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PUMP-TUNING KTP OPTICAL PARAMETRIC OSCILLATOR WITH CONTINUOUS OUTPUT WAVELENGTH PUMPED BY A PULSED TUNABLE Ti:SAPPHIRE LASER*

Ding Xin(丁 欣)[a], Yao Jian-quan(姚建铨)[b], Yu Yi-zhong(于意仲)[b],
Yu Xuan-yi(禹宣伊)[a], Xu Jing-jun(许京军)[a], and Zhang Guang-yin(张光寅)[a]

[a] *Optoelectronic Information Science and Technology Laboratory, Photonic Center, Nankai University, Tianjin* 300071, *China*
[b] *Optoelectronic Information Science and Technology Laboratory, Institute of Laser and Opto-Electronics, Tianjin University, Tianjin* 300072, *China*

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We report on the implementation of a KTP optical parametric oscillator pumped by a pulsed tunable Ti:sapphire laser. Two major improvements were achieved, including the connection of the signal and idler tuning ranges and the high-output conversion efficiency through the signal and idler tuning ranges. Both in the signal and idler, the continuous output wavelength from 1.261 to 2.532μm was obtained by varying the pump wavelength from 0.7 to 0.98μm. The maximum output pulse energy was 27.2mJ and the maximum conversion efficiency was 35.7% at 1.311μm (signal).

Keywords: Ti:sapphire laser, pump-tuning, optical parametric oscillator, phase-matching condition
PACC: 4255R, 4260B

I. INTRODUCTION

The Ti:sapphire laser is the most widely tunable laser in current laser technology. It has a tuning range from 0.68 to 1.1μm. Using nonlinear optical frequency conversion technology to expand its output wavelength is quite important and useful. Nonlinear wavelength conversion pumped with a Ti:sapphire laser has been reported in the literature.[1–6] With the pumping of a nsec Ti:sapphire laser, Rines *et al.*[1] have implemented second-harmonic generation (SHG) at 462nm with type-I phase-matching in BBO, third-harmonic generation at 308nm with types-I and II phase-matching in BBO, fourth-harmonic generation at 220nm in BBO and LBO, sum-frequency mixing (SFM) at 194nm in LBO, and optical parametric oscillation (OPO) for up to 3μm with type-II non-critical phase-matching in KTP, KTA and CTA crystals. Also, Bartoshevich *et al.*[2] reported their results of a large tuning range from 0.43 to 2.3μm with SHG and difference frequency mixing (DFM), pumped with a dual-wavelength Ti:sapphire laser. This large tuning range consists of three blocks: the fundamental wavelength (Ti:sapphire laser, 0.68–1.05μm), the SHG (0.34–0.525μm), and the two sections of DFM (0.503–0.79μm and 0.83–2.3μm). Non-critically phase-matched KTP optical parametric oscillators pumped by tunable Ti:sapphire lasers were also reported. By tuning the pump wavelength, a cw signal range of 1.05–1.37μm and an idler range of 2.2–3.1μm were obtained.[3] Another implementation of non-critically phase-matched KTP OPO provided a pulsed signal range of 1.03–1.28μm and an idler range of 2.18–3.03μm.[4] Although their tuning ranges are quite large and there is no walk-off problem under non-critical phase-matching condition, the signal and idler wavelength ranges are disconnected. In other words, continuous tuning from near infrared to mid-infrared is not allowed. Also, their singly resonant oscillators for the signal resulted in quite a weak output power for the idler.

In this paper, we report our results of a continuously tunable KTP OPO pumped by a pulsed tunable Ti:sapphire laser. The Ti:sapphire laser was pumped with the second-harmonic of a Q-switched Nd:YAG laser. By choosing appropriate phase-matching angles, we could connect the signal and idler wavelength ranges for continuous tuning from 1.261 to 2.532μm. Also, because we used five sets of resonator mirrors of different coatings for oscillating different bands of signal and idler, the OPO output conversion efficiency could exceed 28.4% in the whole tuning range. These results are different from most of those previously reported in the literature, in which typically only either the signal or idler oscillates. Hence, the non-

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oscillating component had a quite weak output power or energy. In Section II of this paper, we describe the theoretical calculations of optimum phase-matching angles and related parameters of KTP for continuous OPO tuning. Then, in Section III, the experimental procedures and the results of the pump-tuning OPO are presented. Finally, conclusions are drawn in Section IV.

Ⅱ. THEORETICAL CALCULATIONS FOR OPO PHASE-MATCHING PARAMETERS

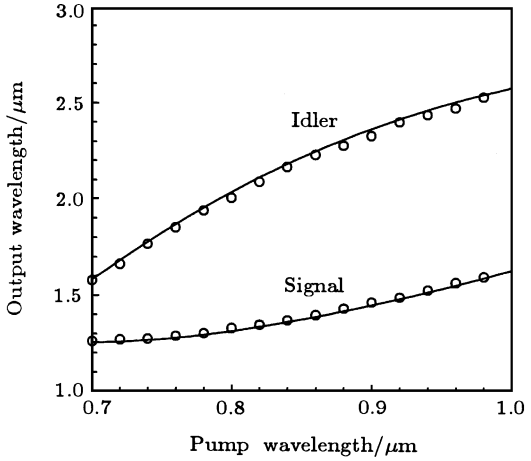


Fig.1. The relationship between the output (signal and idler) and pump wavelength of KTP OPO (at θ=62.5°, φ=0°). The solid line denotes the calculated results, and the white dots represent the experimental data.

Methods for calculating the phase-matching parameters, including phase-matching curve, effective nonlinear coefficient, acceptance angle, walk-off angle and acceptance wavelength, of a biaxial nonlinear crystal such as KTP, have been reported.[7,8] In the calculations described below, we first search for type-II phase-matching angles (θ and φ) of KTP for connecting the signal and idler wavelength ranges in the optical parametric process. With these angles, continuous tuning across the signal and idler ranges becomes possible. We fix the φ=0° or φ=90° plane of KTP OPO and calculate the tuning curve under the condition of the Sellmeier function of KTP and phase-matching condition when the pump laser varies from 0.7 to 0.98μm. When the signal curve is connected with the idler curve at a certain angle $\theta(\varphi = 0°$ or $\varphi = 90°)$, the angle θ is the proper angle needed. With the pump laser varying from 0.7 to 0.98μm in the experiment, the cutting angle of the KTP crystal is $\theta = 62.5°$, $\varphi = 0°$ and $\theta = 53°$, $\varphi = 90°$. Figure 1 shows the signal and idler wavelength variations as the pump wavelength is tuned from 0.7 to 0.98μm for the phase-matching angle θ=62.5°, φ=0°. From Fig.1, one can read that at 0.7 (0.98)μm pump wavelength, the signal wavelength is 1.255 (1.593)μm and the idler wavelength is 1.582 (2.546)μm. The signal wavelength 1.593μm is larger than that of the idler, 1.582μm. Therefore, by tuning the pump wavelength from 0.7 to 0.98μm, we can obtain a continuous output spectrum from 1.255 to 2.546μm. To achieve such a continuously, broadly tunable range with angle tuning of KTP, pumped by a laser of a fixed wavelength at 0.8μm, the θ angle needs to be rotated from 53° to 73° (assuming φ=0°). For this purpose, more than one KTP crystal are usually required.

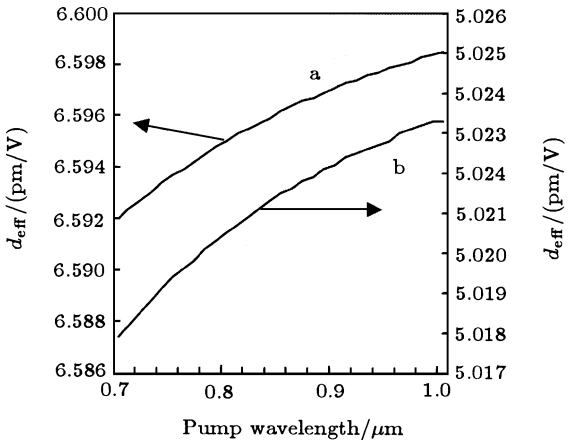


Fig.2. The dependence of $d_{\rm eff}$ on pump wavelength (λ_p) at (a) θ=62.5°, φ=0° and (b) θ=53°, φ=90°.

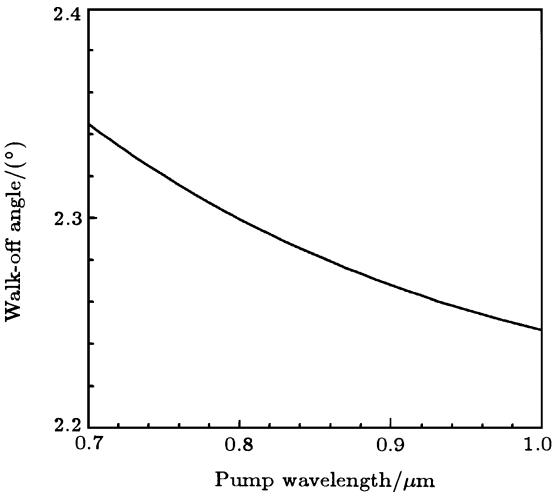


Fig.3. The dependence of walk-off angle on pump wavelength (λ_p) at θ=62.5°, φ=0°.

Next, we calculate the effective nonlinear coeffi-

cient, d_{eff}, for the two sets of phase-matching angles. We can find that the effective nonlinear coefficient is larger for the angles: θ=62.5°, φ=0° than for the angle: θ=53°, φ=90°, as shown in Fig.2. In this case, d_{eff} varies from 6.592 to 6.598pm/V as the pump wavelength is tuned from 0.7 to 0.98μm. These values are slightly smaller than that in the case of the non-critical phase-matching condition (θ=90°, φ=90°), which is 7.6pm/V. Therefore, Fig.1 is preferred in the experiment. The variation of walk-off angle for the idler in the case of θ=62.5°, φ=0° is shown in Fig.3. This angle varies between 2.25° and 2.35°. Note that in this case, there is no walk-off between the pump laser and signal.

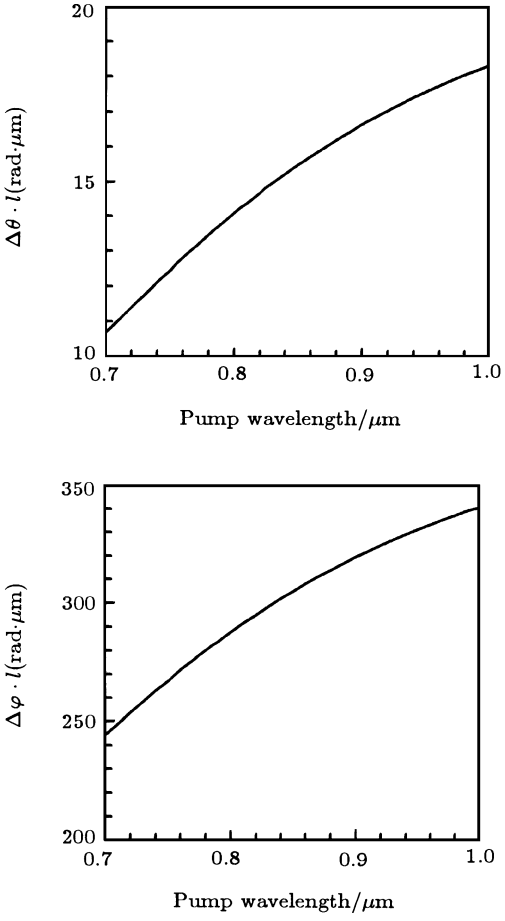


Fig.4. The dependence of KTP OPO acceptance angles $\Delta\theta \cdot l$(rad·μm) and $\Delta\varphi \cdot l$(rad·μm) on pump wavelength at θ=62.5°, φ=0°.

The acceptance angle for efficient nonlinear conversion is usually defined as the angular ranges $\Delta\theta$ and $\Delta\varphi$ such that the wavenumber mismatch Δk satisfies $|\Delta k| \leq \pi/l$. Here, l is the length of the crystal. With the aforementioned phase-matching conditions, $\Delta\theta \cdot l$ and $\Delta\varphi \cdot l$ are plotted as functions of the pump wavelength in Fig.4 (θ=62.5°, φ=0°). Figure 4(a) shows that $\Delta\theta \cdot l$ always lies between 10 and 18rad·μm. Also, Fig.4(b) shows that $\Delta\varphi \cdot l$ always lies between 240 and 340rad·μm. The acceptance angles correspond to the acceptance conversion wavelength ranges or the spectral widths ($\Delta\lambda$) of the signal and idler. The variations of $\Delta\lambda \cdot l$ of the signal and idler are shown in Fig.5. These results were obtained by assuming that the pump spectral width was zero. If there is a finite pump spectral width, the spectral widths of the signal and idler can be obtained by the superposition of the contributions from different components of the pump frequency. Because the mode competition exists inside an oscillator, the results of the superposition can only be regarded as the upper bounds of the output spectral widths of the signal and idler.

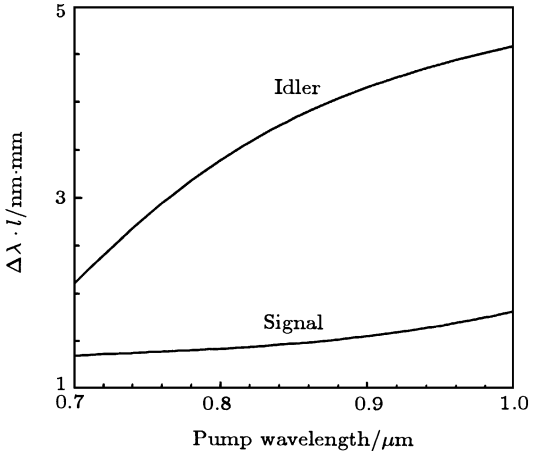


Fig.5. The dependence of KTP OPO acceptance wavelength $\Delta\lambda \cdot l$(nm·mm) on pump wavelength at θ=62.5°, φ=0°.

Ⅲ. EXPERIMENTAL PROCEDURES AND RESULTS OF OPO

The OPO set-up is sketched in Fig.6, in which the pulsed Ti:sapphire laser, tunable from 0.7 to 0.98μm, is pumped by a Q-switched (10Hz) frequency-doubled Nd:YAG laser. The Ti:sapphire laser could provide pulses with pulse energy range from 76.2mJ (at 795nm) to 31mJ (at 980nm), line width around 1.1nm, pulse width 10–12ns, and output divergence angle about 1.2 mrad. With type-II phase matching, the KTP crystal of OPO was cut at θ= 62.5°, φ=0°, which corresponded to one of the phase-matching conditions described in Section II. The KTP crystal had the dimensions of 5×5.7×8.6mm. There was no coating on either end face of the crystal. The OPO resonator had a flat–flat configuration. To obtain a suf-

ficiently high output pulse energy for both the signal and idler, five sets of mirrors with high reflectivity wavelength ranges of 1.2–1.5, 1.49–1.8, 1.79–2.1, 2.09–2.4 and 2.39–2.6μm were used for the resonator. The reflectivity levels of the end mirrors of the resonator were always higher than 99%. Those of the output couplers were between 89 and 92%. To reduce the threshold, we choose the short cavity length to be 34mm. The Ti:sapphire pump beam was focused with a lens of 500mm in focal length into a spot size of 2.3mm in diameter. The focal point was located 14mm behind the KTP crystal to avoid crystal damage. The linear polarization of the pump was along the y-axis of the KTP crystal. The two short-wavelength mirror sets were used to oscillate the signal and the three long-wavelength mirror sets were used for the oscillation of the idler. Such combinations guarantee a sufficiently high output pulse energy for both the signal and idler. Therefore, the experimental results discussed below always refer to those of the oscillating wavelength, either the signal or idler.

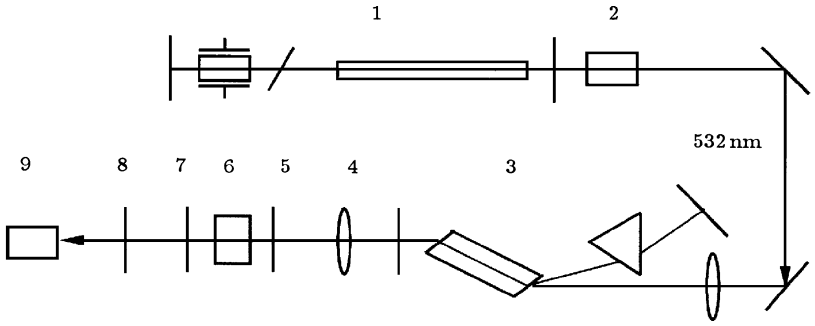


Fig.6. The experimental set-up of the KTP OPO pumped by a pulsed Ti:sapphire laser: 1, Nd:YAG; 2, KTP for SHG; 3, Ti:sapphire resonator (700–980nm); 4, lens (f=500mm); 5, mirror (HT for output wavelength of Ti:sapphire laser, HR for optical parametric oscillating wave); 6, KTP crystal; 7, OPO output coupler; 8, filter; 9, detector.

Combining the results of the five mirror sets, we obtained the tuning curves shown in Fig.1. Here, the empty circles represent the experimental data and the continuous curves the theoretical predictions. With the pump laser tuned from 0.7 to 0.98μm, signal wavelengths from 1.261 to 1.599μm and idler wavelengths from 1.576 to 2.532μm were achieved. The typical oscillating output line width was around 1.7nm. The experimental and theoretical results in Fig.1 agree well with each other, except for a 10–14nm discrepancy. The discrepancy may originate from the slight inaccuracies of the Sellmeier equation for KTP and the cutting angles of the crystal. The average pulse energy of the Ti:sapphire laser used in the experiment was 41.3mJ and the maximum value was 76.2mJ at 795nm. In the whole tuning range (1.261–2.532μm), the oscillating output pulse energy could always exceed 8.4mJ and the maximum output energy was 27.2.mJ when the output wavelength was 1311μm with the pump pulse energy of 76.2mJ at 795nm (the pump pulse energy dropped as the wavelength moved away from this value). In the tuning range, the OPO conversion efficiency was almost the same, which was between 28.4 and 35.7% because the difference of the effective nonlinear coefficients was slight. It is expected that a lower reflectivity of the output coupler led to a higher conversion efficiency. Because a small part of the idler (signal) light also oscillates when the signal (idler) light oscillates in the cavity, a small part of the parametric light can convert to the pump light, and this makes the conversion efficiency saturated as the pump increases.

IV. CONCLUSIONS

In summary, we have implemented a KTP OPO pumped by a pulsed Ti:sapphire laser. For both the signal and idler, the output wavelength could be continuously tuned from 1.261 to 2.532μm by varying the pump wavelength. There are two major improvements in our OPO system. Firstly, by considering a particular set of critical phase-matching angles (θ=62.5°, φ=0°) for KTP, the signal and idler tuning ranges could be connected so that the continuous tuning range 1.261–2.532μm could be achieved by changing the Ti:sapphire laser wavelength from 0.7 to 0.98μm. Secondly, to obtain a significantly high output pulse energy through the whole tuning range, five sets of oscillator mirrors of different coatings were used for oscillating the signal and idler, section by section. In the whole tuning range, the maximum output pulse

energy of 27.2mJ and the maximum conversion efficiency 35.7% at 1.311μm were achieved. Besides the experimental implementation, theoretical calculations were also conducted for the effective nonlinear coefficient, walk-off angle and phase-matching acceptance angle for the phase-matching angle: θ= 62.5°, φ=0°, with which pump-tuning KTP OPO (pumped by a Ti:sapphire laser) could result in continuous tuning from the signal to idler range.

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