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High-repetition-rate eye-safe optical parametric oscillator intracavity pumped by a diode-pumped Q-switched Nd:YVO$_4$ laser

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ABSTRACT A high-repetition-rate eye-safe optical parametric oscillator (OPO), using a non-critically phase-matched KTP crystal intracavity pumped by an acousto-optically (AO) Q-switched Nd:YVO$_4$ laser, is experimentally demonstrated. It is found that the average OPO signal power at 1573 nm can be efficiently increased by increasing the pulse repetition rate. Moreover, the intracavity OPO process effectively shortens the pulse width so that it is in the range 5 ∼ 8 ns for pulse repetition rates of 10 to 80 kHz. As a result of the relatively short pulse, the peak power at 1573 nm is higher than 2 kW at a pulse repetition rate of 80 kHz.

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1 Introduction

Nanosecond pulsed lasers emitting in the eye-safe wavelength region (1.5–1.6 μm) are indispensable for applications such as telemetry and for use in range finders [1]. The need for high-peak-power eye-safe laser sources has stimulated much interest in intracavity optical parametric oscillators (OPO's). Intracavity OPO's take advantage of a high power level within the oscillator to allow a low threshold and high efficiency compared to extracavity 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]. Several crystals belonging to the potassium titanyl phosphate (KTP) family, when pumped by Nd-doped laser pumps around 1050–1070 nm, generate signal wavelengths around 1.55 μm [8–11]. One advantage of the KTP family is the non-critical phase-matching configuration that allows a good OPO conversion efficiency even with poor-beam-quality pump lasers. Another advantage is the large available crystal size that allows the generation of high energies. Furthermore, using a diode-pumped Nd-doped laser to intracavity pump the OPO can offer a compact and rugged design with a low threshold and high efficiency.

The conventional intracavity OPO's, in which flash lamps or quasi-cw diodes are used as the pump sources, typically restrict operations to low repetition rates less than 1 kHz [12, 13]. Even though a compact diode-pumped Q-switched intracavity OPO has been demonstrated at frequency repetition rates from 1 to 20 kHz, the overall output peak power was less than 70 W [14]. A recent study has shown that a high-peak-power (> 1 kW) laser with a high repetition rate (> 10 kHz) is beneficial to the performance of a scanning, photon-counting laser altimeter [15].

In this work, we report the demonstration of a high-repetition-rate intracavity OPO based on a non-critically phase-matched KTP crystal excited by a cw-diode-pumped acousto-optically (AO) Q-switched Nd:YVO$_4$ laser operating at 10 ∼ 80 kHz. With an absorbed pump power of 12.6 W, the compact intracavity OPO cavity, operating at 80 kHz, produces average powers at 1.573 μm up to 1.33 W and peak powers higher than 2 kW.

2 Experimental

A schematic of the basic laser setup is shown in Fig. 1. The experimental setup makes use of a 0.8 mm core fiber with a numerical aperture of 0.16 and a maximum output power of 15 W. A focusing lens with a 12.5 mm focal length and 85% coupling efficiency was used to re-image the pump beam into the laser crystal. The waist diameter of the pump beam was around 300 μm. The fundamental cavity was formed by a coated Nd:YVO$_4$ crystal and an output coupler. The *a*-cut 0.3 at. % Nd^{3+}, 7-mm-long Nd:YVO$_4$ crys-

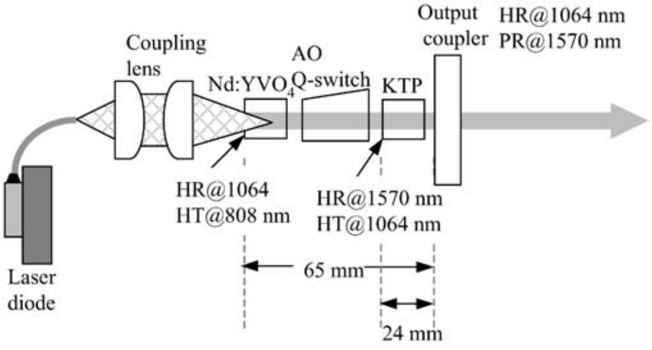

FIGURE 1 Schematic of the intracavity OPO pumped by a cw-diode-pumped AO Q-switched Nd:YVO$_4$ laser

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tal was coated for high reflectivity at 1064 nm ($R > 99.9\%$) and high transmission at 808 nm ($T > 95\%$) on one side. The other side was antireflection coated at 1064 nm. A Nd:YVO$_4$ crystal with only a low doping concentration was used to avoid the thermally induced fracture [16]. The output coupler had a dichroic coating that was highly reflective at 1064 nm ($R > 99.8\%$) and 85% partially reflective at 1573 nm. The 20-mm-long AO Q-switcher (Gooch and Housego) had antireflectance coatings at 1064 nm on both faces and was driven at a 40.68 MHz center frequency with 3.0 W of rf power. The OPO cavity was formed by a coated KTP crystal and an output coupler. The 20-mm-long KTP crystal was used in a type II non-critical 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. 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. Both the Nd:YVO$_4$ and KTP crystals were wrapped with indium foil and mounted in a water-cooled copper block. The water temperature was maintained at 25 °C. The overall Nd:YVO$_4$ laser cavity length was 65 mm and the OPO cavity length was 25 mm.

The present flat-flat cavity was stabilized by the thermally induced lens in the laser crystal. This concept was found at nearly the same time by Zayhowski [17] and by Dixon et al. [18]. However, an end-pump-induced thermal lens is not a perfect lens, but is rather an aberrated lens. The thermally induced diffraction losses have been found to rapidly increase with the increase of the mode-to-pump size ratio at a given pump power [19]. In practice, the optimum mode-to-pump ratio is in the range of approximately 0.8–1.0 when the incident pump power is greater than 5 W. In fact, the present cavity configuration has been applied to a diode-pumped Q-switched intracavity frequency-doubled Nd:YVO$_4$/KTP green laser [16]. It has been experimentally and theoretically shown that an excellent mode matching can be obtained for pump powers in the range 5 $\sim$ 20 W at a cavity length of approximately 60 $\sim$ 70 mm.

To avoid damage to the intracavity optical components, the Q switcher was operated above 10 kHz. Figure 2 shows the operation of the intracavity OPO for several pulse repetition rates. Over this entire frequency range and for all pump powers the beam quality M^2 factor was found to be less than 1.3. The threshold for signal parametric oscillation was approximately 3 $\sim$ 4 W and its dependence on different pulse repetition rates was not significant. At a repetition rate of 10 kHz, the average output power at 1573 nm was almost saturated to 0.26 W beyond 2.5 times the OPO threshold. In other words, the signal pulse energy was nearly saturated to 26 μJ beyond 2.5 times the OPO threshold. Although the maximum signal pulse energy is limited for the present cavity, increasing the pulse repetition rate can efficiently increase the average signal output power, as shown in Fig. 2. At a pulse repetition rate of 80 kHz, the average signal power was up to 1.33 W with an absorbed pump power of 12.6 W. The conversion efficiency from diode laser input power to OPO signal output power was 10.6% and the corresponding slope efficiency reached 15.5%. To the best of our knowledge, this is the highest efficiency for average power conversion reported to date. The pulse temporal behavior at 1573 nm was recorded by a LeCroy 9362 digital oscilloscope (500 MHz bandwidth) with a fast germanium photodiode. Figure 3 depicts the peak power and pulse width versus the absorbed pump power at a pulse repetition rate of 80 kHz. A typical 1573 nm pulse is shown in Fig. 4. It can be seen that the overall pulse width was shorter than 10 ns at a pulse repetition rate of 80 kHz. The relatively short signal pulse indicates that the OPO effectively cavity dumps the laser energy. The striking feature

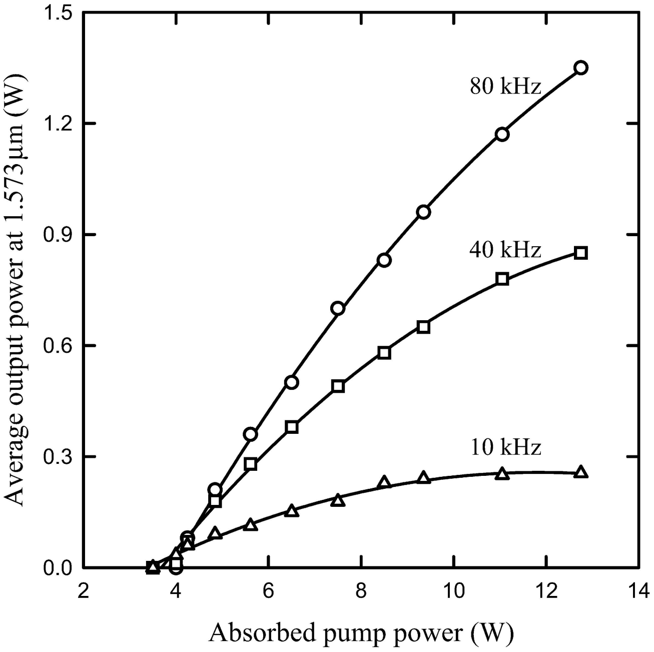

FIGURE 2 The average output power at 1573 nm versus the absorbed pump power for several pulse repetition rates

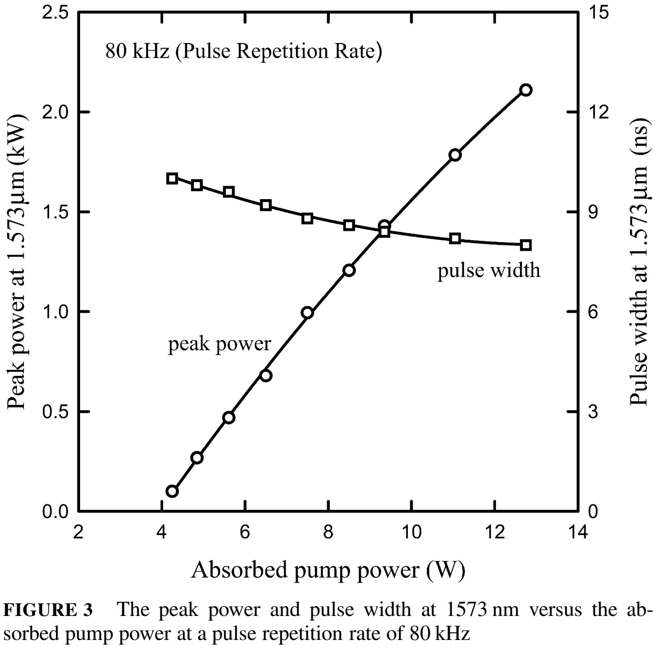

FIGURE 3 The peak power and pulse width at 1573 nm versus the absorbed pump power at a pulse repetition rate of 80 kHz

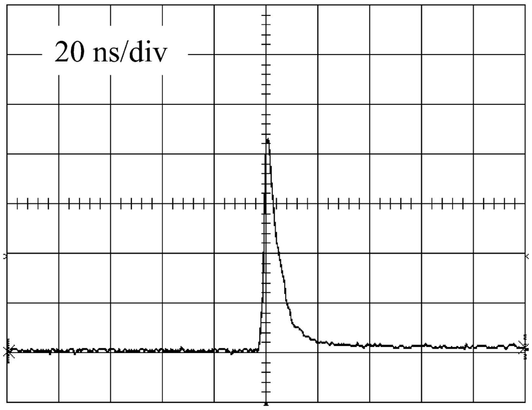

FIGURE 4 A typical pulse-shape at 1573 nm for a signal reflectivity of 85% on the output coupler

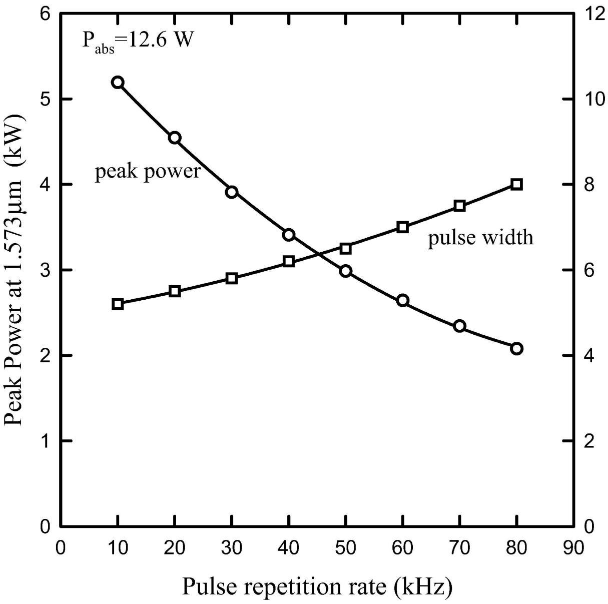

FIGURE 5 The dependence of the peak power and pulse width at 1573 nm on the pulse repetition rate at the maximum pump power of 12.6 W

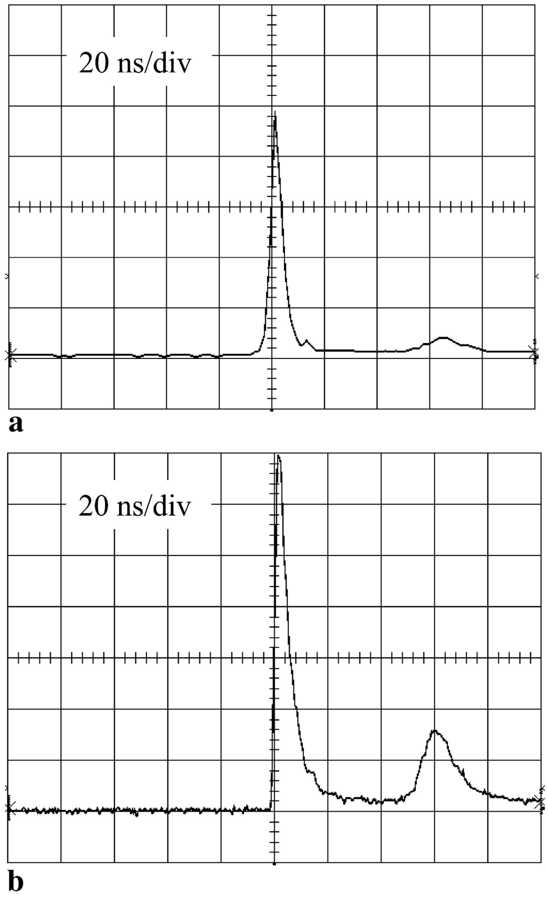

FIGURE 6 A typical pulse-shape at 1573 nm for signal reflectivities of **a** 90% and **b** 95% on the output coupler

is that with a 12.6 W absorbed pump power, the signal peak power can be higher than 2 kW at a pulse repetition rate of 80 kHz.

Figure 5 shows the dependence of the peak power and pulse width at 1573 nm on the repetition rate at a pump power of 12.6 W. Once again, the increase in the pulse width with increasing pulse repetition rate was not significant because of the effective cavity dump of the intracavity OPO. It can be seen that the pulse width slightly increased from 5 to 8 ns as the repetition rate varied from 10 to 80 kHz. As a result of the relatively short pulse, the peak power was generally on the order of several kilowatts at pulse repetition rates from 10 to 80 kHz.

Finally, experimental results reveal that the maximum signal pulse energy mainly depends on the signal reflectivity of the output coupler for a given cavity. In general, lowering the signal reflectivity results in higher signal pulse energies. This behavior was predicted in [20]. The maximum signal pulse energies were experimentally found to be 15, 20, and 26 µJ for signal reflectivities of 95, 90 and 85%, respectively. Increasing the signal reflectivity of the output mirror not only reduces the pulse energy, but also may lead to satellite pulses accompanying the signal pulse, as shown in Fig. 6. Therefore, the intracavity OPO can be improved by optimization of the signal reflectivity of the output mirror and by variation of the pulse repetition rate.

3 Conclusions

Operation of a singly resonant pulsed KTP intracavity OPO pumped by an AO Q-switched Nd:YVO4 laser has been demonstrated. Using a type II non-critically phase-matched x-cut KTP crystal, eye-safe signal radiation at 1573 nm was generated in a plane-parallel to the intracavity OPO resonator. It was found that the maximum pulse energy may saturate beyond a given above-threshold intracavity OPO factor, but increasing the signal reflectivity of the output coupler can efficiently increases the average output power. The conversion efficiency for the average power is up to 10.6% from pump diode input to OPO signal output. The effective cavity dump of intracavity OPO leads to a relatively short signal pulse width for repetition rates from 10 to 80 kHz. As a consequence, the peak power for signal output can be up to several kilowatts for the entire frequency range. The compact size and high efficiency of the present laser make it an attractive source for practical applications.

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