Intracavity optical parametric oscillator at 1.57-μm wavelength pumped by passive Q-switched Nd:$GdVO_4$ laser

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A high-repetition-rate eye-safe optical parametric oscillator (OPO), using a non-critically phase-matched KTP crystal intracavity pumped by a passively Q-switched Nd:$GdVO_4$/Cr^{4+}:YAG laser, is experimentally demonstrated. The conversion efficiency for the average power is 7% from pump diode input to OPO signal output and the slope efficiency is up to 10.3%. With an incident pump power of 7.3 W, the compact intracavity OPO (IOPO) cavity, operating at 15 kHz, produces an average power of 0.57 W at 1570 nm with a pulse width as short as 6 ns. The peak power at 1570 nm is higher than 6.3 kW.

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Short-pulse, high-peak-power, high-repetition-rate lasers at the so-called eye-safe region near $1.5 - 1.6$ μm have attracted extensive interests since their increasing applications in telemetry and range finders. One approach to generate high-peak-power eye-safe laser is based on KTP optical parameter oscillators (OPO) pumped by Nd-doped laser[1]. But the limited pump peak power in the extracavity KTP OPO configuration has made it difficult due to the lower effective nonlinear coefficiency. The main idea of the pumped KTP intracavity OPO (IOPO) is to take the advantage of the strong laser radiation inside the cavity to increase the overall conversion efficiency and reduce the pumping threshold compared with extracavity configuration[2−11]. End-pumped saturable-absorber Q-switched laser has the advantages of low cost, simplicity in assemble, and high quality output beam. In recent years, Cr^{4+}:YAG crystal has been widely used as a saturable-absorber Q-switch for a variety of gain crystals such as Nd:YAG, Nd:YVO_4, Nd:$GdVO_4$ etc.[12]. The main disadvantages of the diode pumped Nd:YAG are the serious thermally induced birefringent effect and bifocals effect in laser crystal, which significantly lowers the efficiency of the polarized output. The Nd:YVO_4 and Nd:$GdVO_4$ have several advantages over Nd:YAG crystal, such as wider absorption bandwidth, larger cross section, and a linear polarized output, which is not only beneficial to high OPO wavelength conversion coefficiency but also avoids the unexpected birefringent effect. As a new high efficient laser gain crystal, Nd:$GdVO_4$ has been intensively investigated both for continuous wave (CW) operation and Q-switching operation[13,14]. But the Nd:$GdVO_4$ lasers have less been used to pump KTP IOPO for the generation of eye-safe laser output.

In this paper, we report a high-peak-power, high-repetition nanosecond KTP IOPO based on a diode pumped passively Q-switched Nd:$GdVO_4$. At an incident pump power of 7.3 W, the compact IOPO cavity, operating at 15 kHz, produces average power at 1570 nm up to 0.57 W with a pulse width as short as 6 ns. As a result of the relatively short pulse, the peak power at 1570 nm is higher than 6.3 kW. Conversion efficiency of 7% with respect to diode pump power and slope efficiency of 10.3% are achieved.

The experimental setup of intracavity passively Q-switched OPO laser is schematically shown in Fig. 1. The gain media was an a-cut 10-mm Nd:$GdVO_4$ crystal with a 0.52 at.-% Nd^{3+} doping concentration. Both sides of the crystal were coated for antireflection (AR) at 1063 nm ($R < 0.2\%$). The Nd:$GdVO_4$ laser resonator was 65 mm long, having two high-reflection (HR) mirrors M_1, M_3. The input concave mirror M_1 with 100-mm curvature radius was coated with HR at 1063 nm ($R > 99.8\%$) and AR at the pumping wavelength of 808 nm at both sides. The Cr^{4+}:YAG crystal with a thickness of 2 mm had a 65% initial transmission at 1063 nm. Both sides of the Cr^{4+}:YAG crystal were coated with AR at 1063 nm. The IOPO cavity with a length of 26 mm consisted of the flat mirror M_2 with HR at the signal wavelength of 1570 nm ($R > 99.5\%$) and AR at the pumping wavelength of 1063 nm at both sides and the flat output coupled mirror M_3 with HR at the pumping wavelength ($R > 99.6\%$) with the transmission of 14% at the signal wavelength. The 20-mm-long KTP crystal was used in type II non-critical phase matching configuration along the x-axis ($\theta = 90°$, $\phi = 0°$) to eliminate the walk-off effect and has a maximum effective nonlinear coefficient. The KTP crystal was coated for high transmission (HT) both at the pumping wavelength and signal wavelength. All crystals were wrapped with indium foil and mounted on a thermal energy converter (TEC)-cooled copper heater.

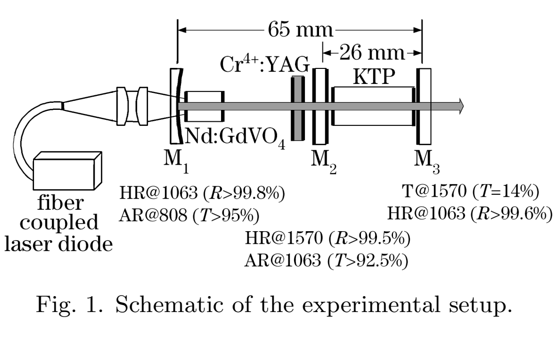

Fig. 1. Schematic of the experimental setup.

The temperature of all crystals were controlled at 20 °C.

The pump source was an 808-nm fiber coupled laser diode (LD) with a core diameter of 400 μm and a numerical aperture (NA) of 0.22. Two focusing lenses with 25-mm focal length were used to focus the pump beam into the laser crystal. The pump spot root mean square (RMS) radius was around 230 μm calculated with a beam tracing software (ZEMAX). For the passively Q-switched IOPO, we measured the average power of the signal output as a function of incident pump power as shown in Fig. 2. The maximal signal average output was 0.57 W for $T_{\mathrm{out}-1570\mathrm{nm}} = 14\%$ was obtained for 7.3-W pump power at 15-kHz repetition rate with a slope efficiency of 10.3%. The wavelength of OPO output was 1570.9 nm measured by a HighFinesse WS/5 laser wavelength meter. Further increasing the pump power caused a decrease of laser output. The decrease of the laser output power was attributed to the thermal lens induced cavity instability which could be confirmed from the same trend of the output power without KTP crystal shown also in Fig. 2. In the experiment, we found that the position of Cr^{4+}:YAG crystal was very important for the laser output property. Figure 3 shows the signal average output as a function of incident pump power for different positions of Cr^{4+}:YAG crystal. The higher OPO efficiency was achieved when the Cr^{4+}:YAG crystal was put forward to the beam waist position which was on the output flat mirror.

The pulse temporal behavior at 1570 nm was recorded by a TEK TDS5052B digital oscilloscope with a NEW-FOCUS 1811 detector. Figure 4 shows a typical temporal wave shape for the signal pulse. It can be seen that a second pulse accompanies the main pulse, which could be testified by using an IOPO function. The rate equation model for the four-level Q-switched IOPO developed by Xiao and Debuisschert *et al.*[3,15] confirms the experimental results. Figure 5 shows the results obtained from the IOPO rate equation model that is built according to the experimental situation.

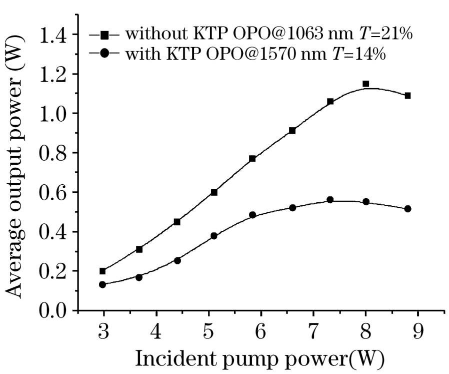

Fig. 2. Average output power at 1570 nm versus the incident pump power.

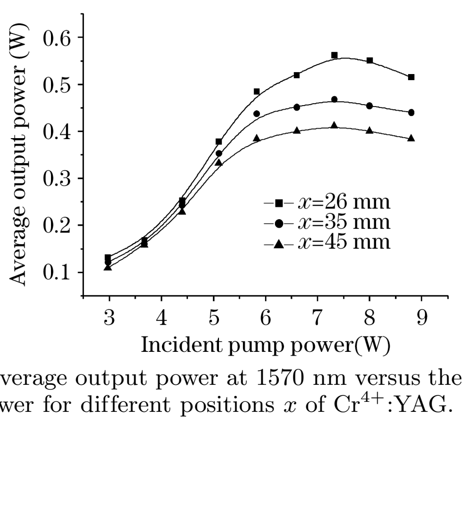

Fig. 3. Average output power at 1570 nm versus the incident pump power for different positions x of Cr^{4+}:YAG.

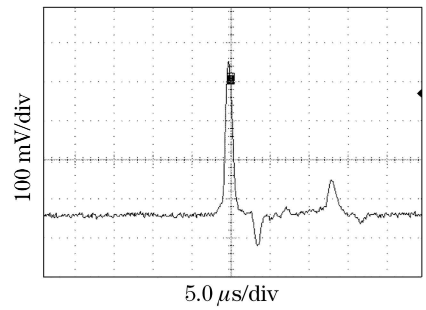

Fig. 4. Typical pulse-shape at 1570 nm for a 15-kHz repetition rate and a 14% transmission output coupled mirror.

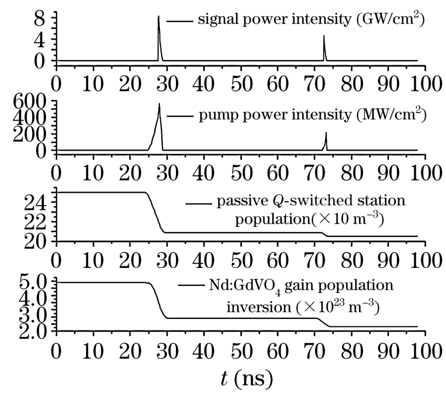

Fig. 5. Evolution of IOPO dynamic parameters according to the experimental situation.

Laser output is initially prevented for the reason of the low Q cavity while the gain medium is pumped to a high population inversion. As soon as the absorber is bleached the 1063-nm pulse starts to build up. When the pump power reaches OPO threshold, the signal pulse is generated at the fundamental 1063-nm laser pulse. If 1570-nm output coupler is with a high reflectivity, the first signal output pulse is not long enough to extract all inversion population. So the remained inversion particles are sufficient to cause another increase of 1063-nm pump light. When the OPO cavity reaches the threshold again, another pulse is generated. This process may occur for several times dependent on the loss of the total cavity. From the IOPO rate equations, it can be found that a single pulse is generated with a higher transmission output coupled mirror ($T = 30\% - 40\%$ according to the experimental situation) but with a lower OPO conversion efficiency. It is noted that a 532-nm green light output was also observed, which may be caused by a little larger divergence of 1063-nm pump light in the KTP crystal. Because the double frequency phase match angle of 1063 nm ($\theta = 90°$, $\phi = 23.6°$) is not too far from the OPO phase match angle, a strong pump situation might let the laser reach the green light output threshold. We observed the output beam with an infrared (IR) camera (Spiricon PY-III). The distribution of output beam was a good fundamental Gaussian shape with a large divergence due to the thermal lens effect caused by idler light absorption of the KTP crystal.

In conclusion, we experimentally present a high efficient intracavity KTP OPO pumped by a passively Q-switched Nd:$GdVO_4$ laser. A maximal signal light average output of 0.57 W with a slope efficiency of 10.3% for $T_{\mathrm{out}-1570\mathrm{nm}} = 14\%$ is obtained for 7.3-W pump power at 15-kHz repetition rate. The peak power is up to 6.3 kW with a pulse width less than 6 ns. Such an efficient, high-peak-power, high-repetition eye-safe laser could be used in several areas, such as range finder, laser radar, etc..

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