High-peak-power, high-repetition-rate intracavity optical parametric oscillator at 1.57 μm

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We report a high-peak-power, high-repetition-rate diode-side-pumped Nd:YAG Q-switched intracavity optical parametric oscillator (IOPO) at 1.57 μm with a type-II non-critically phase-matched x-cut KTP crystal. The average power of 1.15 W at 1.57 μm is obtained at 4.3-kHz repetition rate. The peak power of the pulses amounts to 33.4 kW with 8-ns duration. The average conversion efficiency from Q-switched 1.064-μm-wavelength input power to OPO signal output power is up to 10.5%.

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High-peak-power, high-repetition-rate 1.57-μm lasers have attracted much attention in many potential applications such as in pollution detection, communications, laser radar, remote sensing, target indicator, and high-repetition-rate laser range finder, due to their merits of locating in the "eye-safe" wavelength region and within an atmospheric transmission window.

The optical parametric oscillator (OPO) provides an efficient mean of obtaining pulsed 1.57-μm laser. Typically such a system consists of a separate pulsed pump laser and a nonlinear crystal in an external-cavity OPO (EOPO). The threshold of this configuration is very high (typically more than several millijoule)[1,2], which limits the repetition rate of the pump laser (usually hertz magnitude) and cannot meet the needs of some applications such as high-repetition-rate laser radar. Besides, extracavity configurations must satisfy the pump laser of single transverse mode and of high optical quality. Moreover, the pump laser needs to be focused tightly into the nonlinear crystal to achieve the OPO threshold, which reduces the mode-coupling efficiency and increases the damage to nonlinear medium and optical coatings. In comparison with EOPOs, intracavity OPO (IOPO) is to place the OPO cavity inside the cavity of the pump laser, which can overcome the issues mentioned above and take advantage of high fundamental power density within the oscillator to realize a low threshold and high efficiency[3−6]. In addition, the intracavity configuration increases the effective interaction length due to many round trips of the pump laser in OPO cavity, and it is easier to align and realize structure compactness than its external counterpart.

High-peak-power, high-repetition-rate 1.57-μm lasers with intracavity OPOs have been reported and studied by some researchers, however, the conventional pump sources using flash lamps or quasi-cw diodes restrict high-repetition-rate (> 1 kHz) operation[7−10]. In 2003, Chen *et al.*[11] firstly reported high-repetition-rate 1.57-μm output utilizing diode-end-pumped acousto-optically (AO) Q-switched $Nd:YVO_4$ lasers with an intracavity KTP-OPO. An output power of 1.33 W with the peak power of more than 2 kW was achieved at 80 kHz. Subsequently, Zendzian *et al.*[12] demonstrated 1.5-W output at 1.57 μm with the peak power of 8 kW at 40 kHz. In the literature mentioned above, high peak power 1.57-μm lasers were obtained by the diode-end-pumped configuration. The end-pumped laser system has some advantages of high efficiency and high beam quality because of excellent geometric match between the pump beam and the cavity mode. However, some disadvantages of the thermal stress inducing fractures of the laser crystal limit the output power scaling of end-pumped laser. On the contrary, the side-pumped configuration is useful for power scaling purpose because in this configuration longer laser crystal rod can be used and more number of diode lasers can be accommodated by placing them side-by-side.

In this paper, we present a diode-side-pumped Q-switched Nd:YAG laser as the pumping laser of IOPO. A high-peak-power, high-repetition-rate IOPO at 1.57 μm based on a non-critically phase-matched KTP crystal is experimentally demonstrated. The maximum average output power of 1.15 W was achieved at 4.3 kHz with a pulse width of 8 ns. The peak power amounts to 33.4 kW. The conversion efficiency with respect to Q-switched output at 1.064-μm wavelength is up to 10.5%. In addition, there is little green light observed during the experiment.

Figure 1 shows the experimental setup for our IOPO. The pump model consisted of 12 diode bars (808-nm wavelength, 20-W output power). The water faucet of

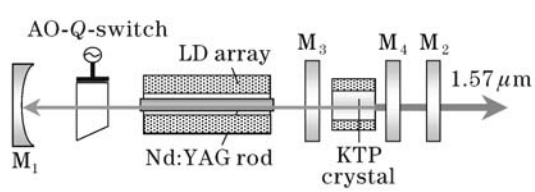

Fig. 1. Schematic diagram of the intracavity optical parametric oscillator.

the pump model can be connected to a water-cooled temperature control system. The Nd:YAG rod (3 mm in diameter, 75 mm in length) was plane-parallelly polished and antireflection-coated on both ends at 1064 nm. Considering the thermal lens effect of the Nd:YAG rod and the KTP crystal in high power operation, we employed a plano-concave cavity structure as the Nd:YAG cavity in order to utilize the high power density in the cavity and to increase the output power. The overall Nd:YAG laser cavity was 369 mm long and was formed by two high reflecting mirrors, M_1 and M_2. The rear mirror M_1 was a 2-m-radius curvature concave mirror with high reflectivity at 1064-nm wavelength, and the M_2 mirror was highly reflective at 1064 nm in order to decrease the laser oscillator threshod[13]. The OPO cavity was formed by mirrors M_3 and M_4, which were both antireflection-coated at 1064 nm. Moreover, M_3 was coated high-reflection at 1550—1630 nm. To avoid the production of several signal pulses and increase the output power[13,14], the transmission of M_4 was chosen to be 20% at 1550—1630 nm. The KTP crystal of the size $5 \times 5 \times 20$ (mm) was x-cut for the type-II noncritical phase matching ($\theta = 90°$, $\phi = 0°$) in order to maximize the effective nonlinear coefficient and essentially eliminate walk-off between the pump, signal, and idler beams. Moreover, it was mounted in a water-cooled copper block with indium foil wrapped to improve the thermal contact between the crystal and the copper heat sink. The temperature of the copper mount was kept at 16 °C during the operation of the laser. The OPO cavity length was 30 mm long, as short as possible, in order to lower the oscillator threshold[15]. Meanwhile, the KTP-OPO cavity, was placed as near as possible to M_2, where the position of the laser beam waist was. The AO Q-switch was put between M_1 and Nd:YAG rod for making use of the other waist for a better hold-off.

Figure 2(a) shows the spectrum of the signal wave.

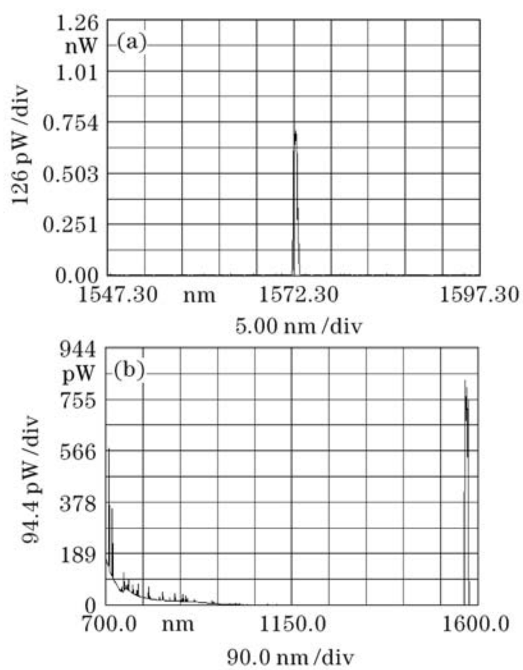

Fig. 2. (a) Output spectrum of signal wave at 1572 nm, (b) the output spectrum demonstrating no 1064-nm output.

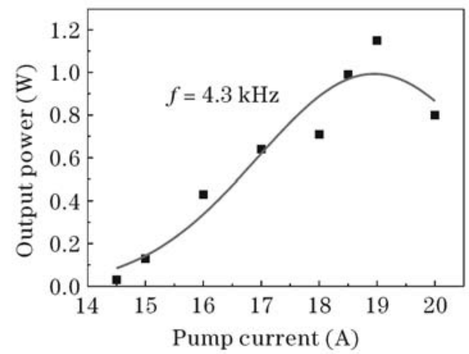

Fig. 3. Output power at 1572 nm versus the pump current.

There was not 1064-nm output through using a filter mirror at 1064-nm wavelength behind M_2, which was demonstrated by Fig. 2(b). The curve of the average output power at 1572 nm versus the incident pump current is depicted in Fig. 3. The threshold incident pump current was 14.5 A. Average power of 1.15 W for the signal was achieved at the repetition rate of $f = 4.3$ kHz when the pump current was 19 A. The signal power increased linearly with the pump current above threshold, suggesting that still higher powers can be achieved by increasing the pump current. However, we find that the OPO output reached to saturate and decreased eventually at higher pump currents. One possible reason is that optical absorption of the idle wave in KTP crystal will lead to the development of thermally induced lens in OPO crystal[16] which may make the mode volume reduce and the output power decrease.

To characterize the pumping Nd:YAG laser, we measured the pump power of 1064 nm in the same cavity without KTP crystal and OPO mirrors, the output power of 11 W was obtained at 4.3 kHz with 10% transmitting at 1064 nm while the pump current was 19 A. Therefore, the conversion efficiency from Q-switched output at 1064-nm wavelength to OPO signal output power was 10.5%. Figure 4 shows that the average powers of pump laser output (without KTP-OPO cavity and configured for maximum output for 1064 nm with 10% transmitting) and the signal output both are functions of the repetition rate. The 1064-nm output power increased with the repetition rate, whereas there was a drop for the signal wave performance from 4.3 to 11 kHz. The maximum power for

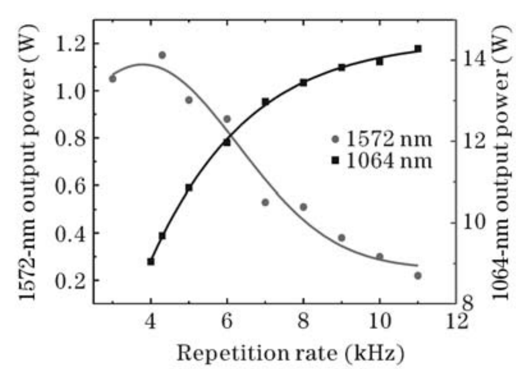

Fig. 4. Average signal power and pump laser power versus Q-switch repetition rate at 19 A.

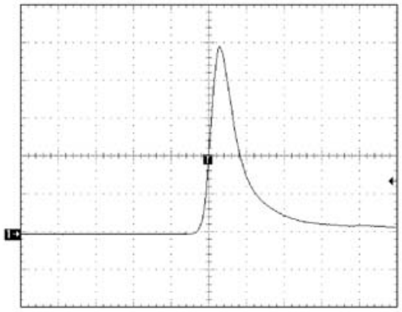

Fig. 5. Oscilloscope trace of 1572-nm output under the pump current of 19 A.

1572 nm was achieved at 4.3 kHz. The degradation of the signal output power above 4.3 kHz was probably due to the reduction of the peak power of the pump laser and the thermal effect in the Nd:YAG rod, along with the enhancement of the OPO threshold[17].

When the pump current is 19 A, the pulse width (full-width at half maximum) of 1572 nm is about 8 ns as shown in Fig. 5. Then, we varied the repetition rate of the Q-switch from 4.3 to 10 kHz under this current, the pulse width of the signal wave changed very slightly, which was due to the effective cavity dump of the IOPO. Moreover, when the pump current changed from 19 to 15 A at the repetition rate of 4.3 kHz, the pulse width also varied little. In addition to the signal pulses, non-phase matched frequency-doubled pulses at 532 nm were observed in our experiment. Because the frequency doubling had severe phase mismatch and the conversion efficiency was very low, it did not have great effect on parametric oscillator.

In conclusion, we have obtained 1.15 W of 1.57 μm at 4.3 kHz from an intracavity KTP-OPO, pumped by a diode-side-pumped Nd:YAG laser. The peak power of the pulses amounts to 33.4 kW with the pulse width of 8 ns. The average conversion efficiency from Q-switched 1.064-μm wavelength input power to OPO signal output power is up to 10.5%. Potentially the cavity length could be shortened by the use of dichroic coating directly applied to the OPO output mirror, which can be used as the pump laser cavity mirror simultaneously. We think such improvement would be advantageous in lowering cavity loss and producing higher-power signal output.

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