporal shapes for the laser and signal pulses with a signal reflectivity of 80% on the output coupler

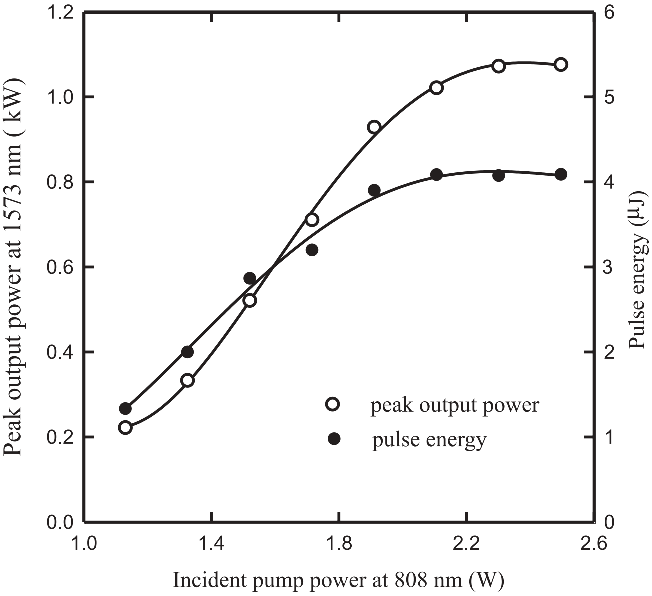


**FIGURE 4** Dependence of the peak power and the pulse energy at 1573 nm on the absorbed pump power

beyond 2 times the OPO threshold. The striking feature is that with the maximum pump power of 2.5 W the signal peak power can exceed 1 kW at a pulse repetition rate of 62.5 kHz.

Finally, it is worthwhile to mention that the temporal characteristics of the present cavity highly depend on the laser alignment, pump spot size and mirror reflectivity. As shown in Fig. 5, a train of laser and signal pulses is usually produced for a higher OPO reflectivity on the output coupler (Rs = 90%). Under the normal mode-matching circumstances, the output optimization of the present cavity mainly consists in the design of the output reflectivity. Experimental results reveal that the maximum conversion efficiency can be obtained with an output coupler of 85 ∼ 90% at the sacrifice of peak power. If the high peak power is desired, the output reflectivity needs to be around 60 ∼ 70%.

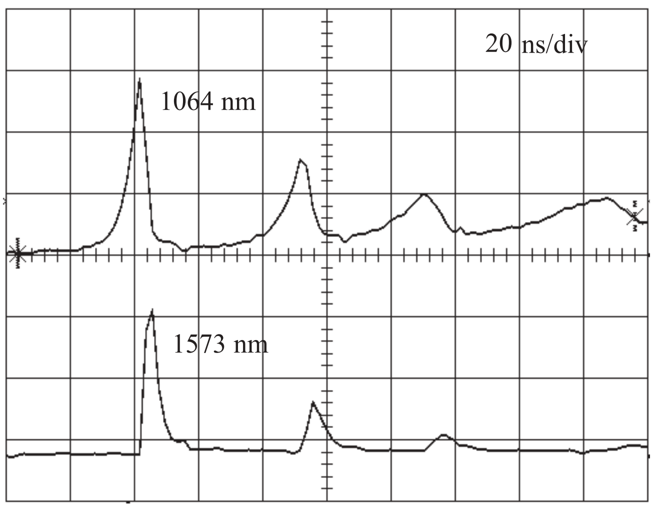


**FIGURE 5** Typical temporal shapes for the laser and signal pulses with a signal reflectivity of 90% on the output coupler

## 4 Summary

In summary, operation of a singly resonant pulsed KTP intracavity OPO pumped by a diode-pumped passively Q-switched $Nd:YVO_4/Cr^{4+}:YAG$ laser has been demonstrated. A saturable absorber $Cr^{4+}:YAG$ was coated as an output coupler of the OPO cavity to constitute a realistic, inexpensive source of eye-safe nanosecond laser. The low threshold power permits the use of a relatively low-power laser diode (2.5 W). The conversion efficiency for the average power is up to 10.2% from pump diode input to OPO signal output. The effective cavity dump of intracavity OPO leads to the relatively short signal pulse width with high repetition rates. As a consequence, the signal peak power can exceed 1 kW with a pulse repetition rate of 62.5 kHz at an incident pump power of 2.5 W.

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