Dual-wavelength single-crystal double-pass KTP optical parametric oscillator and its application in terahertz wave generation

Ming Tang,1,2* Hiroaki Minamide,1 Yuye Wang,3 Takashi Notake,1 Seigo Ohno,2 and Hiromasa Ito1
1RIKEN ASI, 519-1399, Aramaki, Aoba, Sendai 980-0845, Japan
2Department of Physics, Tohoku University, 6-3 Aoba Aramaki, Sendai 980-8578, Japan
*Corresponding author: tangming@riken.jp

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A tunable dual-wavelength double-pass singly resonant optical parametric oscillator based on a single KTP crystal has been proposed and demonstrated. By setting the rear mirror tuning angle precisely, collinear and noncollinear dual phase matching can be established simultaneously and leads to a two-wavelength oscillation at steady state. With high-speed KTP angle tuning, two wavelengths and their frequency difference can be adjusted continuously and accurately. By using this newly developed dual-wavelength optical parametric oscillator to pump a DAST crystal, a monochromatic terahertz wave ranging from 0.5 to 3 THz has been successfully generated in a difference-frequency generation system. © 2010 Optical Society of America

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Optical parametric oscillators (OPOs) are efficient devices to generate widely tunable coherent radiation for applications in the UV, visible, and IR spectral range [1]. With the advent of high-power solid-state pumping lasers and high-quality nonlinear optical crystals, various OPO systems are being developed both for scientific investigation and real world applications [2–5]. Recently, for applications like differential absorption lidar [2] and mid-IR or terahertz (THz)-wave generation [3], high-peak-power OPOs with multiple wavelength emission are highly desired. An ultrawidely tunable dual-KTiOPO4 (KTP)-crystal-based OPO has been demonstrated in our group to generate THz waves through difference-frequency generation (DFG) in organic 4-dimethylamino-N-methyl-4-stilbazolium tosylate (DAST) crystals [4]. Similarly, a two-crystal cross-resonant OPO has been studied and applied in the mid-IR DFG process [5]. However, the two-crystal-based OPO cavity is costly and complicated. A single periodically poled crystal with a periodically phase-reversed grating structure or multiple grating structures can be used to generate a two-wavelength beam from a singly resonant OPO [6,7], requires specially designed crystals. Also, retracing behavior could generate broadband or multiwavelength oscillation in the OPO in which two pairs of signal–idle waves can be phase matched [8,9]. However, retracing behaviors are always limited to certain nonlinear optical crystals with limited wavelength ranges [9].

In this Letter, we propose and demonstrate a single-KTP-crystal-based tunable dual-wavelength OPO. The collinear and noncollinear phase-matched parametric processes are established in our double-pass system with a slightly tilted rear reflecting mirror. By controlling the rear mirror tilting angle and the KTP crystal angle, the frequency difference between two wavelengths can be adjusted continuously and covers the 0.5–3 THz frequency range. As an immediate application, we perform a DFG process with DAST crystal pumped by this newly developed OPO. Monochromatic tunable 0.5–3 THz radiation has been successfully generated.

The proposed single KTP-OPO-based dual-wavelength system is shown in Fig. 1. The 532 nm pump beam is from a frequency-doubled Q-switched Nd:YAG laser (8 ns, 100 Hz repetition rate). The KTP crystal with dimensions 10 mm × 5 mm × 27 mm has a cut angle of 60° (x–y plane) and is antireflection coated on both faces for 532 nm, 750–950 nm, and 1250–1700 nm. The crystal is mounted inside a linear Type II OPO resonator with mirrors M1 and M2. The input mirror M1 is coated for high reflectivity of signal waves (R > 98%) and high transmittance of 532 nm and idle waves. M2 is a broadband silver mirror to reflect the pump, signal, and idle waves efficiently (R > 99%). M3 is coated for high reflection of idle waves and high transmittance at 532 nm. Thus the signal wave will resonate in this double-pass singly resonant OPO (DPSRO), and the idle wave will be output. The KTP crystal angle is precisely controlled by using the Galvano optical scanner.

Compared with the single-pass singly resonant OPO, the DPSRO is effective to reduce the pump threshold and improve the conversion efficiency. With the first-pass pump beam, conventional collinear phase matching is achieved, and the resonant wavelength is determined by the x-cut angle of the KTP crystal. Additionally, with a very small tilt of M2, the reflected pump beam in the OPO cavity is able to build a noncollinear light path in the gain medium. As a result, the collinear and noncollinear phase-matched parametric processes will take place simultaneously at steady state. The dual-phase-matching criteria exhibit a dual-wavelength phenomenon in which the frequency difference is determined by the noncollinear angle ε and KTP crystal angle β, as shown in Fig. 1. Assuming very small M2 tilting angle δ and β, the DPSRO leads to two pairs of signal and idle waves: ωs, ωi and ωs', ωi'. The output idle wave ωi is determined by the conventional collinear phase-matching condition, and another idle wave ωi' is governed by the noncollinear phase matching. Since the Type II phase-matched KTP OPO in the x–z plane is similar to that of uniaxial crystals, we can analyze the phase-mismatch effect by using a
The input pump has 13.5 mJ of pulse energy and a 1.5 mm beam diameter. The corresponding idle wave energy is 1.1 mJ. Two wavelengths are clearly demonstrated, and their frequency difference is adjusted through the KTP angle \( \beta \) while the M2 tilting angle \( \delta \) is fixed at 22.8 mrad. The corresponding OPO idle wave input–output characteristic versus 532 nm pump energy is plotted in Fig. 2(b). The oscillation threshold of our dual-phase-matched DPSRO is 3.5 mJ. The linewidth of each idle wave is measured at 75 GHz. The pump beam diameter is large enough for the beam path relative to the mirror angle deviation for oscillation.

The calculated and measured wavelength evolution and frequency difference of OPO output are illustrated in Figs. 3(a) and 3(b) as functions of \( \beta \). Excellent agreement between theoretical calculation and experimental data is achieved. As predicted by our theory, the collinear phase-matched \( \Delta \lambda \) has a faster changing rate than the noncollinear phase-matched \( \Delta \lambda \). The frequency difference exhibits a tuning rate of 0.354 THz/mrad in the 0.5–3 THz range. The maximum frequency difference is obtained when KTP crystal angle \( \beta = 0 \), and it can be adjusted by setting the M2 tilting angle \( \delta \). Figure 3(c) shows the measured and calculated maximal frequency difference of dual-wavelength output by changing the angle \( \delta \). The experimental and theoretical results agree qualitatively and validate our interpretation of the dual-wavelength phenomena. The relatively larger discrepancy at the larger tilting angle should be attributed to the pump beam divergence and the assumption we made in solving Eq. (1). When angles \( \delta \) and \( \beta \) increase further, the variation of refractive indices along different angles could not be negligible; thus the noncollinear parametric process efficiency drops.

Using this single KTP-based DPSRO, a DAST DFG system has been implemented to generate monochromatic

In the above equations, \( p, s, \) and \( i \) represent pump, signal, and idle waves, respectively; \( n \) means refractive index; \( n_g \) means the group refractive index; \( \omega \) is the angular frequency; \( c \) is the speed of light in vacuum; and \( k \) is the wavenumber. The first term in Eq. (1) describes the variations of refractive indices in different directions, in which \( \theta_m \) is the angle between the pump wave and the optical axis in the collinear phase-matching conditions and \( \Delta \theta \) is the change in this angle. The second term represents the sum of three wave vectors in the noncollinear geometry. The last term relates to the central frequency shift of the signal–idle wave. Besides the collinear phase-matched wavelength, another wavelength with frequency shift \( \Delta \omega_s \) will be generated under the perfect noncollinear phase-matching condition. By neglecting the variation of refractive indices, \( \Delta \omega_s \), related to \( \delta \) and \( \beta \), is derived as \( \Delta \omega_s = c \epsilon^2 k_s k_p / [2 k_i (n_g - n_i) \delta] \), where the noncollinear phase-matching angle is \( \epsilon = \sqrt{2 \Delta - (n_g - 1) \beta / n_g} \). At the same time, the collinear phase-matched signal–idle wave frequency change with different KTP crystal angle \( \beta \) is \( \Delta \omega_s (\theta_m) = \Delta \omega_s (60^\circ - \beta / n_g) \), which follows the conventional collinear KTP OPO angle tuning behavior [11]. The overall frequency difference between two wavelengths of our DPSRO is calculated as \( \Delta \omega_i = \Delta \omega_i (\theta_m) \).

Figure 2(a) shows the dual-wavelength idle spectra measured by an optical spectrum analyzer (ANDO 6315A) from the M2 tilted DPSRO with KTP angle tuning.

\[ \Delta k = \left( \frac{\omega_p}{c} \right) \cdot \Delta n_p + g n_p^2 - b \Delta \omega_i, \]

where

\[ g = k_s k_p / (2 k_i), \]

\[ \Delta n_p = \frac{\partial n_p}{\partial \theta} \bigg|_{\theta_m} \cdot \Delta \theta, \]

\[ b = \frac{\partial k_s}{\partial \omega_s} - \frac{\partial k_i}{\partial \omega_i} = (n_g^2 - n_g^1) / c. \]

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THz wave radiation from sub-THz to several THz. As depicted in Fig. 4, the dual-wavelength idle wave is focused to a 0.6 mm beam diameter on a DAST crystal with 440 μm thickness. The generated THz radiation is collimated by an off-axis parabolic mirror. A low-pass Yoshinaga filter and black polyethylene film are used to eliminate any residual near-IR light. The THz wave is then focused by a Tsurupica lens and detected by a 4 K silicon bolometer. The DPSRO has the same configuration as in Fig. 2. The KTP angle is swept to adjust the THz frequency. The a axis of the DAST crystal is set parallel to the incident pump polarization. The largest nonlinear optic coefficient $d_{11}$ is used to achieve type-0 collinear phase matching for the DFG THz process [4]. The inset of Fig. 4 shows the THz output pulse train when the 2.1 THz frequency is detected. The repetition rate is 100 Hz. In Fig. 5(a), THz output power versus incident OPO idle wave energy for three frequencies (0.63, 1.34, and 2.1 THz) are illustrated. All data traces can be well fitted by quadratic curves, a typical DFG feature. When the incident pump energy is fixed at 1.1 mJ, THz power spectrum from 0.5 THz to 3 THz is obtained by tuning the KTP angle, as shown in Fig. 5(b). The lowest THz output is around 1.1 THz, at which the strong absorption peak of DAST crystal exists [4,7]. The measured power product of two pumping wavelengths is also plotted. The larger frequency difference implies a bigger M2 tilting angle; thus the larger misalignment in the OPO cavity affects the dual-wavelength oscillation. Consequently, the peak intensities of dual wavelengths are less similar. Since DFG efficiency is proportional to the power product, the THz-wave output decreases above 2 THz.

In conclusion, we proposed and demonstrated, for the first time to our knowledge, a tunable dual-wavelength single-KTP DPSRO for THz generation. Collinear and noncollinear phase-matched parametric processes established in the OPO cavity produce two wavelengths simultaneously. A 0.5–3 THz frequency difference can be randomly accessed by adjusting the KTP crystal angle. We applied this novel OPO source to successfully generate THz radiation ranging from sub-THz to several THz with DAST crystal. The oscillating wavelength can be easily tailored by choosing the proper crystal cutting angle and cavity mirror coating; therefore this kind of dual-wavelength DPSRO is promising for various applications.

References
11. SNLO version 50, nonlinear optics code available from A. V. Smith, AS-Photonics, Albuquerque, New Mexico, USA.