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Physics

FREQUENCY TUNABLE *THz*-GENERATION IN PERIODICALLY POLED LITHIUM NIOBATE CRYSTAL

G. K. ABGARYAN[*]

Chair of Microwave Radiophysics and Telecommunications YSU, Armenia

A simple method for the generation of quasi-monochromatic tunable terahertz (*THz*) pulses via optical rectification of femtosecond laser pulses in periodically poled lithium niobate (PPLN) crystal was proposed. It is shown that when the incidence angle on the crystal of the optical beam changes in the range of –50° to +50°, the central frequency of the generated THz radiation varies from ~0.77 to ~ 0.93 *THz* and the direction of *THz*-radiation changes in the range of –10° to +10°. Thus, an appropriate choice of parameters PPLN and the angle of incidence of the laser beam is possible to obtain quasi-monochromatic *THz*-radiation tunable over a sufficiently wide frequency range.

Keywords**:** terahertz generation, difference-frequency generation, optical rectification.

Introduction. The band (0.1÷10 *THz*) has larger variety of applications such as high-speed communication, molecular spectroscopy, security imagining, and medical diagnosis, among many others [1]. However, the applicability of *THz* sources still critically depends on the power available with current technology, which has prompted much research in developing compact table-top *THz* sources.

The difference-frequency generation [2–4] and optical rectification (OR) of femtosecond laser pulses [5–9] are widely used methods for the generation of narrowband radiation in *THz*-range. It was demonstrated that application of wide-aperture beam in transversely patterned PPLN crystal leads to *THz*-generation with $\Delta f \approx 14$ *GHz* bandwidth [10]. The Fs-laser beam propagates collinear to PPLN domain wall. *THz* wave is generated in the direction determined by Cherenkov radiation angle $\theta_{Ch} = \cos^{-1}(n_g / n_{THz})$, where $n_g = c/u$ is the group index, u is the group velocity of the laser pulse, c is the light velocity and n_{THz} is the refractive index at generated frequency. The periodical domain-inverted structure in the PPLN crystal serves to obtain a constructive interference of *THz*-fields radiated by separate PPLN's domains. The resultant *THz*-radiation is a quasi-monochromatic wave with central frequency f_{THz} determined by spatial period Λ of PPLN crystal.

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[*] E-mail: gevorg.gak@gmail.com

The main drawback of this method is that the periodical domain inverting technique may be applied only to ferroelectric materials, such as $LiNbO_3$. In addition, generation frequency f_{THz} is predetermined by the spatial period of the domain-inverted structure Λ and, therefore, it cannot be modified after the sample fabrication. Variations of the frequency f_{THz} are possible by changing direction of the optical beam propagation.

In the paper the optical beam influence on the central frequency and direction of the excited *THz*-radiation from a periodically poled lithium niobate (PPLN) crystal is assessed, when beam incidence angle is varied with respect to the PPLN domain wall. The central frequency and direction of *THz*-radiation depends on optical beam incidence angle (α). The deviation angle between the direction of *THz* wave and Cherenkov radiation direction is assigned as η in Fig. 1.

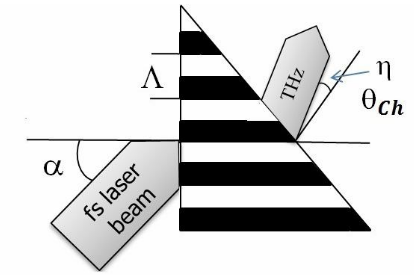

Fig. 1. Schematic view of *THz* wave generation in PPLN crystal, where black and white regions represent crystal parts with opposite sign of the nonlinear coefficient.

Calculation. To calculate the spatial period of PPLN crystal, the OR is considered as difference frequency generation between spectral components of Fourier transform-limited laser pulse (Fig. 2, a). The wave vector diagram forms (Fig. 2, b) [10].

Phase matching condition can be written in the following form:

$$k_{THz}^2 = k_g^2 + k_\Lambda^2 - 2\, k_g\, k_\Lambda \cos(90+\beta), \tag{1}$$

where $k_{THz} = (\omega_{THz} n_{THz})/c$ is the wave number at frequency of *THz*-generation ω_{THz}, $k_\Lambda = 2\pi/\Lambda$ is the spatial wave number corresponding to PPLN structure with period Λ, $k_g = k(\omega+\omega_{THz}) - k(\omega) \approx (\omega_{THz} n_{THz})/c$, $k(\omega+\omega_{THz})$ and $k(\omega)$ are the wave numbers of spectral components at $\omega+\omega_{THz}$ and ω frequencies of the laser radiation respectively.

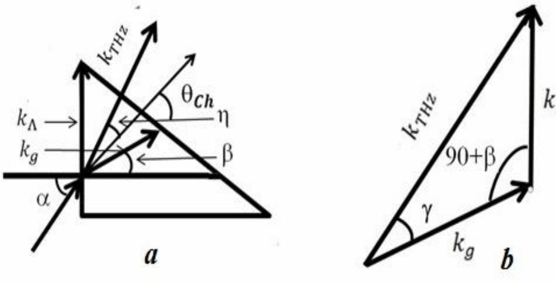

Fig. 2.
a) The wave vector diagram forms, where β refraction angle of optical beam, γ is angle between k_g and k_{THz};
b) corresponding wave vectors diagram.

From (1) we can get:

$$\omega_{THz}^2 \cdot \frac{n_{THz}^2 - n_g^2}{c^2} - \omega_{THz} \cdot \frac{4\pi n_g \sin\beta}{c\Lambda} - \frac{4\pi^2}{\Lambda^2} = 0. \tag{2}$$

Considering $\sin\beta = \sin\alpha / n_g$ and using Eq. (2), the frequency of *THz*-radiation ω_{THz}, which satisfied synchronism condition, is given by

$$\omega_{THz} = \frac{2\pi c \sin\alpha}{2\Lambda(n_{THz}^2 - n_g^2)} + \frac{c^2\sqrt{\dfrac{2\pi c\sin\alpha}{c\Lambda} + \dfrac{16\pi^2(n_{THz}^2 - n_g^2)}{(c\Lambda)^2}}}{2(n_{THz}^2 - n_g^2)}. \tag{3}$$

Hence, for dependence $\omega_{THz}(\alpha)$ we obtain the following graph (see Fig. 3).

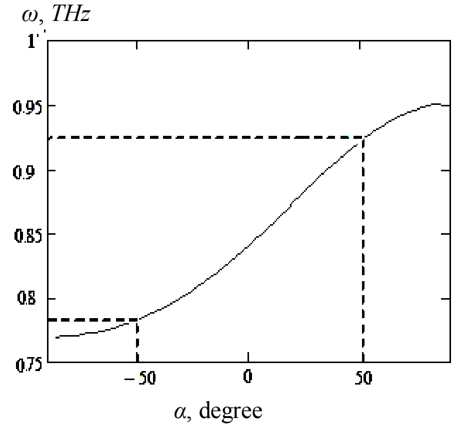

Fig. 3. Dependence of $\omega_{THz}(\alpha)$.

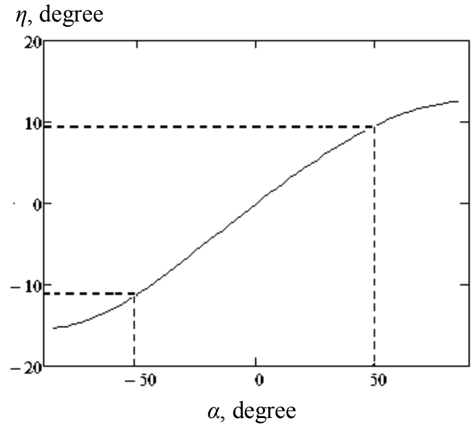

Fig. 4. Dependence of $\eta(\alpha)$.

Fig. 3 show, that when the incidence angle changes from –50° to +50°, the central frequency of *THz*-radiation changes in the range $0.77 \div 0.93$ *THz*.

In the paper the deviation of *THz*-radiation direction from Cherenkov radiation direction was calculated.

From Fig. 2, b we can write

$$\eta = \gamma + \beta - \theta_{Ch}. \tag{4}$$

Using the wave vector diagram, we get:

$$k_\Lambda^2 = k_{THz}^2 + k_g^2 - 2k_g k_{THz} \cos\gamma. \tag{5}$$

Inserting value of k_{THz}, k_g, k_Λ in (5), we obtain

$$\frac{4\pi^2}{\Lambda^2} = \omega_{THz}^2 \cdot \frac{n_{THz}^2}{c^2} + \omega_{THz}^2 \cdot \frac{n_g^2}{c^2} + 2\omega_{THz}^2 \cdot \frac{n_g n_{THz}}{c^2} \cdot \cos\gamma. \tag{6}$$

From (6) the frequency dependence for γ takes a form

$$\gamma = \cos^{-1}\left(\frac{n_{THz}^2 + n_g^2}{2n_g n_{THz}} - \frac{4\pi^2}{\Lambda^2} \cdot \frac{c^2}{2n_g n_{THz}} \cdot \frac{1}{\omega_{THz}^2} \right). \tag{7}$$

The dependence η (α) shown in Fig 4 was obtained, inserting the γ values from Eq. (7) into the equation (4).

Fig. 4 shows, that when the incidence angle changes from –50° to +50° degrees, the direction of *THz*-radiation changes only ~ ±10 degrees.

Conclusion. We assess the influence of change of optical beam direction on the central frequency and direction of the generated excited *THz*-radiation from a periodically poled lithium niobate (PPLN) crystal. The beam incidence angle is varied with respect to the PPLN domain wall. The central frequency of generated *THz* radiation changes in the range 0.77÷0.93 *THz* by varying the incidence angle from –50° to +50° respectively. This variation causes excited beam direction deviation from ~ –10° to ~ +10°. The obtained results propose the possibility of a single PPLN crystal application for the generation of 0.77÷0.93 range *THz*-radiation.

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