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Terahertz generation by difference frequency generation from a compact optical parametric oscillator

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ABSTRACT

Terahertz (THz) generation by difference frequency generation (DFG) processes with dual idler waves is theoretically analyzed. The dual idler waves are generated by a compact optical parametric oscillator (OPO) with periodically poled lithium niobate (PPLN). The phase-matching conditions in a same PPLN for the optical parametric oscillation generating signal and idler waves and for the DFG generating THz waves can be simultaneously satisfied by selecting the poling period of PPLN. Moreover, 3-order cascaded DFG processes generating THz waves can be realized in the same PPLN. To take an example of 8.341 THz which locates in the vicinity of polariton resonances, THz intensities and quantum conversion efficiencies are calculated. Compared with non-cascaded DFG processes, THz intensities of 8.341 THz in 3-order cascaded DFG processes increase to 2.57 times. When the pump intensity equals to 20 MW/mm^2, the quantum conversion efficiency of 106% in 3-order cascaded DFG processes can be realized, which exceeds the Manley-Rowe limit.

1. Introduction

Among many optical methods for the terahertz (THz) wave generation, difference frequency generation (DFG) is of importance because it offers the advantages of narrow-linewidth, wide tuning range, high-power output and room-temperature working environment [1–4]. In DFG, two optical pump waves, with their frequencies separated by a few THz, interact through a second order nonlinear optical process to generate a THz wave. Although a conventional optical parametric oscillator (OPO) is capable of generating the two optical pump waves near the degeneracy point, spatial walk-off in a nonlinear crystal not only increases the threshold for the oscillation but also sacrifices the beam quality. Recently, it was demonstrated that two sets of signal and idler waves can be simultaneously generated by a single pump wavelength in an OPO based on adhesive-free-bonded (AFB) periodically inverted $KTiOPO_4$ (KTP) plates [5–7]. Similarly, the two sets of signal and idler waves can be obtained by an OPO with periodically poled lithium niobate (PPLN). The frequency separation of several THz between the signal waves or that between the idler waves can be realized by selecting the poling period of PPLN. Moreover, if the phase-matching conditions in the same PPLN for the optical parametric oscillation generating signal and idler waves and for the DFG generating THz waves are simultaneously satisfied, the signal waves, idler waves and THz waves can be simultaneously generated in the same PPLN.

To increase the quantum conversion efficiency of DFG generating THz wave, cascaded DFG is an effective method. In a conventional non-cascaded DFG, at best, a single THz photon is generated from each pump photon. Cascaded DFG in which more than one THz photon is generated from the depletion of a single pump photon can enhance the quantum conversion efficiency. Theoretical descriptions and experimental demonstrations of an enhancement output of THz wave via cascaded DFG processes have been reported recently [8–10]. To modulate and increase the intensity of THz wave, external cavity semiconductor laser used as a pump source is a good choice [11,12]. The output power of external cavity semiconductor laser can be optimized by proper choices of parameters, such as cavity length and injected current.

In this paper, we present the theoretical analysis of THz generation by DFG processes with dual idler waves. The dual idler waves are generated by a compact OPO with PPLN. The phase-matching conditions of the optical parametric oscillation generating signal and idler waves and for the DFG generating THz waves are analyzed. The cascaded DFG processes generating THz waves are investigated. THz intensities and quantum conversion efficiencies in 3-order cascaded DFG processes are calculated from coupled wave equations.

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2. Theoretical model

Fig. 1 shows a schematic diagram of THz wave generation by DFG with PPLN from an OPO. Pump wave propagates along the x-axis of the PPLN. The electric field of pump wave is along the z-axis of PPLN. The poling period of PPLN is Λ. Two flat mirrors M_1 and M_2 with high reflection coating of idler wavelengths are designed as the cavity mirrors. The mirror M_1 has high transmittance for pump wave. A cubic polarizer is placed inside the cavity, which allows the o-polarized signal waves to pass through and reflects the e-polarized idler waves. Since the polarization of idler waves is perpendicular to that of the corresponding signal waves, just the idler waves oscillate inside the cavity. THz wave is generated by DFG process between the dual idler waves. The generated THz wave is deflected out of the resonator by a parabolic mirror which transmits the signal and idler waves.

3. Phase-matching characteristics

In order to achieve the efficient conversion of OPO from the pump wave to the signal and idler waves, and of DFG from idler waves to THz waves, a phase-matching condition for the nonlinear parametric process must be satisfied. Two sets of the signal and idler waves can be simultaneously generated by OPO with a single pump wavelength. The wavelengths for each set of the signal and idler waves must satisfy two new QPM conditions,

$$\vec{k}_{\rm p} - \vec{k}_{\rm s1} - \vec{k}_{\rm i1} - \vec{k}_{\Lambda} = 0 \tag{1}$$

$$\vec{k}_{\rm p} - \vec{k}_{\rm s2} - \vec{k}_{\rm i2} + \vec{k}_{\Lambda} = 0 \tag{2}$$

where $\vec{k}_{\rm p}$ is the wave vectors of pump wave, $\vec{k}_{\rm s1}$ and $\vec{k}_{\rm s2}$ are the wave vector of the dual signal waves respectively, $\vec{k}_{\rm i1}$ and $\vec{k}_{\rm i2}$ are the wave vector of the dual idler waves respectively. $\vec{k}_{\Lambda} = 2\pi/\Lambda$ is the grating vector, which provides small perturbations to the phase-matching conditions. Here, the pump, signals and idlers are e-wave, o-wave and e -wave, respectively. The energy conservation condition has to be fulfilled,

$$\frac{1}{\lambda_{\rm p}} - \frac{1}{\lambda_{\rm s1}} - \frac{1}{\lambda_{\rm i1}} = 0 \tag{3}$$

$$\frac{1}{\lambda_{\rm p}} - \frac{1}{\lambda_{\rm s2}} - \frac{1}{\lambda_{\rm i2}} = 0 \tag{4}$$

where $\lambda_{\rm p}$ is the wavelength of pump wave, $\lambda_{\rm s1}$ and $\lambda_{\rm s2}$ are the wavelengths of the dual signal waves respectively, $\lambda_{\rm i1}$ and $\lambda_{\rm i2}$ are the wavelengths of the dual idler waves respectively. The signal and idler wavelengths can be calculated by using the phase-matching conditions with the Sellmeier equations [13] and energy conservation conditions. Fig. 2 shows the relationship between the wavelengths of signal and idler waves and the poling period of PPLN with pump wavelength $\lambda_{\rm p}$ of 532 nm. From the figure we find that the wavelengths of signal and idler waves vary with the period Λ. The wavelength separation between two signal waves or two idler waves is inverse proportional to the poling period Λ. As the frequency separation between the dual idler waves is several THz, THz generation can be realized by interacting the dual idler waves in the same PPLN if the phase mismatch is small enough. Here, both the idler waves and the THz waves are e-wave to employ the nonlinear optical coefficient d_{33}, the phase mismatch can be expressed

$$\Delta k_{\rm T1} = \vec{k}_{\rm i2} - \vec{k}_{\rm i1} - \vec{k}_{\rm T1} + \vec{k}_{\Lambda} \tag{5}$$

$$\Delta k_{\rm T2} = \vec{k}_{\rm i2} - \vec{k}_{\rm i1} - \vec{k}_{\rm T2} - \vec{k}_{\Lambda} \tag{6}$$

where $\Delta k_{\rm T1}$ and $\Delta k_{\rm T2}$ are the phase mismatch during THz generation. $\vec{k}_{\rm T1}$ and $\vec{k}_{\rm T2}$ are the wave vector of the dual THz waves, respectively. $\vec{k}_{\Lambda}$ provides small perturbations to the phase-matching conditions. The energy conservation condition has to be fulfilled,

$$\frac{1}{\lambda_{\rm i2}} - \frac{1}{\lambda_{\rm i1}} - \frac{1}{\lambda_{\rm T1}} = 0 \tag{7}$$

$$\frac{1}{\lambda_{\rm i2}} - \frac{1}{\lambda_{\rm i1}} - \frac{1}{\lambda_{\rm T2}} = 0 \tag{8}$$

where $\lambda_{\rm T1}$ and $\lambda_{\rm T2}$ are the wavelengths of the dual THz waves, respectively. Fig. 3 shows the phase mismatch $\Delta k_{\rm T1}$ and $\Delta k_{\rm T2}$ in DFG processes. From the figure we find that $\Delta k_{\rm T1}$ of 0.013 $\rm cm^{-1}$ and $\Delta k_{\rm T2}$ of 0.024 $\rm cm^{-1}$ are small enough to fulfill the phase-matching conditions. $\Delta k_{\rm T1}$ of 0.013 $\rm cm^{-1}$ corresponds to THz frequency of 8.341 THz and poling period of 325.1 μm, and $\Delta k_{\rm T2}$ of 0.024 $\rm cm^{-1}$ corresponds to THz frequency of 8.381 THz and poling period of 335.4 μm. When poling period of Λ is 325.1 μm or 335.4 μm, THz waves, dual signals and duals idlers can be generated simultaneously. 8.341 THz and 8.381 THz locate in the vicinity of polariton resonances of 248 $\rm cm^{-1}$ [14]. Polariton resonances can induce giant nonlinear optical coefficients and absorption coefficients of THz wave. The giant nonlinear optical coefficients in the vicinity of polariton resonances can be exploited to enhance the output power of THz wave [15]. Next we take an example of 8.341 THz to calculate the intensities of generated THz wave by cascaded DFG.

4. Cascaded DFG

THz wave with frequency of 8.341 THz is generated by dual idler waves with wavelengths of 1.919 μm and 2.027 μm respectively in the first-order DFG process, which consumes the higher

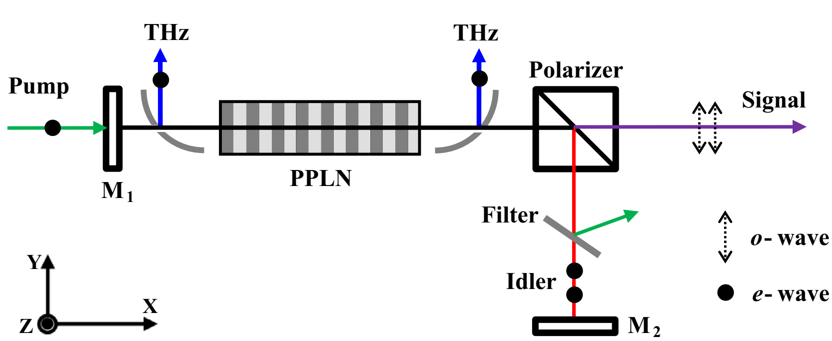

Fig. 1. Schematic diagram of THz wave generation by DFG with PPLN from an OPO.