CHIN. PHYS. LETT. Vol. 26, No. 12 (2009) 124213

# Low Threshold and High Conversion Efficiency Nanosecond Mid-Infrared KTA OPO *

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(Received 18 August 2009)

*Based on a Type Ⅱ non-critically phase-matched KTA crystal, a low-threshold and high conversion efficiency mid-infrared optical parametric oscillator (OPO) pumped by a diode-end-pumped Nd:$YVO_4$ laser is demonstrated. The OPO threshold is only 0.825 W. The maximum output power of 435 mW at 3.47 μm is achieved with the repetition rate of 30 kHz, corresponding to an optical-to-optical conversion efficiency of 4.4%. The photon conversion efficiency is as high as about 64%. The pulse width is 3.5 ns with a peak power of 4 kW for the maximum output power.*

*PACS: 42. 65. Yj, 42. 65. Lm, 42. 55. Xi*

Mid-infrared laser sources are of great interest for paramount applications from remote sensing and spectrum analysis to industrial process control, photobiology, photochemistry, military and so on. The timely advancement of coherent mid-infrared sources plays a vital part in these application areas. The development of material science, crystal growth and semiconductor material processing have led to the realization of new methods and novel operating principles for mid-infrared laser sources such as quantum cascade lasers, new types of semiconductor lasers, crystalline and fiber lasers based on new solid-state laser materials and structures.[1] At the same time, great progress has been made for traditional nonlinear optical parametric down-conversion methods with the development of high-quality birefringent materials.

As one of the atmospheric windows, the 3–5 μm mid-infrared laser sources have been researched since the early 1980s. Various materials such as $LiNbO_3$,[2] KTP and its isomorphs (KTA, RTA, CTA, *et al*),[3–6] as well as mid-infrared crystals like $ZnGeP_2$, $AgGaS_2$, $AgGaSe_2$, GaSe and so on,[7–11] have been exploited for the generation of this band. On the other hand, quasi-phase-matched (QPM) nonlinear crystals such as PPLN, PPKTP, PPKTA, PPRTA, PP-GaAs etc.,[12–16] have been particularly widespread in the cw and low-intensity pulsed regimes. However, the small size and complicated grown procedure limit the spreading of the periodically-poled crystals and most of the mid-infrared crystals as well. With excellent physical, optical characteristics and a large transmission range (0.35–5.3 μm), KTA crystal has shown its importance in high-power optical parametric conversion, especially for eye-safe and mid-infrared OPOs employing the non-critically phase-matching (NCPM) schemes. Short-pulse mid-infrared OPOs based on KTA have been demonstrated since the last century,[17,18] but high-repetition-rate nanosecond mid-infrared KTA-based laser sources have not been much exploited. Wu *et al.*[4] reported a 4.1 W KTA OPO pumped by a diode-side-pumped Nd:YALO laser in 2001, but the diode-to-mid-infrared conversion efficiency was less than 1%. Driven by a diode-end-pumped Nd:$GdVO_4$ laser, a 356 mW mid-infrared KTA OPO with conversion efficiency of about 3.9% was presented by Miao *et al.*,[5] but it was passively Q-switched and the repetition rate could not be changed in practical applications.

In this Letter, we demonstrate the first high-repetition-rate nanosecond mid-infrared KTA OPO pumped by an actively Q-switched diode-end-pumped Nd:$YVO_4$ laser. It is compact, low-threshold, highly-efficient and the repetition rate could be changed from 10 kHz to 40 kHz. Taking advantage of the high power intensity of intracavity optical parametric oscillator (IOPO) and the highly-efficient Nd:$YVO_4$ laser, a maximum output power of 435 mW and a photon conversion efficiency of about 64% from the pump at

*Supported by the Research Fund for the Doctoral Program of Higher Education under Grant No 20070420118, the Tianjin Municipal Primary Application and Frontier Technology Research Plan under Grant No 07JCYBJC06200, the National Basic Research Program of China under Grant No 2007CB310403, and the National Natural Science Foundation of China under Grant No 60801017.

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1064 nm is obtained. The OPO threshold is no more than 0.9 W from 10 kHz to 40 kHz.

The experimental setup is shown in Fig. 1. A fiber coupled diode laser emitting at 808 nm with a maximum output power of 30 W is used as the pump source. The core diameter of the fiber is 400 μm with a numerical aperture of 0.22. It is focused by the coupling system into a Nd:$YVO_4$ crystal. We make use of a simple concave-plane cavity for the fundamental laser. The commercial $3 \times 3 \times 10\,\text{mm}^3$ Nd:$YVO_4$ crystal is $a$-cut and 0.3 at% doped, with antireflective (AR) coatings at 808 nm and 1064 nm on both faces. The rear mirror $M_1$ is plano-cancave with a curvature radius of 300 mm. Its both faces are AR coated at 808 nm and the concave face is also highly-reflective (HR) coated at 1064 nm. The 45 mm-long A-O Q-switch (Gooch and Housego) is AR coated at 1064 nm and driven at 27.12 MHz with the maximum rf power up to 100 W. The KTA crystal is 20 mm-long $x$-cut, type Ⅱ non-critically phase matched ($\theta = 90°$, $\phi = 0°$) and AR coated on both faces for pump (1.06 μm), signal (1.5–1.6 μm) and idler (3–3.6 μm) waves. $M_2$ and $M_3$ construct a singly resonant OPO with a KTA crystal. $M_2$ is coated for AR at 1.06 μm and HR at 1.5–1.6 μm. The OPO output coupler $M_3$ is coated for HR ($R \approx 99.9\%$) at both 1.06 μm and 1.4–1.7 μm ($R > 99.7\%$), and AR ($R < 4\%$) at 3–5 μm. $M_4$ is the same with $M_3$ as a filter. The overall fundamental laser cavity is 130 mm long and the OPO cavity is about 26 mm. The crystals Nd:$YVO_4$ and KTA, as well as the A-O Q-switch, are cooled by circulating water.

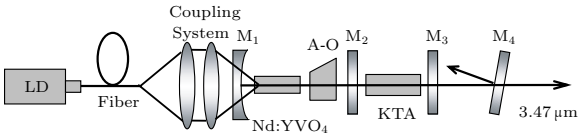



**Fig. 1.** Schematic diagram of the intracavity mid-infrared KTA OPO pumped by a Nd:$YVO_4$ laser.

As the most commonly used material for cavity mirrors in near-infrared lasers, BK7 glass has a cut-off wavelength of 2.1 μm in its transparent range, therefore it cannot be used as the output mirrors in mid-infrared OPOs with the wavelengths above 3 μm. In order to obtain mid-infrared output, an output coupler made of $CaF_2$ is used in this experiment. Its transparent range is from 0.15–9 μm and its absorption coefficient is lower than $0.03\,\text{cm}^{-1}$ for the idler wavelength of the KTA OPO at 3.47 μm. Both the faces of $M_3$ are coated to avoid its deliquescence in air and to increase mid-infrared transmittance.

It should also be noted that an extremely low-loss singly resonant OPO cavity for signal wave was employed in our experiment, and the generated idler wave can be fully extracted. In an eye-safe KTA OPO emitting the resonant signal wave, the transmittance of the output coupler should be optimized to enhance the maximum output power and conversion efficiency, or else the saturation effect will easily come forth if the signal transmittance is too low. However, for a singly resonant mid-infrared OPO shown in Fig. 1, the wavelength we look for is non-resonant, an idler and a signal photon is generated simultaneously through the frequency conversion process $\omega_p \rightarrow \omega_s + \omega_i$. Thus the higher the intensity of the signal wave inside the cavity, the higher the idler power coupled out. A low-loss singly resonant OPO cavity not only enhances the output mid-infrared power, but also decreases the oscillating threshold, according to marshall's equation in Ref. [19].

To evaluate the performance of the pump laser, firstly the output power of the free-running 1064nm Nd:$YVO_4$ laser is measured, as shown in Fig. 2. The cavity is the same as that in Fig. 1 without mirror $M_2$ and the KTA crystal. The cavity length was 130 mm and the output coupler transmission at 1064 nm was 30%. While continuous-wave operating, the output power reach 5.7 W with the diode pump power of 9.9 W, corresponding to a conversion efficiency of 57.6%. With the same pump power in the Q-switched regime, the maximum average powers are 5 W, 4.46 W, 3.75 W and 2.6 W under different repetition rates of 40 kHz, 30 kHz, 20 kHz and 10 kHz, respectively. The pulse widths are 12–14 ns when the diode pump power was above 5 W.

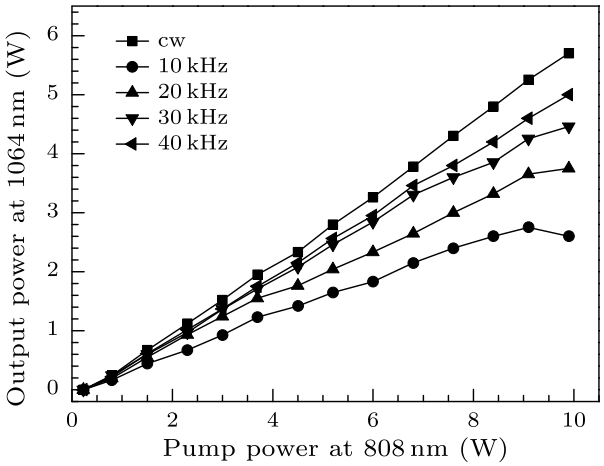



**Fig. 2.** Output characteristics of the Nd:$YVO_4$ laser. The output power was measured under the condition of cw, 10 kHz, 20 kHz and 30 kHz with a output mirror of $T_{1064} = 30\%$.

With the experimental setup shown in Fig. 1, we obtain a compact and efficient mid-infrared OPO based on KTA. The performance of the mid-infrared OPO versus the diode pump power at 808 nm is shown in Fig. 3. The output power is measured with a Molectron PM10 power meter. The maximum output power of 435 mW is achieved at 30 kHz with a pump power of 9.9 W, corresponding to an optical-to-optical conver-

sion efficiency of 4.4% and 14.5 μJ for a single pulse. The simultaneous output powers of both the fundamental and signal wavelength at 1064 nm and 1536 nm are only around 60 mW, owing to the high reflectivity in both of these two spectrum ranges. It is worth mentioning that only half of the generated mid-infrared power is collected because $M_2$ is not HR coated at the idler wavelength. Taking account of the quantum defect between the pump and idler photons and considering the actually generated mid-infrared power is 870 mW while the maximum power at 1064 nm that can be extracted is 4.46 W under the same condition, the photon conversion efficiency is about 64% from the pump wave. Changing the repetition rate, the OPO threshold is 0.825 W at 10 kHz, 20 kHz and 30 kHz, and slightly higher, that is, 0.9 W at 40 kHz. Both the conversion efficiency and the threshold are better than the mid-infrared OPOs with similar configurations reported before.

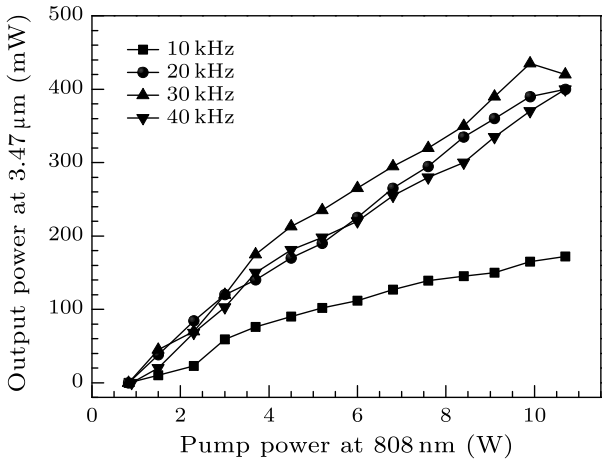



**Fig. 3.** Output characteristics of the mid-infrared OPO at 3.47 μm with different repetition rates of 10, 20, 30 and 40 kHz.

The typical profile of the temporal pump and signal pulses were detected by a fast response InGaAs photodiode and displayed on a Tektronix TDS620B oscilloscope. The recorded picture is shown in Fig. 4. The phenomenon of signal pulse series is observed, of which the dynamics was explained in detail in Refs. [20,21]. The high signal reflectivity of the two OPO mirrors results in the reduction of the build time of the first signal pulse, leaving sufficient population inversion to generate a second even more signal pulses, as depicted by the temporal depleted pump pulse. The main signal pulse width is about 3.5 ns. According to the principles of OPO, two photons at the signal and idler wavelengths come out synchronously whenever a pump photon is depleted. Thus the pulse width for idler wave at 3.47 μm was the same as the signal pulse, indicating a peak power of 4 kW for the maximum output power at 30 kHz.

The output spectra of the OPO are shown in Fig. 5. The central wavelengths for the fundamental and signal wave are 1064.6 nm and 1535.7 nm, respectively. Thus the corresponding idler wavelength should be 3.47 μm (the measuring range of the Agilent 86142B spectrum analyzer is limited to 600–1700 nm and the idler wave could not be detected directly). Some faint green and red light owing to the second harmonic generation (SHG) of the fundamental (no phase-matching (PM) angle) and signal wave (PM angle $\theta = 54.2°$, $\phi = 0°$) is also observed, but the output power is too low to be measured.

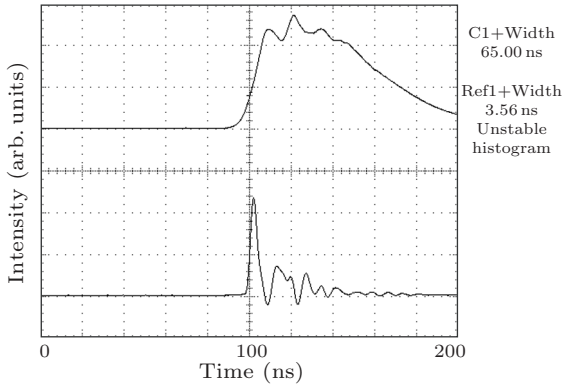



**Fig. 4.** Temporal profile of the signal and depleted pump pulses.

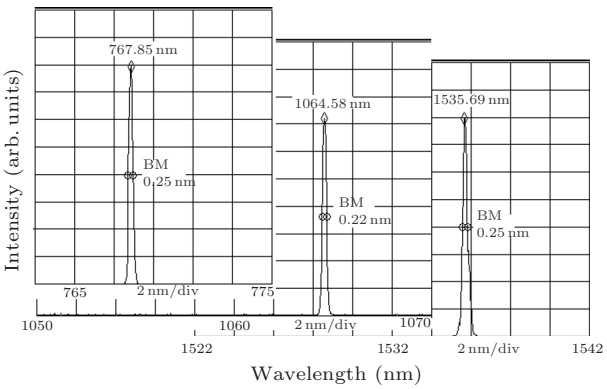



**Fig. 5.** Output spectra (fundamental, signal and its SHG) of the KTA OPO.

With the knife-edge method, the far-field divergence half angle of the signal wave is measured to be about 3.5 mrad. We also investigate the operating stability of the mid-infrared OPO. Using the rms error equation $\Delta\overline{P} = \sqrt{\sum_{i=1}^{n}(P_i - \overline{P})^2/n} \cdot \frac{1}{\overline{P}}$, the power instability $\Delta\overline{P}/\overline{P}$ of the mid-infrared OPO output power around 350 mW during an hour is about 5% in the experiment. The evident fluctuation should be attributed to the thermal lens effects of the Nd:$YVO_4$ laser and pump depletion during the optical parametric conversion.

In conclusion, we have demonstrated a high-repetition-rate nanosecond mid-infrared IOPO based on a KTA emitting at 3.47 μm. It is compact and efficient with a maximum output power of 435 mW,

corresponding to an optical-to-optical conversion efficiency of 4.4%. The photon conversion efficiency reaches about 64%. The output power can be doubled if a suitable mirror is available and the generated mid-infrared wave in the other direction can be collected. The pulse width is 3.5 ns with a peak power of 4 kW. The OPO threshold is as low as 0.825 W. We have obtained the highest diode-to-idler conversion efficiency, as well as the lowest pump threshold among the mid-infrared OPOs pumped by Nd-doped lasers based on similar bulk crystals.

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