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Electro-optic Q-switched intracavity optical parametric oscillator at 1.53 μm based on $KTiOAsO_4$

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ABSTRACT

An eye-safe, high peak power optical parameter oscillator (OPO) intracavity pumped by electro-optic Q-switched Nd:YAG laser is presented. This OPO is based on a 20 mm length $KTiOAsO_4$ crystal with non-critical phase matching ($\theta = 90°$, $\phi = 0°$) cut. An aperture ∅3 mm acted as limiting diaphragm to get good beam quality of pumping laser. The output energy of 25 mJ at the signal wavelength 1.53 μm was obtained with repetition rate of 1 Hz. The highest peak power intensity was up to 88 MW/cm^2 with pulse width of 4 ns. Without diaphragm, the maximum output energy of 90 mJ was achieved with area of light spot (∅6 mm) four times larger, but the peak power intensity was lower.

1. Introduction

$KTiOAsO_4$ (KTA), as a relatively new nonlinear optical crystal, has attracted a great deal of attention in recent years [1]. In comparison to its analog $KTiOPO_4$ (KTP), KTA not only possesses a large nonlinear coefficient, high figure of merit, and low ionic conductivity, but also owns wider transparency range (0.35–5.3 μm), higher optical damage threshold, which makes it widely used in the high power mid-infrared optical parameter amplification and oscillation (OPA and OPO) [2–4]. Especially for OPO to produce laser around 1.5 μm, KTA can operate with non-critical phase matching (NCPM).

Lasers operating around 1.5 μm, which has characteristics for eye safety and for transparency in the atmosphere and in silica based optical waveguides and fibers, are in demand for applications in remote sensing, lidar systems, laser range finding, and optical communications, etc. NCPM OPO pumped by 1.064 μm laser based on KTP and KTA technology is one promising approach for producing an efficient and reliable pulsed eye-safe laser for the applications mentioned above. Intracavity pumped OPO (IPOPO) has advantages of stableness, compactness, low threshold, and high efficiency. OPO based on KTP to produce 1.5 μm laser has been extensively studied [5–8]. OPO based on KTA was first introduced by Powers et al. [9], which was pumped by 780 nm Ti:sapphire laser. Recently, some researches have been done on OPO by KTA, but most of the results concentrated on low pulse energy with high repetition rate. Lasers (10.9 W and 1.1 W 1.5 μm) have been achieved based on KTA pumped by acousto-optical Q-switched Nd:YALO [10] and Nd:YVO_4 [11] lasers, respectively.

In this paper, a pulsed laser at 1.53 μm, using a KTA crystal with 20 mm length and non-critical phase matching cut in an IPOPO, is reported. The output characteristic of the laser with different transmissions output couplers and cavity lengths, as well as a limited diaphragm used, have been studied. This OPO pumped by electro-optic Q-switched Nd:YAG laser owns a high peak power.

2. Theory analysis of tuning KTA–OPO pumped at 1.064 μm

KTA belongs to the orthorombic crystal system, and therefore is optically biaxial. The indices of refraction for any propagation direction are given by the index ellipsoid defined by [12]

$$\frac{\sin^2\theta\cos^2\phi}{n^{-2}-n_x^{-2}}+\frac{\sin^2\theta\sin^2\phi}{n^{-2}-n_y^{-2}}+\frac{\cos^2\theta}{n^{-2}-n_z^{-2}}=0, \quad (1)$$

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where θ is the angle to the z axis, and ϕ is the angle to the x axis in the x–y plane. The indices of refraction versus wavelength are given by Sellmeier equations [13]:

$$\begin{cases} n_x^2 = 5.55552 + \frac{0.04703}{\lambda^2 - 0.04030} + \frac{602.9734}{\lambda^2 - 249.6806}, \\ n_y^2 = 5.70174 + \frac{0.04837}{\lambda^2 - 0.04706} + \frac{647.9035}{\lambda^2 - 254.7727}, \\ n_z^2 = 6.98362 + \frac{0.06644}{\lambda^2 - 0.05279} + \frac{920.3789}{\lambda^2 - 259.8645}, \end{cases} \quad (2)$$

where λ is in μm.

As an isomorph of KTP, type I interactions in the KTA have very low nonlinear coefficients, and type II interactions are widely used. For propagation in the x–z plane ($\phi = 0^\circ$) and in the y–z plane in KTA, type II interactions correspond to type II phase matching in a positive uniaxial crystal. For propagation in the x–z plane ($\phi = 0^\circ$), the polarization of the pump wave is along the y-axis (named ordinary wave, "o-wave") of the crystal as is that of the signal wave. The idler wave is polarized in the x–z plane (named extraordinary wave, "e-wave"). For this type II phase matching, the wavelengths for three waves should satisfy energy conservation and the momentum-matching condition,

$$\begin{cases} \frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i}, \\ \frac{n_y(\lambda_p)}{\lambda_p} = \frac{n_y(\lambda_s)}{\lambda_s} + \frac{n(\theta, \lambda_i)}{\lambda_i}. \end{cases} \quad (3)$$

Put $\phi = 0$ into Eq. (1), $n(\theta, \lambda_i)$ can be revised as

$$n(\theta, \lambda_i) = (n_x^{-2}(\lambda_i)\cos^2\theta + n_z^{-2}(\lambda_i)\sin^2\theta)^{-1/2}. \quad (4)$$

However, for propagation in the y–z plane ($\phi = 90^\circ$), the polarization of the pump wave is along the x-axis (o-wave) of the crystal as that of the signal wave. The idler wave is polarized in the y–z plane (e-wave).

Fig. 1 exhibits the calculated signal and idler wavelengths, walk-off angle, and the effective nonlinear coefficient (d_{eff}) for KTA optical parametric converter pumped at 1.064 μm propagating in both the x–z plane and y–z plane. The calculations of the effective coefficient and walk-off angle are detailed in Ref. [14]. In both principal planes, the highest d_{eff} and the lowest walk-off occur for non-critical phase matching at θ = 90°, corresponding to the signal wavelength around 1.5 μm and to the idler wavelength around 3 μm. But d_{eff} for phase-matching in the x–z plane, which depends on the nonlinear coefficient d24, is much larger than that in the y–z plane where d_{eff} is governed by d15 [14]. The maximum effective nonlinear coefficient is at the phase matching angle of θ = 90°and $\phi = 0^\circ$, which is about 3.64 pm/V and much larger than 2.3 pm/V at the phase matching angle of θ = 90°and $\phi = 90^\circ$. So we chosen the non-critical phase matching in x–z plane along the x-axis to profit from the maximum of the effective nonlinear coefficient and essentially eliminate to the full elimination of the spatial walk-off.

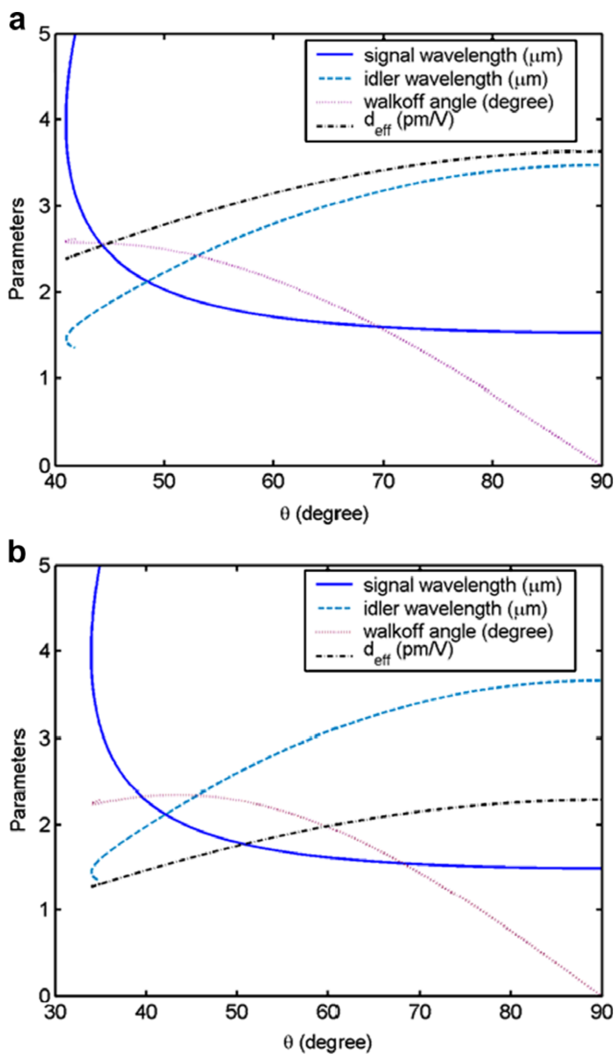

Fig. 1. Calculated tuning curve for the KTA–OPO pumped at 1.064 μm showing the signal and idler wavelengths, walk-off angle, and d_{eff} (a) in x–z plane ($\phi = 0^\circ$) (b) in y–z plane ($\phi = 90^\circ$).

3. Experiments design

The experimental arrangement of the IPOPO based on KTA for generation of 1.53 μm radiation is shown in Fig. 2. The active medium of the laser oscillator was a Nd:YAG rod, 100 mm long, 6 mm in diameter, pumped by a xenon lamp with repetition rate of 1 Hz. In order to obtain Q-switched operation, the cavity also contained a thin-film polarizer and a KD*P-based electro-optic Q-switch modulator. The laser cavity of the Nd:YAG laser, 60 cm long, was formed by a high reflector M1 (R > 99% @ 1.064 μm) and an output coupler M3 (R = 94% @ 1.064 μm). We did not use R = 100% for the M3 in this experiment because we wanted to prevented optical damage due to fluctuations of high laser intensities when tuning the OPO. In addition, this can also determine the laser intensities of the OPO pump light. An aperture with diameter of 3 mm acts as limiting diaphragm, in order to get good beam quality of pump light.

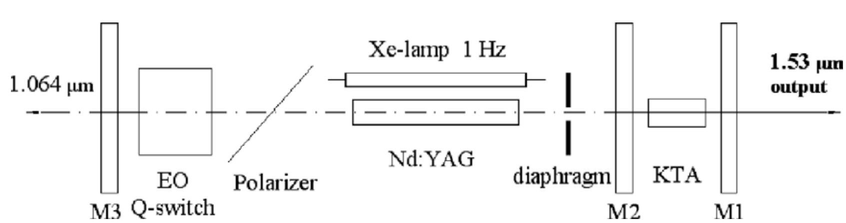

Fig. 2. Schematic experimental arrangement of the IPOPO.

The OPO cavity, 30 mm-long, was formed by a pair of plane-parallel mirrors, M1 and M2. Besides acting as a high reflecting mirror at 1.064 μm, the M1 also acted as the output coupler for the OPO, which was partially reflective coated at 1.53 μm and different transmissions was used. Whereas the M2 was anti-reflective (AR) coated at 1.064 μm ($R < 1\%$) and high-reflective (HR) coated at the signal wavelength of 1.53 μm ($R > 99\%$). The KTA crystal (CRYSTECH Inc), 7 mm × 7 mm × 20 mm, was cut to achieve type II NCPM interaction along the x crystallographic axis ($\theta = 90°$, $\phi = 0°$) for a pump wavelength of 1.064 μm and a signal wavelength of 1.53 μm. NCPM permits efficient OPO operation even with multi-transverse-mode pump lasers for its maximum effective nonlinear coefficient and acceptance angle, and essentially eliminated walk-off. Both end faces of KTA crystal were AR coated at both 1.064 and 1.53 μm.

4. Experimental results

The performance of the OPO using the output couplers with different transmissions is presented in Fig. 3, which shows the output energy at the signal wavelength 1.53 μm as a function of the electrical pump energy. Because both the OPO cavity mirror M1 and M2 were made of K9 glass, the idler wave at around 3.5 μm was strongly absorbed. As a result, we did not observe the idler wave through the output mirror M1.

The OPO output with the transmission of 10% at 1.53 μm had much lower output energy and a little lower threshold for its too low transmission. At the pump energy of 25 J, the maximum output energy of 25 mJ at 1.53 μm was achieved using the output mirror M1 with the transmission of 35%, meanwhile, the output energies at 1.064 μm measured from the output of M3 was about 3 mJ. The energy of the pump light in the cavity was calculated to be about 97 mJ, so the efficiency of pump light to signal light is about 26%. The output energy linearly increased with the electrical pump energy before the 1.064 μm can not be held off by Q-switch.

The pulse width of 1.064 μm pump light and 1.53 μm signal laser is presented in Fig. 4, which was received by a PIN photodiode, and displayed by a Model TDS3052B (500 MHz) dual-line oscilloscope. The pump laser pulse was compressed for OPO generating, and the pulse width corresponding to the pump laser before conversion and after conversion are 16.2 ns and 12.4 ns, respectively. The pulse width of 1.53 μm signal light was much narrower than that of 1.064 μm pump light. The narrowest pulse width was 4 ns and the highest peak power intensity was calculated to be about 88 MW/cm^2.

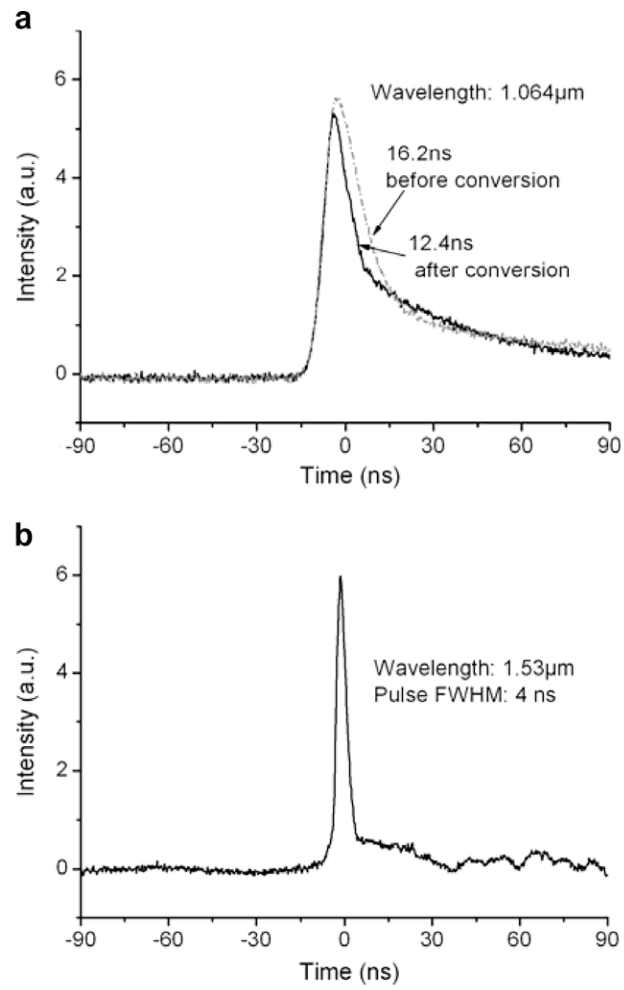

Fig. 4. The temporal pulse profile: (a) for signal light (b) for pump light.

The OPOs with different cavity lengths (3 cm, 6 cm, and 10 cm) were studied, but the output energy was without evidently change (vary between 24 and 25 mJ) and the pulse width of 1.53 μm

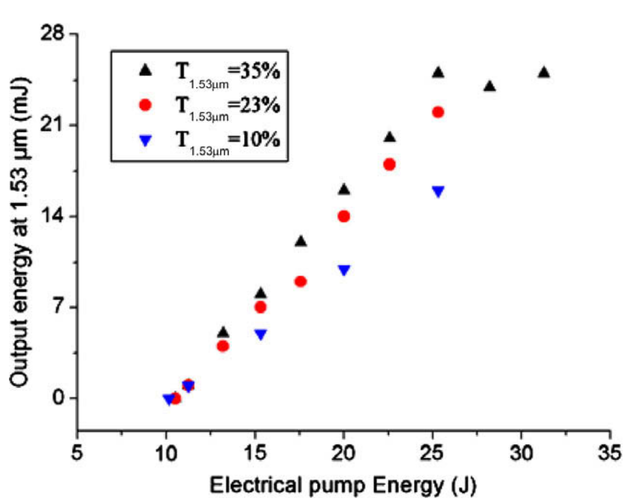

Fig. 3. Output energy at the wavelength 1.53 μm versus the electrical pump energy.

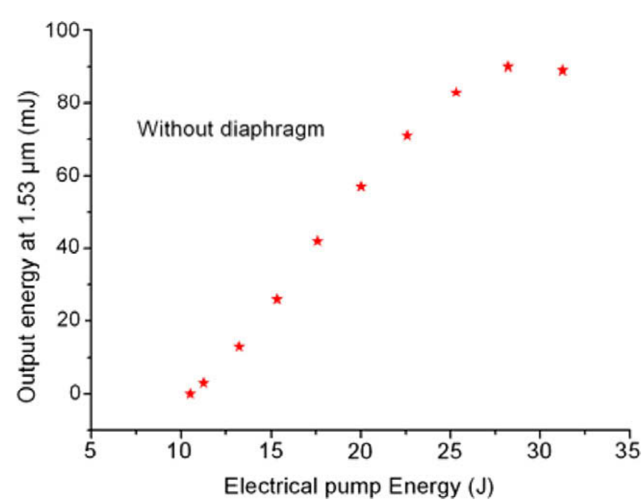

Fig. 5. Output energy at the wavelength 1.53 μm versus the electrical pump energy without limiting diaphragm.

varied from 4 ns with cavity length of 3 cm to 5 ns with cavity length of 10 cm.

Fig. 5 shows the output energy at the signal wavelength 1.53 μm when the diaphragm in the cavity was moved out. The 1.064 μm laser can still be held off until the electrical pump energy of about 28 J. The area of light spot (∅6 mm) was four times larger, so the output energy was also much larger and the maximum energy of 90 mJ was achieved. The peak power intensity was calculated to be about 79 MW/cm^2, which was lower than that with diaphragm. The output energy at 1.064 μm measured from the output of M3 was about 12 mJ, which was also four times larger than that with diaphragm (∅3 mm).

5. Conclusion

NCPM OPO intracavity pumped by electro-optic Q-switched Nd:YAG pulsed laser to produce 1.53 μm eye-safe laser has been demonstrated. A 20 mm length KTA with non-critical phase matching ($\theta = 90°$, $\phi = 0°$) cut was adopted for high OPO conversion efficiency. The parameters of tuning KTA–OPO pumped at 1.064 μm were calculated. The OPOs with different output coupler transmissions and cavity lengths were studied. When a ∅3 mm limiting diaphragm was used, the maximum output energy of 25 mJ was obtained with pulse width of 4 ns and repetition rate of 1 Hz. The efficiency of pump light to signal light is about 26%. The highest peak power intensity was up to 88 MW/cm^2 corresponding to the pump pulse width of 16.2 ns. Without diaphragm, the maximum output energy of 90 mJ was achieved, but the peak power intensity was lower. In view of its results in this experiment, the KTA may also have an excellent performance in the high energy mid-infrared OPO.

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