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Investigation on frequency mixing effects in terahertz parametric oscillator with a noncollinear phase-matching scheme

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ABSTRACT

The frequency mixing effects in terahertz parametric oscillator (TPO) with a noncollinear phase-matching scheme based on bulk lithium niobate ($LiNbO_3$), including sum frequency generation (SFG), difference-frequency generation (DFG), optical parametric oscillation and cascaded optical processes are investigated. The analysis results indicate that the terahertz wave (THz-wave) with *N*-times frequency can be generated simultaneously from frequency mixing effects in TPO with noncollinear phase-matching scheme. To our best knowledge, this is the first study of the TPO generating THz-wave with *N*-times frequency in bulk $LiNbO_3$. The frequency tuning characteristics of THz-waves via varying pump wavelength, phase-matching angle and working temperature are theoretically analyzed.

1. Introduction

In the research of modern terahertz (THz) optoelectronics, development of compact, tunable, high-power, room temperature operation, coherent sources in the THz regime is one of the hottest issues, while terahertz radiation offers researchers many intriguing possibilities, ranging from fundamental science to applications in communications, imaging and spectroscopy, security and defense, and non-destructive evaluation [1–6]. Among many electronic and optical methods for the terahertz wave (THz-wave) generation, THz-wave parametric oscillator (TPO) and difference-frequency generation (DFG) in a second-order nonlinear medium exhibit many advantages, such as narrow linewidth, coherent, wide tunable range, high-power output and room temperature operation [7–9]. Unfortunately, the quantum conversion efficiency of the TPO and DFG is extremely low as the THz-wave is intensely absorbed by the gain medium. To improve the low quantum conversion efficiency, Kiessling et al. [10] reported a novel mechanism for the tuning THz-wave generation in cascaded THz-wave parametric processes in a periodically poled $LiNbO_3$ (PPLN) TPO. Thomson et al. [11] reported the observation of a cascaded process in intracavity terahertz optical parametric oscillators based on $LiNbO_3$. With high-order cascaded parametric processes one pump photon can generate several THz photons, suggesting that the overall quantum conversion efficiency for the THz radiation can overcome the Manley–Rowe limit.

In this paper, we investigate the frequency mixing effects in TPO with a noncollinear phase-matching based on bulk $LiNbO_3$, including sum frequency generation (SFG), DFG, optical parametric oscillation and cascaded optical processes. The frequency tuning characteristics of THz-waves and high-order Stokes waves via varying pump wavelength, phase-matching angle and working temperature are theoretically analyzed.

2. Theoretical model

A TPO with a noncollinear phase-matching scheme comprises a single-resonant optical parametric oscillator with a Fabry–Perot cavity, as shown in Fig. 1. The nonlinear gain medium is 5 mol% MgO doped $LiNbO_3$ crystals. The resonant cavity for the first-order Stokes wave consists of two plane-parallel mirrors, M_1 and M_2 with high reflectance. The pump wave passes through the cavity at the edge of M_1 and M_2. The THz-wave is extracted by a line of high resistivity silicon avoiding total reflection at the exit facet of the $LiNbO_3$ crystal. The polarizations of the pump wave, Stokes wave and THz-wave are all along the *z*-axis of the $MgO:LiNbO_3$ crystal. The cavity mirrors and the $MgO:LiNbO_3$ crystal are mounted on a rotating stage. The wavelength of the Stokes wave, and hence the wavelength of the THz-wave can be tuned by rotating the stage continuously

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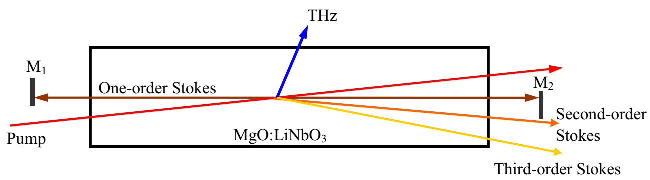

Fig. 1. Schematic diagram of the TPO with noncollinear phase-matching scheme.

since the angle between the pump wave vector and the optical axis of the Stokes wave cavity are changing continuously.

The theoretical values of the pump and Stokes wavelengths are calculated using a wavelength- and temperature-independent Sellmeier equation for 5% MgO-doped congruent $LiNbO_3$ (MgO:cLN) in the IR [12] and THz range, respectively.[13] The Sellmeier equation for MgO:cLN of Gayer et al. [12] in the IR range in a temperature range from 20 °C to 200 °C can be written as

$$n_e^2 = a_1 + b_1 f + \frac{a_2 + b_2 f}{\lambda^2 - (a_3 + b_3 f)^2} + \frac{a_4 + b_4 f}{\lambda^2 - a_5} - a_6 \lambda^2 \quad (1)$$

where $a_1 = 5.756$, $a_2 = 0.0983$, $a_3 = 0.202$, $a_4 = 189.32$, $a_5 = 12.52$, $a_6 = 1.32 \times 10^{-2}$, $b_1 = 2.86 \times 10^{-6}$, $b_2 = 4.7 \times 10^{-8}$, $b_3 = 6.113 \times 10^{-8}$, $b_4 = 1.516 \times 10^{-4}$, and $f = (T - 24.5) \times (T + 570.82)$, T is the crystal temperature in °C. The Sellmeier equation for MgO:cLN of Kiessling et al. [13] in the THz range in a temperature range from 30 °C to 200 °C can be written as

$$n_{THz}^2 = A_0 + B_0 f + \frac{A_1 + B_1 f}{\lambda^2 - (A_2 + B_2 f)^2} \quad (2)$$

where $A_0 = 24.326$, $A_1 = 31298$, $A_2 = 48.084$, $B_0 = 2.14 \times 10^{-5}$, $B_1 = 0.15824$, $B_2 = -3.097 \times 10^{-4}$.

3. Investigation on frequency mixing effects

The generation of THz-wave resulting from optical parametric oscillation is based upon tunable light scattering from the long-wavelength side of the A_1-symmetry soft mode in $LiNbO_3$ crystal. The pump photon at near-infrared stimulates a near-infrared Stokes photon at the difference frequency between the pump photon and the polariton. At the same time, the THz-wave is generated by the parametric process due to the nonlinearity arising from both electronic and vibrational contributions of the crystal. For the first-order THz-wave parametric process, two requirements have to be fulfilled: the energy conservation condition:

$$\frac{1}{\lambda_p} = \frac{1}{\lambda_{s1}} + \frac{1}{\lambda_T} \quad (3)$$

and the phase-matching condition:

$$\vec{k}_p = \vec{k}_{s1} + \vec{k}_T \quad (4)$$

here, λ is the wavelength, while $\vec{k}$ is the wave-vector, the subscripts p, $s1$ and T denote the pump wave, first-order Stokes wave and THz-wave, respectively. The magnitudes of the corresponding wave vectors (within the nonlinear gain medium) are calculated using the following equation:

$$k_j = \frac{2\pi n_j}{\lambda_j} \quad (5)$$

where the subscript j indicates the wave of interest, and n_j is the refractive index for that wave. The phase-matching condition (4) can be rewritten as

$$k_T^2 = k_p^2 + k_{s1}^2 - 2k_p k_{s1} \cos\ \theta_1 \quad (6)$$

where θ_1 is the angle between the pump wave vector and the first-order Stokes wave vector. The first-order parametric process

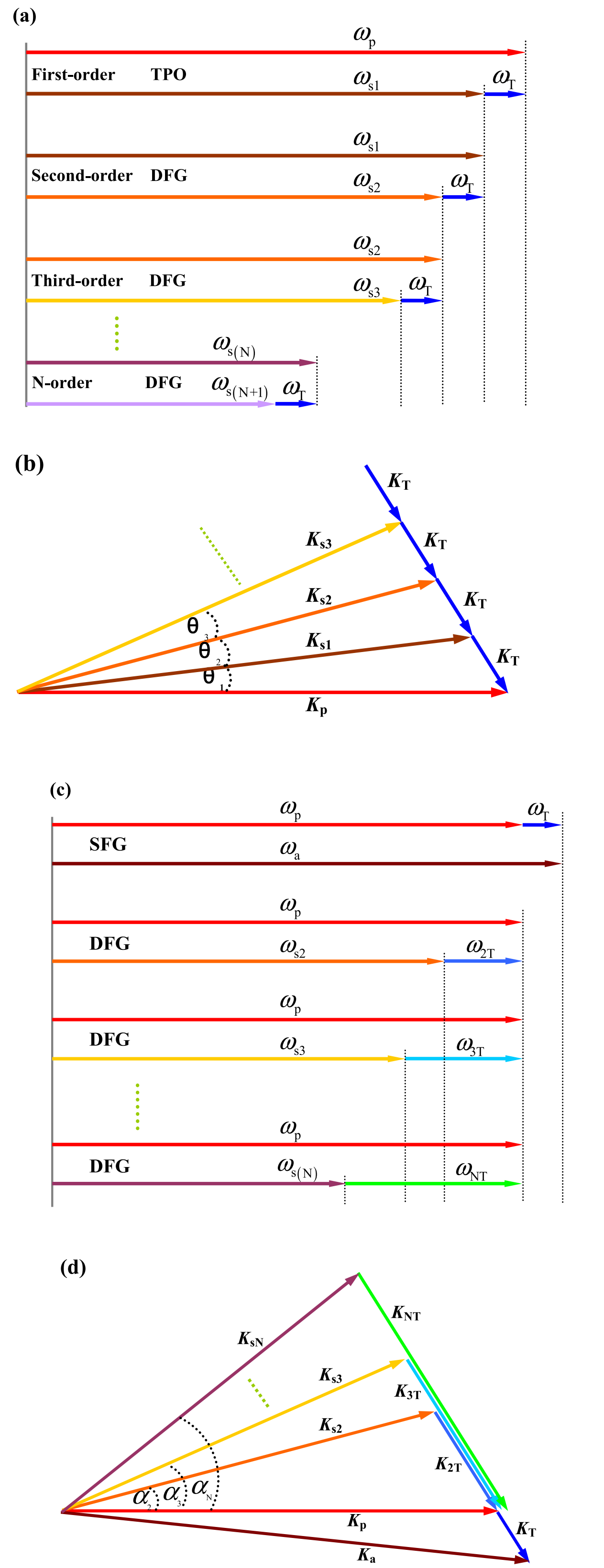

Fig. 2. (a) Energy diagram of cascaded optical processes generating high-order Stokes waves. (b) Phase-matching diagram of cascaded optical processes generating high-order Stokes waves. (c) Energy diagram of optical processes generating THz-wave with N-times frequency, N denotes positive integer. (d) Phase-matching diagram of optical processes generating THz-wave with N-times frequency. The lengths of the wavevectors do not scale.