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Investigation of operational characteristics of terahertz-wave parametric oscillators pumped by picosecond based on $MgO:LiNbO_3$ crystal

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ABSTRACT

Based on the technology of the non-collinear phase-matching about three-wave interaction in uniaxial crystal, the performance of nonlinear crystal $MgO:LiNbO_3$(MgO:LN) including the phase-matching angles, effective nonlinear coefficient and THz-wave gain as well as its absorption coefficients are theoretically discussed under e-ee type phase-matching condition. And an external cavity is developed for terahertz-wave parametric oscillators pumped by picosecond laser (*ps*-TPOs). For optimizing the *ps*-TPOs performance, the focusing spot size in MgO:LN crystal, the geometric size of the MgO:LN crystal, the conversion efficiencies, and the stability of the THz-wave generation are designed and calculated. The calculated results provide a comprehensive theoretical basis for the *ps*-TPOs using difference-frequency generation (DFG) method and optimal performance to generate widely tunable terahertz waves in MgO:LN crystal.

1. Introduction

The THz waves have been attracted recently because of its wide ranging applications in various fields, including THz imaging [1,2], communications [3], sensing [4], spectroscopy [5,6], and many fields of fundamental and applied physics and technology [7,8]. Since the appearance of a high power near-infrared light source, coherent terahertz waves have been generated successfully using PC antennas [9,10], Q-switched Nd: YAG laser [11,12] or femtosecond ultrashort pulses laser [13].

However, there are few tunable and high-reputation THz-wave sources pumped by picosecond pulsed laser. Then, we have been focusing on picosecond pulsed laser, because picosecond pulsed laser has smaller linewidth than femtosecond pulse and higher-repetition than Q-switched Nd: YAG laser. Furthermore, it has been shown that by mixing two bandwidth-limited picosecond pulses in the DFG scheme [14,15], one could achieve conversion efficiency, which is the same as in the case of femtosecond pulses with the same fluence (or same pulse energy for the focused pump beams). In addition, picosecond pulses' peak power can be enhanced in a high finesse compact external cavity to overcome the threshold and the spectrum is relatively narrow [16,17].

Therefore, the characteristics of *ps*-TPOs are analyzed in this paper that organized as follows.

In Section 2, we theoretically discuss the performance of nonlinear crystal MgO:LN including the phase-matching angles, effective nonlinear coefficient and THz-wave gain as well as its absorption coefficients. In Section 3, we develop an external cavity for the doubly resonant *ps*-TPOs. We also consider optimal focusing spot size; design the geometric size of the MgO:LN crystal; and optimize conversion efficiencies. In the same section, we also discuss the stability of the THz-wave generation using the Runge–Kutta algorithm to simulate the parametric interaction. In Section 4, we draw conclusions.

2. Theoretical performance of nonlinear crystal MgO:LN

Using the 1.064 μm as one of the pump wavelengths, only e-ee type can be phase-matched for the configuration of the THz DFG in MgO:LN crystal, where the first and second letters designate the polarizations for the pump and second (Stokes) beams, while the third letter corresponds to the polarization for the THz waves, respectively. In the stimulated scattering process (as shown in Fig. 1), the generated far-infrared radiation together with the

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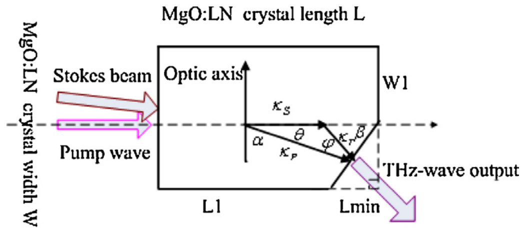

Fig. 1. Non-collinear phase-matching condition and cross section geometric size in MgO:LN crystal.

Stokes radiations are created parametrically from the pump beam according to the phase-matching condition and energy conservation law

$$\frac{n_e(\lambda_P,\alpha)}{\lambda_P}=\frac{n_e(\lambda_S,\alpha+\theta)}{\lambda_S}+\frac{n_e(\lambda_T)}{\lambda_T} \tag{1}$$

$$\frac{1}{\lambda_P}=\frac{1}{\lambda_S}+\frac{1}{\lambda_T} \tag{2}$$

where λ_m are the wavelengths with m = P, S, and T representing the pump, Stokes, and THz waves, respectively.θ is the phase-matching angle and α is the angle between the pump and optic axis. $n_e(\lambda_P,\alpha)$ and $n_e(\lambda_S,\alpha+\theta)$ are the angle-dependent extraordinary refractive indices of the Stokes and terahertz waves, respectively. And the indices of refraction can be determined by the following traditional dispersion relationships [18]

$$n_e^2=1+\frac{2.245\lambda^2}{\lambda^2-0.01242}+\frac{1.3005\lambda^2}{\lambda^2-0.05313}+\frac{6.897\lambda^2}{\lambda^2-331.33} \tag{3}$$

$$n_o^2=1+\frac{2.427\lambda^2}{\lambda^2-0.01478}+\frac{1.4617\lambda^2}{\lambda^2-0.05612}+\frac{9.6536\lambda^2}{\lambda^2-371.216} \tag{4}$$

when the Eqs. (3) and (4) are satisfied, the range of wavelengths λ and the temperature T are given in 0.4–5 μm and T = 294K, respectively. Utilizing the refractive-index ellipsoid equation, the indices of refraction $n_e(\lambda_P,\alpha)$ and $n_e(\lambda_S,\alpha+\theta)$ in uniaxial crystals are given by [19]

$$n_e(\lambda_p,\alpha)=\frac{n_o n_e}{\sqrt{n_o^2\sin^2\alpha+n_e^2\cos^2\alpha}} \tag{5}$$

$$n_e(\lambda_s,\alpha+\theta)=\frac{n_o n_e}{\sqrt{n_o^2\sin^2(\alpha+\theta)+n_e^2\cos^2(\alpha+\theta)}} \tag{6}$$

Experimentally, it has been shown that the ordinary and extraordinary refractive indices in MgO:LN do not hold to Eqs. (3) and (4) in the THz domain. The Sellmeier dispersion for the refractive index of MgO:LN crystal in the terahertz region must be formulated using a new dispersion relation model. Assume a THz beam propagating through MgO:LN crystal with complex refractive index $n_{THz}=n(\omega)+ik(\omega)$. In this paper, the extraordinary wave $n_e(\omega_T)$ whose polarization is parallel to the optical axis (along the z axis) corresponds to the $A_1(z)$ mode, while the ordinary wave $n_o(\omega_T)$ whose polarization is parallel to the y axis corresponds to the $E(y)$ mode, which $A_1(z)$and $E(y)$ are both Raman- and infrared-active polar modes. Such a case can be described in the framework of the classical damped harmonic oscillator model [20]

$$\varepsilon(\gamma)=(\varepsilon_\infty+\sum_j\frac{S_j\omega_j^2}{\omega_j^2-(\omega_{THz}/2\pi)^2-i(\omega_{THz}/2\pi)^2\Gamma_j})$$
$$=(n(\omega)+ik(\omega))^2 \tag{7}$$

where $\varepsilon(\gamma)$ is the complex dielectric constant. ω_j, S_j and Γ_j are the jth eigenfrequency, oscillator strength and damping coefficient of the lowest A_1-symmetry phonon mode, respectively, and ε_∞ is the high-frequency dielectric constant.

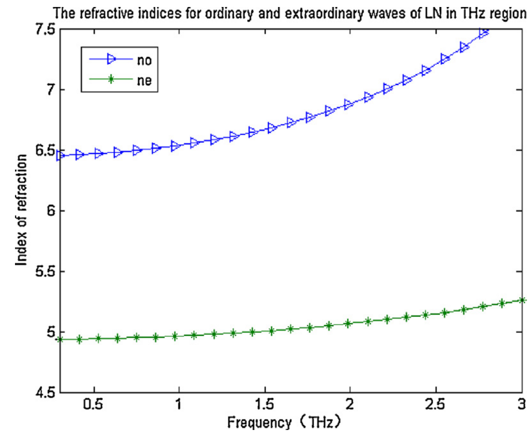

Fig. 2. The refractive indices of ordinary.

According to [21], the refractive indices of ordinary and extraordinary waves in MgO:LN crystal can be calculated in the frequency range from 0.3 to 3 THz (as shown in the Fig. 2). It should be noted that since some parameters, such as the lattice vibration parameters, used in this paper are mainly cited from the Refs. [22] and [23]. And the calculated results maybe slightly but negligible discrepancy with others. But we think that the conclusions in our paper still apply. See Fig. 1. The three waves satisfy the e-ee type non-collinear phase-matching condition at all times. This leads to the angle-dispersive characteristics of the Stokes and THz waves (as shown in the Fig. 3). Thus, the generation of widely tunable and continuous THz-wave radiations (typically 1–3 THz) can be accomplished simply by changing the angle between the incident pump beam and the resonator axis.

We notice from [24] that the amplitudes of the three optical fields are coupled to one another through effective nonlinear coefficient d_{eff}, which is the most important physical quantities dictating the efficient THz parametric conversion. For the configuration introduced above, the effective nonlinear coefficient depends on the azimuth angles (α,φ) according to [25] as follows

$$d_{eff}^{e\text{-}ee}=d_{22}\cos^2\alpha\cos 3\varphi \tag{8}$$

where the effective second-order susceptibility d_{22} is about 6.3 ± 0.7 pm/v[26]. Obviously, $d_{eff}^{e\text{-}ee}$ reaches a maximum value at α = 0 corresponding to the phase-matching angle $\theta=0.40°$ at $\lambda_S=1.067$ μm, $n_e(\omega_T)=4.95$. That condition is the primary factor for designing the size of the MgO:LN crystal in Section 3.2.

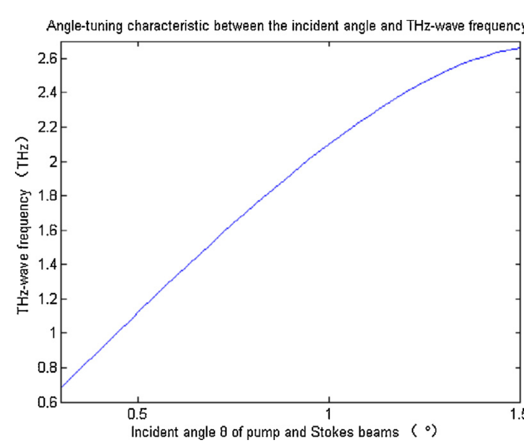

Fig. 3. Theoretical angle-tuning characteristics extraordinary waves in the frequency range of the THz DFG in MgO:LN crystal from 0.3 to 3 THz.