The advantages of optical parametric oscillator (OPO) based on noncritical phase matching (NCPM) crystal include a no walk-off angle and a large acceptance angle [1]. Especially for the NCPM cut KTiOPO₄ (KTP) crystal and its isomorphs, the signal wavelength emits at an eye safe wavelength region around 1.5–1.6 μm and the idler wavelength emits at mid-infrared wavelength region around 3.0–3.5 μm.

These lasers are useful for applications such as range-finding, environmental sensing, telecommunications, and medical surgery. The crystal RbTiOPO₄ (RTP), as one isomorphs of KTP crystal is a great candidate for nonlinear and electro-optic applications [2,3]. It has similar nonlinear optical coefficients as KTP, but has a much higher damage threshold, which has been proven to be 1.8 times larger than that of KTP [4,5]. Therefore, RTP crystal has an advantage in high average power operations.

The OPO based on NCPM cut KTP and KTiOAsO₄ (KTA) has been widely investigated [6–11]. For the NCPM KTP-OPO, the mid-infrared idler wavelength located at about 3.3 μm can be strongly absorbed by KTP. As a result, it is often used to generate an efficient eye-safe laser at 1572 nm [12,13]. Miao et al. also reported a 580 mW signal light at 1.57 μm and 100 mW idler light at 3.29 μm output with the incident diode pump power of 4 W, corresponding to the conversion efficiency from the input diode pump power to the total OPO output of 17% [14].

The idler light output was only one-seventh of the total OPO output. The KTA crystal, on the other hand, has wider transparency range (0.35–5.3 μm), and no absorption for the idler wavelength at about 3.5 μm. Dong et al. reported a 13.6 W signal light at 1534 nm and 3 W idler light at 3473 nm that were obtained based on an intracavity KTA-OPO driven by a diode-side-pumped Q-switched Nd:YAG laser, with a conversion efficiency of about 5.7% [15]. Recently, at the end-pumping diode power of 25.9 W, signal (1535 nm) power of 3.77 W and idler (3467 nm) power of 1.18 W were achieved using an Nd:YVO₄/KTA-OPO system by Bai et al. [16].

For both NCPM KTP-OPO and KTA-OPO pumped at 1.06 μm, the signal wavelengths are in 1.5 μm band. However, the signal wavelength of NCPM RTP-OPO can be extended to 1.62 μm, corresponding to an idler wavelength of about 3.1 μm. Although its transmission falls from 3 μm upward as that of KTP, RTP offers the advantage of absorbing the idler at 3.1 μm much less than KTP with its idler wavelength at about 3.3 μm. Albrecht et al. reported extra-cavity RTP-OPO pumped by a pulse length of 6 ns and a 10 Hz repetition rate pulsed Nd:YAG laser [2], with the 1.06 μm to 1.62 μm average conversion efficiency of about 31.3%. A Laser diode end-pumped intracavity OPO has the advantage of a compact, low threshold and high overall efficiency by taking the high power density inside the laser cavity.

In this Letter, we present an intracavity pumped NCPM cut RTP-OPO with simultaneous outputs of signal and idler light. A laser diode end pumped acousto-optic Q-switched Nd:YVO₄ laser at 1.06 μm was used as the pump source. At an incident pump power of 10.5 W and a Q-switching pulse repetition frequency (PRF) of 60 kHz, we obtained 1.42 W of signal light at 1619 nm with and 0.38 W of idler light at 3108 nm, with the diode to OPO total output conversion efficiency of 17.1%. The pulse width is about ~6.5 ns for the signal light. The spectral widths of the signal and idler light are narrower than 0.5 and 1.0 nm.

Sellmeier equations are important for the phase-matching calculation. Different equations for RTP have been reported [4,17]. In this Letter, the parameters for the phase-matching of the RTP crystal have been calculated by using the nonlinear coefficient [18] and Sellmeier equations by Mikami et al. [17] as follows:
\[
\begin{aligned}
\nu_2^2 &= 4.65575 + \frac{0.04068}{\lambda^2-0.04750} + \frac{204.2586}{\lambda^2-130.7684} \\
\nu_2^2 &= 4.76892 + \frac{0.04490}{\lambda^2-0.05130} + \frac{211.3200}{\lambda^2-134.2882} \\
\nu_2^2 &= 7.97109 + \frac{0.06070}{\lambda^2-0.05968} + \frac{1234.6913}{\lambda^2-269.5094} \\
\end{aligned}
\]

\((0.5321 \mu m \leq \lambda \leq 3.1842 \mu m, \lambda: \text{wavelength})\)  \(1\)

Figure 1 shows the parameters of the calculated tuning curve, including signal and idler wavelengths, walk-off angle, and the effective nonlinear coefficient \((d_{eff})\) for RTP-OPO pumped at 1064 nm in the \(x-z\) plane. The highest \(d_{eff}\) and no walk-off occur in NCPM at \((\theta = 90^\circ, \phi = 0^\circ)\), corresponding to the signal wavelength around 1.62 \(\mu m\) and the idler wavelength around 3.1 \(\mu m\). The acceptance angle, temperature and bandwidth of this NCPM RTP-OPO in the \(x-z\) plane are calculated with the SNLO software \([19]\), which are 75 mrad \cdot cm, 147 K \cdot cm, and 64 cm\(^{-1}\) \cdot cm, respectively.

Figure 2 shows the experimental configuration. A 0.3 at. \% Nd\(^{3+}\) doped, a-cut Nd:YVO\(_4\) crystal with a dimension of 3 \(mm \times 3 \ mm \times 10 \ mm\) was used as the laser crystal, which was end pumped by a fiber-coupled laser diode array at 808 nm. The coupling fiber had a core diameter of 200 \(\mu m\) and a numerical aperture of 0.22. The pump light was reimaged into the Nd:YVO\(_4\) crystal with a spot size of about 320 \(\mu m\) in diameter using a pair of achromatic lenses with focal lengths of 50 and 80 mm, respectively. The Nd:YVO\(_4\) crystal was wrapped with indium foil and mounted a water-cooled copper block, whose temperature was maintained at 25°C during the experiment.

The pump incident facet, which also acted as one of the cavity mirrors for the fundamental laser oscillation at 1.06 \(\mu m\), was high-transmission (HT, \(T > 95\%\)) coated at 808 nm, and high-reflection (HR, \(R > 99.9\%\)) coated at 1.06 \(\mu m\). The other facet of the laser crystal was anti-reflection (AR) coated at 1.06 \(\mu m\). A 30-mm-long acousto-optic \(Q\)-switcher (AOS, Gooch & Housego Co.) driven at a radio frequency of 40 MHz was used for \(Q\)-switching the 1.06 \(\mu m\) laser.

![Fig. 2. Experimental arrangement configuration for the RTP-OPO pumped by an acousto-optic \(Q\)-switched Nd:YVO\(_4\) at 1.06 \(\mu m\).](image)

RTP crystal with 4 \(mm \times 4 \ mm \times 20 \ mm\) in dimension was used as the nonlinear optical crystal, which was grown by the top-seeded solvent growth (TSSG) method with pulling from a modified self-flux in Crystech Inc. It was type II NCPM \((\theta = 90^\circ, \phi = 0^\circ)\) cut for the pump wavelength of 1.06 \(\mu m\) and signal wavelength of 1.62 \(\mu m\). Both end facets of the crystal were AR coated at 1.06, 1.62, and 3.1 \(\mu m\). The crystal was mounted in a thermoelectric cooled copper block whose surface temperature was kept at about 25°C.

The OPO cavity was formed by an intracavity plane mirror (IM) and an output coupler (OC), which were using infrared quartz glass as the substrate for reducing the absorption of the mid-wavelength idler light at 3.1 \(\mu m\). IM was AR coated at 1.06 \(\mu m\) \((R < 1\%\)) and HR coated at 1.62 and 3.1 \(\mu m\) \((R > 99\%\)). OC with 500 mm for radius of curvature was HR coated at 1.06 \(\mu m\), HT coated at 3.1 \(\mu m\) \((T > 90\%\)), and partial-reflection (PR) coated \((T = 8.3\%)\) at 1.62 \(\mu m\). The pump incident facet of the Nd:YVO\(_4\) crystal S1 and the OC forms the cavity of the 1.06 \(\mu m\) laser oscillation. The cavity has a length of 9 cm.

During the experiment the output power of the signal light was maximized by adjusting the \(Q\)-switching PRF and the position of the pump beam waist in the Nd:YVO\(_4\) crystal. Figure 3 shows total average output power of signal and idler lights versus incident pump power with different \(Q\)-switching PRFs. The output power of leaked fundamental light 1.06 \(\mu m\) was measured to be lower than

![Fig. 3. Total average output power versus incident diode pump power with different \(Q\)-switching PRFs. Inset shows the spectra of the output light.](image)
10 mW after it is filtered by the mirror with the coating the same as IM coating. The OPO thresholds were around 2.5–3 W, which reduced with the PRF. The output power increased with the pump power first and reach a maximum for a given incident pump power and then decreased at higher pump power.

The Q-switching PRF of 60 kHz realized the maximum output power. The maximum output power of 1.8 W was obtained under an incident pump power of 10.5 W, with the diode to OPO total output conversion efficiency of 17.1%. We also replaced the OC by another mirror optimized transmission ($T = 13\%$) for 1.06 μm output to investigate the fundamental light operation without OPO conversion. A 3.6 W 1.06 μm laser output was obtained at a pump power of 10.5 W at the PRF of 60 kHz. The efficiency for OPO total output power to this optimized fundamental output reached 50%. We found that the 1.06 μm laser output power did not rollover for the pump power below 10.5 W with the PRF varied from 60 to 10 kHz. Therefore, the rollover was likely not caused by resonator stability.

The mode radii at the center of RTP crystal for both the fundamental cavity and the OPO cavity have been simulated by the ABCD ray transfer matrix (the thermal effects of Q-switch crystal and RTP were ignored). Figure 4 shows mode radii of both cavities at the center of RTP crystal versus thermal focal length of laser crystal. The mode radius of fundamental cavity is related to thermal focal length of laser crystal, while that of the OPO cavity is not. With the increasing of pump power, the radius difference between fundamental cavity mode and OPO cavity mode enlarged as the thermal focal length of laser crystal reduced.

The enlarged mode mismatching between both cavities modes resulted in the reduction of OPO conversion and the decrease of output power. As for the Nd:YVO₄ with low thermal conductivity, thermal loading of the LD end-pumped Q-switched laser increased with reducing of PRF, which resulted in a much lower critical pump power being rolled over and a lower maximum output power [20,21].

The output laser spectra were measured by the grating monochromator. Both signal wavelength at 1.62 μm and idler wavelength at 3.1 μm were detected. Then we separated the signal light and idler light by dichroic mirrors (DM) with AR coated at 3.1 μm, and HR coated at signal light 1.62 μm. Figure 5 shows the average output power of the separated signal and idler light versus incident diode pump power with the Q-switching PRF of 60 kHz. A 1.42 W signal light at 1619 nm and 0.38 W idler at 3108 nm light were obtained at the incident pump power of 10.5 W. The spectral widths of the signal and idler light were narrower than 0.5 and 1.0 μm, as shown in the inset of Fig. 5. Both the signal and idler wavelengths were well matched with the calculated wavelengths using the Sellmeier equation (1).

Under the maximum OPO output power, leaked fundamental light at 1064 nm and signal light at 1619 nm were separated from the total output, and the temporal pulse profile of them was recorded by a PIN photodiode, and
then displayed on a 500 MHz oscilloscope (Model DPO3052B). Figure 6 shows the recorded temporal pulse profile for fundamental and signal light at the Q-switching PRF of 60 kHz and an incident pump power of 10.5 W, as well as the pulse train of the signal wave. The pulse-to-pulse stability for signal light was better than 12% according to the pulse train. The signal pulse width was about 6.5 ns, corresponding pump light pulse width of about 10 ns. The peak power of the signal pulse is calculated as 3.64 kW.

In conclusion, we have demonstrated an intracavity NCPM cut RTP OPO driven by a diode end-pumping acousto-optic Q-switched Nd:YVO$_4$ laser at 1.06$\mu$m. The outputs of 1.42 W signal light at 1619 nm and 0.38 W idler light at 3108 nm were obtained under the incident pump power of 10.5 W, with the total conversion efficiency of 17.1%. The pulse width is about $\sim$6.5 ns for the signal light. The spectral widths of the signal and idler light are narrower than 0.5 nm and 1.0 nm. Compared with the NCPM OPO by its isomorphs KTP and KTA, the NCPM RTP-OPO can extend signal wavelength up to 1.6$\mu$m. The RTP crystal has a higher damage threshold and absorbs less idler wavelength than KTP, which is important for high average power operation.

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