An efficient intracavity-pumped KTP optical parametric oscillator at 1572 nm

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We demonstrate an efficient and eye-safe wavelength intracavity optical parametric oscillator (OPO), based on a KTP crystal inside a Q-switched Nd:YVO_4 laser end pumped by a fiber-coupled diode laser. In the acousto-optic Q-switched operation with the pulse repetition rate of 10 kHz, a 1572-nm eye-safe laser with the average power of 237 mW at the incident pump power of 5.64 W is obtained. Under the pulse repetition rate of 5 kHz, the signal light with pulse width of 2 ns and peak power of 18.5 kW is achieved. The conversion efficiency of the average power is 4.2% from pump diode to OPO signal output and the signal pulse duration is about 13 times shorter than that of the depleted pump light.

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Nanosencond pulsed lasers emitting in the eye-safe wavelength region (1.5—1.6 μm) are vital for applications involving coherent laser radar, remote sensing, obstacle avoidance, active imaging, and communications[1−3]. The need for high-peak-power eye-safe laser sources has stimulated much interest in intracavity optical parametric oscillators (IOPOs). IOPOs take advantage of the high fundamental field inside the pump laser cavity to increase overall conversion efficiency; moreover, IOPOs increase the effective interaction length due to the many round trips of the pump radiation inside the optical parametric oscillator (OPO) cavity. In comparison with external OPOs and other types of eye-safe lasers, IOPOs offer higher conversion efficiency, lower threshold for a given diode pump power[3−5]. The conventional IOPOs in which flash lamps or quasi-cw diodes are used as the pump sources typically restrict operations in low repetition rates, less than 1 kHz[6]. Only recent years with the advent of high-damage-threshold nonlinear crystals and diode-pumped Nd-doped lasers, IOPO's merits have been more and more appreciated[2,5−10]. In this letter, we demonstrate an IOPO based on a type II phase-matched KTP crystal inside an acousto-optic (A-O) Q-switched Nd:YVO_4 laser end pumped by a diode laser. The maximum average output power at 1572-nm eye-safe wavelength is 237 mW, the minimum pulse width is 2 ns, and the peak power is up to 18.5 kW. The conversion efficiency for the average power is 4.2% from pump diode input to OPO signal output and the pulse duration is about 13 times shorter than that of the depleted pump light.

Conventionally, the usually used active medium for the IOPO operation is mostly focused on Nd:YAG and Nd:YVO_4 crystals. When Nd:YAG crystal is used, due to its intrinsical isotropy, a polarizer is often required in order to enhance the parametric conversion efficiency, which inevitably brings additional inserting-loss into the cavity. Compared with Nd:YAG crystal, Nd:YVO_4 crystal has several advantages including higher absorption cross section, wider absorption bandwidth, and a polarized output. The linearly polarized laser output is beneficial not only to nonlinear wavelength conversion, but also to avoiding of undesired birefringent effects[10]. In the experiments, therefore, we chose Nd:YVO_4 crystal as gain medium, and KTP as the nonlinear optical crystal due to its high damage threshold, relatively wide acceptance angle, and large nonlinear coefficient[11]. The KTP crystal was cut to achieve type II non-critical phase matching for a pump wavelength of 1064 nm and a signal wavelength near 1572 nm; the idler wavelength was therefore near 3293 nm. Non-critical phase matching maximizes the effective nonlinear coefficient and essentially eliminates walk-off between the pump, signal, and idler beams.

The experimental setup for 1572-nm generation is shown in Fig. 1. A plano-concave cavity, formed by M and M_2, is used for the generation of the pulsed fundamental wave at 1064 nm. The total length of the laser cavity is approximately 128 mm. The Nd:YVO_4 crystal (0.5 at.-%, a-cut, $4 \times 4 \times 8$ (mm)) is pumped by a fiber coupled semiconductor laser with the wavelength of 808 nm, maximum output power of 8 W, and numerical aperture (NA) of 0.12. The output from the semiconductor laser is focused into the Nd:YVO_4 crystal by a collimating lens with the coupling efficiency of 85%. The two sides of the crystal are coated antireflection (AR) at the 1064 and 808 nm. The input mirror, M, is a 200-mm radius-of-curvature concave mirror with AR coating at 808 nm on the entrance face, high-reflection (HR) coating

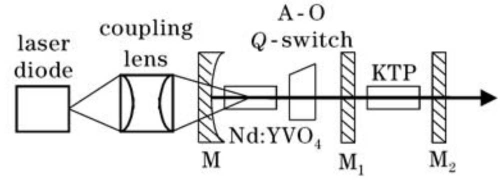

Fig. 1. Schematic of the intracavity OPO pumped by a diode-pumped Q-switched Nd:YVO_4 laser.

at 1064 nm, and high-transmission (HT) coating at 808 nm on the other surface. The output coupler M_2 has a dichroic coating with HR at 1064 nm and partly transparent at 1572 nm (T=30%). The IOPO cavity consists of an internal flat mirror M_1 and the flat output-coupling mirror M_2. M_1 is coated HR at 1572 nm and HT at 1064 nm toward to the IOPO cavity and AR at 1064 nm on the other side. The length of the IOPO cavity is 45 mm. The 20-mm-length KTP crystal is coated AR at 1064 and 1572 nm on both faces. The A-O Q-switching was driven at a center frequency of 40 MHz with the diffraction loss of 85%. In the experiments, both Nd:YVO_4 and KTP crystals were wrapped with indium foil and mounted in a water-cooled block. The water temperature was maintained at 25 °C.

Figure 2 shows the operation of the IOPO at several pulse repetition rates. In order to avoid the damage of the intracavity optical components, the diode laser was operated below the output power of 7.10 W, that is to say, the maximum incident pump power was 6.04 W. The threshold for signal parametric oscillation is about 2.7 W and its dependence on different pulse repetition rates is not significant. When the pump power is 5.64 W, the maximum output power of 1572 nm at 10 kHz is 237 mW, and is dropped to 185 mW for 5-kHz repetition rate. Basically, increasing the pulse repetition rate can efficiently increase the average output power at 1572 nm. The minimum value of a pulse width is obtained for about 5.64-W pump power, which are 2 and 2.4 ns at 5 and 10 kHz, respectively. At this point, the conversion efficiency for the average power is 4.2% at 10 kHz and the peak power is up to 18.5 kW at the pulse repetition rate of 5 kHz. The highest peak power can be obtained with the output reflectivity about 60%—70%, whereas the maximum conversion efficiency can be obtained with an output coupler of 85%—90%. If the higher conversion efficiency is desired, the output reflectivity needs to be around 85%—90% at the sacrifice of peak power[6]. In the experiments, the high output coupling of T = 30% is not the best choice for a high conversion efficiency, so the threshold is higher and the efficiency is lower, but it is good for the IOPO of short pulse width and high peak power. In addition, the high absorption of the idler radiation in the KTP crystal also increases the threshold of IOPO. With increasing the pump power the average output power increases. When the pump power reaches 6.04 W, the conjunct impact of the thermal lens in the laser rod and KTP crystal becomes serious, resulting in a little

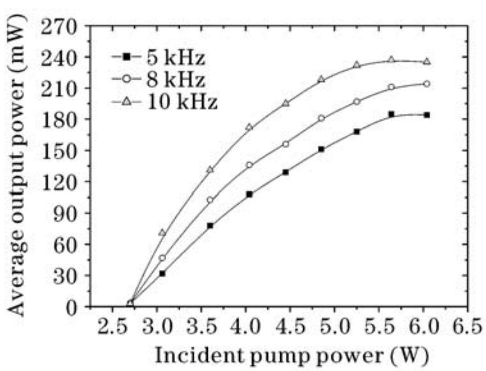

Fig. 2. Output power at 1572 nm versus the incident pump power for several pulse repetition rates.

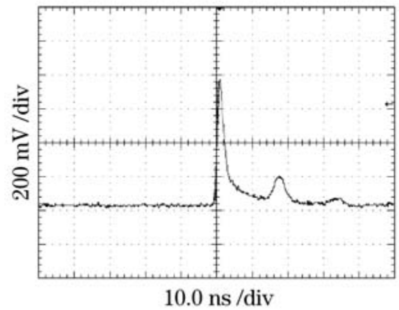

Fig. 3. Typical signal pulse shape at 1572 nm with signal transmission of 30% on the output coupler.

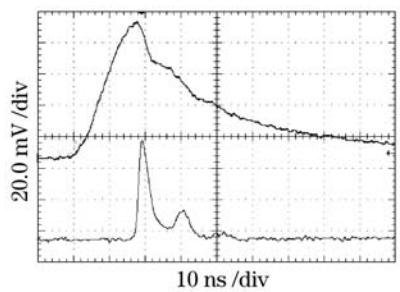

Fig. 4. Typical temporal shapes for the depleted 1064-nm beam and 1572-nm signal pulses with a signal transmission of 30% on the output coupler.

increase and even fall-off of the output signal power. A typical pulse shape at 1572 nm is shown in Fig. 3. It can be seen that the overall pulse width is 2 ns at 5 kHz. Figure 4 shows the typical temporal shapes for the depleted pump and signal pulses at the pulse repetition rate of 8 kHz and the incident pump power of 4.45 W. The typical pulse width of the depleted 1064-nm laser pulse is about 31 ns and the pulse width of signal pulse is about 2.4 ns, which is about 13 times shorter than that of the depleted pump laser. Figure 4 reveals that after the Q-switch is opened and the pump laser intensity increases to the IOPO threshold, the parametric process converts the fundamental energy to the signal and idler fields. The IOPO serves as a nonlinear cavity dump to extract the stored energy in the intracavity optical field. If the stored energy is fully extracted, one single pulse is generated, and if the intracavity fundamental frequency light is very intense, the system can create multiple pulses to extract the stored energy fully. As shown in Fig. 4, the stored energy is not fully extracted in a single output pulse. Since the remaining energy is sufficient to evolve the pump field, the OPO threshold can be obtained again and a second signal pulse is produced. Multiple pulse operation is undesirable and should be avoided in practice, which can be suppressed by carefully choosing an OPO output coupler with appropriate reflectivity[12,13]. While the OPO output is principal at the signal and idler frequencies, there are a number of other nonlinear frequency-mixing effects occurring in the KTP crystal[11]. In the experiments, we observed weak outputs at 532 nm, which corresponding to the second harmonics of the pump frequency.

In conclusion, we have reported an efficient, eye-safe wavelength IOPO based on a KTP crystal inside an A-O Q-switched Nd:YVO_4 laser pumped by a diode laser. By using a type II non-critical phase-matched KTP crystal, we have obtained 1572-nm eye-safe wavelength laser, with pulse width of 2 ns and peak power of 18.5 kW at the pulse repetition rate of 5 kHz, and power of 237 mW at the incident pump power of 5.64 W at the pulse repetition rate of 10 kHz. The conversion efficiency for the average power is 4.2% from pump diode input to OPO signal output and the pulse duration is about 13 times shorter than that of the depleted pump light.

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