Investigation on phase matching in a THz-wave parametric oscillator*

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The characteristics of noncollinear phase matching and quasi-phase-matching in the THz-wave parametric oscillator (TPO) are investigated. The expression of the effective parametric gain length under the condition of noncollinear phase matching configuration is deduced. The relationship between the poling period of periodically poled $LiNbO_3$ crystal and the generated THz frequency under the condition of quasi-phase-matching configuration is analyzed. Based on the analyses above we propose a new TPO configuration which ensures the three mixing waves interact collinearly. The effects of operation temperature on phase matching are analyzed.

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The THz-wave parametric oscillator (TPO) based on stimulated polariton scattering has many advantages, such as high efficiency, narrow linewidth. In recent years, the THz parametric oscillators (TPOs) have been developed rapidly[1-4]. Phase matching in TPO is necessary to avoid destructive interference of the Stokes wave and THz-wave which are produced by the stimulated Raman scattering. As the pump wave, Stokes wave and THz-wave have widely separated refractive indices in MgO:$LiNbO_3$ crystal, and birefringence phase matching is not applicable in this case. One method which has been used by several groups is noncollinear phase matching[5,6]. The tuning output of THz-wave is realized conveniently in noncollinear phase matching configuration. The demerit is that the effective interaction volume among the three mixing waves is seriously restricted, because no pair of the three waves is parallel. An alternative to achieve phase matching is to utilize periodically poled $LiNbO_3$ (PPLN) crystal, which could ensure two or even three mixing waves interact collinearly, resulting in a higher interaction volume among them[7,8]. As a given poling period corresponds to a particular frequency of THz-wave, the tuning output of THz-wave is inconvenient. Phase matching in TPO can be also realized by changing operating temperature, as the refractive index of $LiNbO_3$ crystal in infrared and THz range is sensitive[9,10]. In addition, the lower operation temperature can enlarge THz-wave gain coefficient and reduce the absorption coefficient, which means that the radiation of THz-wave can be enhanced[11].

In this paper, the relationship among phase matching angle, pump wavelength and THz frequency in noncollinear phase matching configuration is investigated theoretically. The expression of the effective parametric gain length under the condition of noncollinear phase matching is deduced. Under the condition of quasi-phase-matching configuration, the relationship between the poling period and the phase matching angle is analyzed. Based on the analyses above we propose a new TPO configuration which ensures the three mixing waves propagate collinearly. At lower temperature, the characteristics of phase matching under the condition of noncollinear phase matching configuration are analyzed. Meanwhile, the gain and absorption characteristics of THz-wave are investigated.

The generation of THz-wave from 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 side stimulates a near-infrared Stokes photon at different frequencies between the pump photon and the polariton. At the same time, THz-wave

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is generated by the parametric process due to the nonlinearity arising from both electronic and vibrational contributions of the crystal. Schematic diagram of typical noncollinear phase matching TPO is shown in Fig.1. In the parametric process, the noncollinear phase matching condition $\boldsymbol{k}_p = \boldsymbol{k}_s + \boldsymbol{k}_T$ and the conservation of energy $\omega_p = \omega_s + \omega_T$ are satisfied (p=pump wave, s=Stokes wave, T=THz-wave). Tunable THz-wave radiation could be obtained by changing the pump wavelength λ_p or the phase matching angle θ between the pump wave and the Stokes wave continuously. The relationship among them is shown in Fig.2. From the figure we know that the rapid frequency tuning can be achieved by changing the angle θ, while the changing of THz-wave frequency is insensitive to the variation of pump wavelength.

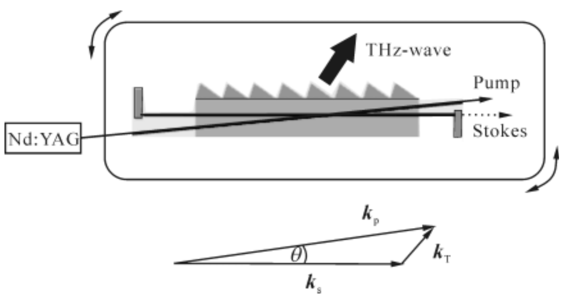

Fig.1 Schematic diagram of typical noncollinear phase matching TPO

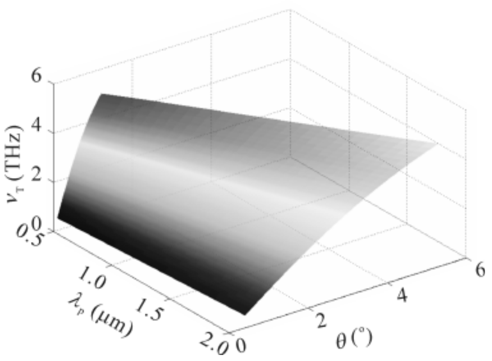

Fig.2 Relationship among the frequency of THz-wave v_T and pump wavelength λ_p and the phase matching angle θ between the pump wave and the Stokes wave

The noncollinear phase matching configuration restricts the effective interaction volume among the three mixing waves, as a consequence, reduces the THz-wave energy conversion efficiency. Next we deduce the expression of the effective parametric gain length under the condition of noncollinear phase matching configuration based on the theoretical model in Ref.[12]. As there is not double refraction phenomenon in TPO, we regard phase matching angle θ as double refraction walk-off angle since the magnitudes of them are equal approximately and the effects of them are identical. Assuming the three mixing waves have Gaussian profiles, the Stokes spot size is narrowed by the gain polarization and broadened by diffraction simultaneously. The balance determines the final spot size of Stokes wave. The relationship between the pump wave radius ω_p and the Stokes wave radius ω_s is given by

$$\left(\frac{\pi}{2L\lambda_s}\right)^2\left(\frac{\omega_p^2\omega_s^2}{\omega_p^2+2\omega_s^2}\right)^3+\frac{\omega_p^2\omega_s^2}{\omega_p^2+2\omega_s^2}-\frac{\omega_p^2}{2}=0\ , \tag{1}$$

where λ_s is the wavelength of Stokes wave and L is the optical cavity length. $L = L' + (n_s-1)l$, where L' is the physical length of Stokes cavity and l is the length of crystal. The walk-off length l_ω is given by

$$l_\omega=\frac{\sqrt{\pi}}{2}\frac{\omega_p}{\theta_{in}}\sqrt{\frac{\omega_p^2+\omega_s^2}{\omega_p^2+\omega_s^2/2}}\ , \tag{2}$$

where θ_{in} is the phase matching angle between pump wave and Stokes wave within MgO:$LiNbO_3$ crystal. Here θ_{in} is used as a substitute for the double refraction walk-off angle. The effective parametric gain length L_{eff} is given by

$$L_{eff}=l_\omega erf(\frac{\sqrt{\pi}}{2}\frac{l}{l_\omega})\ . \tag{3}$$

The effective parametric gain length versus the radius of pump wave and the length of MgO:$LiNbO_3$ crystal is shown in Fig.3. From the figure we know that the pump beam with larger radius and the crystal with longer length can both increase the effective parametric gain length. The pump wave with larger beam radius can generate the Stokes wave and THz-wave with larger beam radius simultaneously, which results in the longer effective parametric gain length. Actually for the maximum conversion efficiency, the beam diameter must be increased until the effective parametric gain

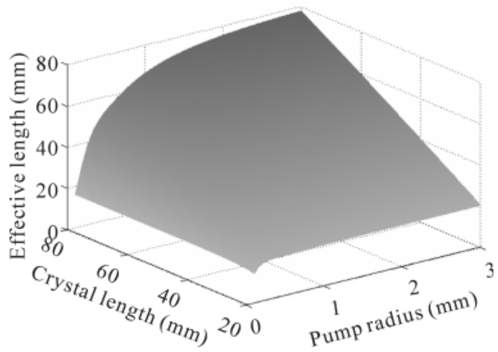

Fig.3 Effective parametric gain length versus radius of pump wave and length of MgO:$LiNbO_3$ crystal (Assuming the cavity physics length is 150 mm and the frequency of the THz-wave is 1.5 THz.)

length is equal to the crystal length.

The effective interaction volume is of vital importance for the enhancement of THz-wave radiation. PPLN crystal could ensure the three mixing waves propagate collinearly, which can result in a larger interaction volume among them. The quasi-phase-matching configuration using PPLN crystal is shown in Fig.4, where pump wave and Stokes wave are collinear. The emitting direction of THz-wave depends on the direction of poling vector. With respect to the direction of pump wave, the THz-wave is emitted under the angle of

$$\alpha = \arcsin\left(\frac{\frac{1}{\Lambda}}{\left[\frac{n_{\mathrm{p}}}{\lambda_{\mathrm{p}}} - n_{\mathrm{s}}(\lambda_{\mathrm{p}}^{-1} - \lambda_{\mathrm{T}}^{-1})\right]}\sin\beta\right), \qquad (4)$$

where λ_T, n_p, n_S and n_T are the THz wavelength, the refractive indices of the pump, Stokes and THz-wave, respectively. α is the angle between the THz-wave and pump and β is the angle between THz-wave and grating vector. The poling period as a function of the pump wavelength and the THz wavelength is given by

$$\Lambda = \left[\left(\frac{n_{\mathrm{T}}}{\lambda_{\mathrm{T}}}\right)^2 + \left(\frac{n_{\mathrm{p}}}{\lambda_{\mathrm{p}}} - n_{\mathrm{s}}(\lambda_{\mathrm{p}}^{-1} - \lambda_{\mathrm{T}}^{-1})\right)^2 - 2\frac{n_{\mathrm{T}}}{\lambda_{\mathrm{T}}}\left(\frac{n_{\mathrm{p}}}{\lambda_{\mathrm{p}}} - n_{\mathrm{s}}(\lambda_{\mathrm{p}}^{-1} - \lambda_{\mathrm{T}}^{-1})\right)\cos(\alpha)\right]^{-\frac{1}{2}}. \qquad (5)$$

When the generated THz-wave frequency is assumed as 1.5 THz, where THz-wave output is maximum[13], the poling period Λ and the angle β as a function of the angle α are shown in Fig.5. It can be seen that with the increase of the angle α the poling period Λ decreases gradually and smoothly while the angle β increases and decreases fast. It is worth noting that as the angle α equals to 0° or 180° the angle β equals to 0°, which means that the three mixing waves propagate collinearly. As discussed above, we propose a quasi-phase-matching intracavity TPO, which is shown in Fig.6. The pump wave and the Stokes wave oscillate simultaneously, and constructive interference among the three mixing waves will generate high-power THz-wave radiation. The PPLN crystal with longer length is utilized to enhance the Stokes wave and the THz-wave. The enhanced THz-wave at output area can be emitted, as the THz-wave at the other area is absorbed by PPLN crystal. Compared with the noncollinear phase matching configuration in Ref.[13], the configuration here will generate more powerful THz-wave radiation, because the interaction volume of the three mixing waves is larger. When the three mixing waves propagate collinearly, tunable THz-wave radiation can be attainable by changing the pump wavelength or poling period, which is shown in Fig.7. The changing of the THz-wave frequency is sensitive to the variation of poling period, so tunable THz-wave radiation can be obtained by utilizing a PPLN crystal with the

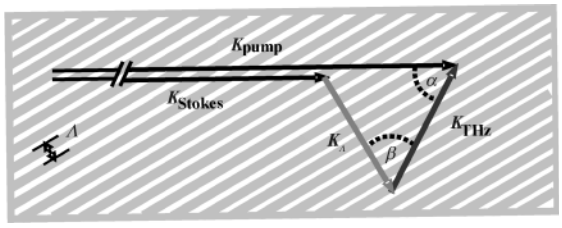

Fig.4 Quasi-phase-matching configuration using PPLN crystal

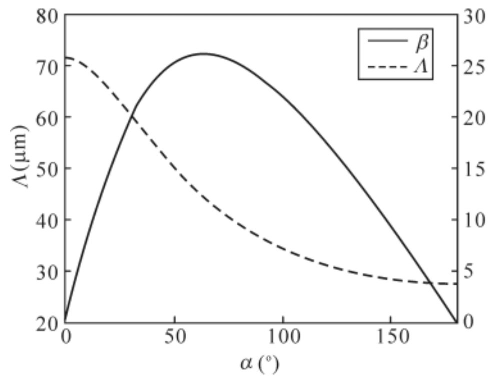

Fig.5 Poling period Λ and the angle β as a function of the angle α

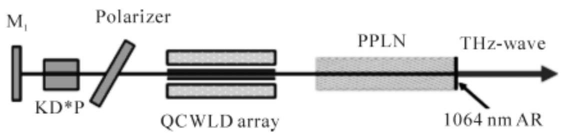

Fig.6 Quasi-phase-matching intracavity TPO (The end mirror M_1 is high reflective at the near infrared side, and the output surface of the PPLN crystal is high-reflection coated at the near infrared side.)

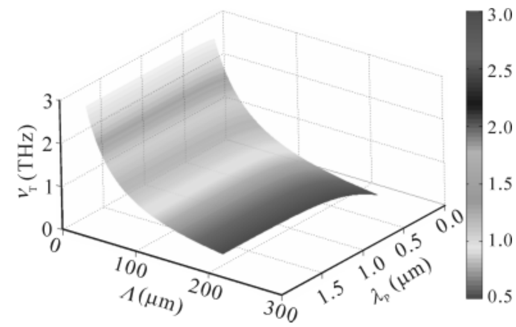

Fig.7 Tuning characteristics of THz-wave as a function of the pump wavelength and poling period when the three mixing waves propagate collinearly

continuous change of grating-period[14]. The changing of the THz-wave frequency is insensitive to the variation of pump wavelength, because the refractive indices of the pump wave and Stokes wave are equal approximately.

The refractive index of extraordinary light in MgO:$LiNbO_3$ crystal is sensitive to operation temperature in infrared and THz ranges, so the phase matching can be realized by changing operating temperature. Assuming λ_p is 1064 nm, the relationship between the THz-wave frequency ν_T and the phase matching angle θ at different operation temperatures in noncollinear phase matching configuration is shown in Fig.8. The Sellmeier equation of MgO:$LiNbO_3$ crystal in the THz range is cited from Ref.[10]. The changing trends of curves at different temperatures are identical approximately. Rapid frequency tuning of THz-wave can be achieved by changing the phase matching angle θ. Moreover, the relatively rapid frequency tuning occurs in lower temperature.

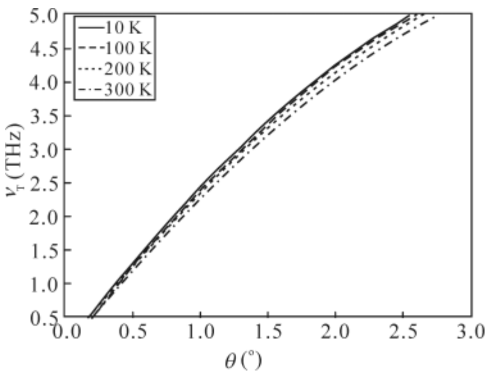

Fig.8 Relationship between the THz frequency ν_T and phase matching angle θ in noncollinear phase matching configuration at different operation temperatures

The operation temperature not only affects the phase matching condition, but also has a significant impact on the gain and absorption coefficients of the generated THz-wave. The gain and absorption coefficients of the generated THz-wave at different temperatures are shown in Fig.9. The damping coefficient of the lowest A_1-symmetry phonon mode in $LiNbO_3$ crystal decreases with the decrease of the temperature[15], which can result in the enlargement of gain coefficient. Moreover, the absorption coefficient α_T of $LiNbO_3$ crystal at THz range is nearly in proportion to the damping coefficient, so the decrease of damping coefficient will reduce the α_T, which means that the radiation of THz-wave will be enhanced at lower operation temperature.

The characteristics of noncollinear phase matching and quasi-phase-matching in TPO are investigated. Under the condition of noncollinear phase matching configuration, the tunable THz-wave radiation can be realized by changing the phase matching angle and pump wavelength. The pump beam with larger radius and the gain medium with longer length

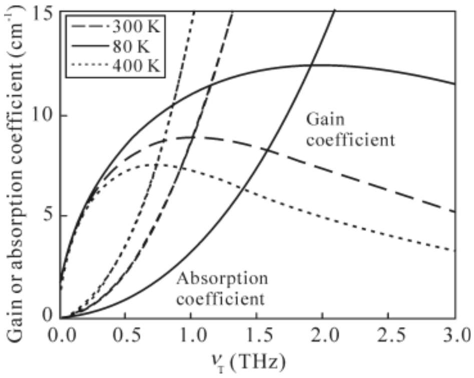

Fig.9 Calculated gain and absorption coefficients of the generated THz-wave at different temperatures (Assuming the pump wavelength and pump power density are 1064 nm and 500 mW/cm², respectively.)

can both increase the effective parametric gain length. Quasi-phase-matching configuration utilizing PPLN crystal can ensure two or even three mixing waves propagate collinearly, which can result in a higher interaction volume among them. At lower temperature the gain coefficient of THz-wave is enhanced and the absorption coefficient is reduced, which means that the radiation of THz-wave will be enhanced.

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