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Investigation of Parameters of Terahertz Pulses Generated in Single-Domain LiNbO3 Crystal by Step-Wise Phase Mask

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Abstract—A new scheme for the efficient generation of broadband terahertz radiation via optical rectification of femtosecond laser pulses in the single-domain lithium niobate crystal equipped with the step-wise phase mask (SPM) is investigated. It is shown that using the SPM one can provide the phase matching for all the spectral components of a terahertz pulse by providing the effective conversion of laser radiation in the terahertz region. The angular distribution of spectral components, as well as the temporal shape of terahertz pulses in the wave zone is studied. These results can be applied in the time-domain spectroscopy, the imaging of hidden objects, and etc.

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1. INTRODUCTION

The electromagnetic waves of terahertz range (~0.1–10 THz) occupy an intermediate region between the microwave and infrared frequency ranges and are of considerable interest for various applications in the fields of the high-speed communications, molecular spectroscopy, medical diagnostics, in the security systems, for visualization of objects, and etc. [1, 2]. Despite the big breakthrough of the last decades in the field of terahertz radiation sources, this area remains one of the technically poorly secured part of spectrum. This encourages many researchers to seek new methods to create the highly effective and affordable terahertz sources with the necessary parameters for the variety of applications. For many applications there is a need for the broadband THz pulses. In particular, the ultrabroadband terahertz video pulses are ideal for the time-domain spectroscopy technique [3, 4].

The difference frequency generation and the optical rectification of femtosecond laser pulses are the widely used methods for generating the terahertz radiation [4, 5]. It was shown in [6–8] that using the wide-aperture beams in the transverse direction of periodically polarized lithium niobate crystal one may obtain the quasi-monochromatic generation of terahertz radiation with the center frequency determined by the spatial period Λ of periodically polarized lithium niobate crystal (PPLN). The periodically inverted domain structure of the PPLN crystal is used to produce the constructive interference of terahertz waves radiated from the separate regions of the PPLN. However, the oscillation frequency in this case is predetermined by the spatial period of the PPLN domain structure and therefore it cannot be changed after the sample preparation.

To overcome this disadvantage in the generation of narrow-band terahertz radiation, the single-domain lithium niobate crystal with the variety of the phase masks (PM) recently has been used. With the shadow or binary PM located in front of the single-domain nonlinear $LiNbO_3$ crystal, the virtual quasi-periodic structure is formed that provides the phase matching for the specific frequency of terahertz radiation. The frequency of the radiation can be tuned by change of the step of PM.

In the present work, the efficiency of broadband terahertz pulses generation via optical rectification of laser radiation in the single-domain $LiNbO_3$ crystal, which has the shape of the triangular prism and equipped with the stepped phase mask (SPM) is investigated. The angular distribution of the spectral components and the temporal form of terahertz pulse in the wave zone are studied, too.

2. PHASE-MATCHING CONDITION FOR GENERATION OF BROADBAND TERAHERTZ RADIATION

To obtain the broadband terahertz radiation it is necessary that the terahertz pulses radiated from each layer of the crystal will reach the output surface of the crystal at the same time. This is possible if the terahertz pulses radiated from each crystal layer will reach the next layer at the same time with the optical pulse. In order to ensure this condition, one must have an optical beams with a sloping amplitude front. This can be reached if the optical beam passes through the prism-like PM, as shown in Fig. 1.

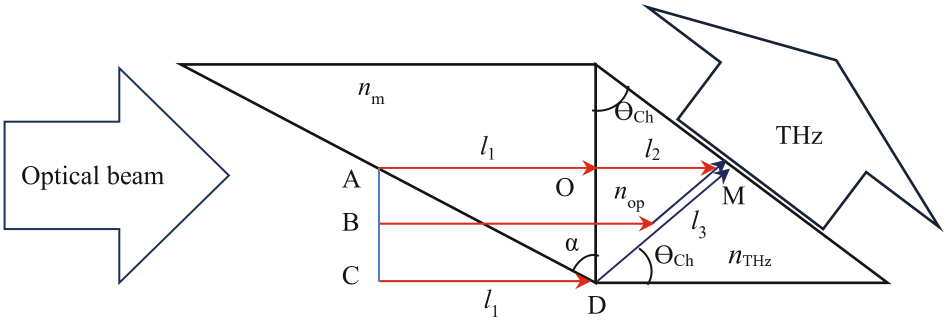

Fig. 1. Scheme for the generation of the broadband terahertz pulses.

To meet the phase matching condition, it is necessary

$$\frac{l_1}{c}n_{\mathrm{m}} + \frac{l_2}{c}n_{\mathrm{op}} = \frac{l_1}{c} + \frac{l_3}{c}n_{\mathrm{THz}}\,, \tag{1}$$

where $l_1 = \mathrm{AO} = \mathrm{CD}$, $l_2 = \mathrm{OM}$, $l_3 = \mathrm{DM}$, n_{op} is the refractive index of crystal for optical radiation, n_{THz} the refractive index of crystal for terahertz waves and n_{m} the refractive index of the mask medium for optical radiation (it is assumed that the dispersion is negligibly small).

From (1) it follows that to obtain the desired slope of the amplitude front, the angle α of the prism-like PM (Fig. 1) should be equal to:

$$\alpha = \arctan\frac{n_{\mathrm{THz}} - n_{\mathrm{op}}\cos\theta_{\mathrm{Ch}}}{(n_{\mathrm{m}} - 1)\sin\theta_{\mathrm{Ch}}}\,, \tag{2}$$

where $\theta_{\mathrm{Ch}} = \arccos\left(n_{\mathrm{op}} / n_{\mathrm{THz}}\right)$ is the Cherenkov angle for the terahertz radiation. Obviously, the prism cannot be used to obtain the necessary slope of the amplitude front due to the optical beam refraction.

In work [9] the method was proposed for ensuring the condition (1) for the efficient generation of broadband terahertz pulses in the single-domain $LiNbO_3$ crystal. The method is based on the using of the

SPM, which creates a quasi-linear time delays of the femtosecond laser pulse in the cross section of the optical beam.

3. GENERATION OF TERAHERTZ PULSES IN THE SINGLE-DOMAIN LiNbO$_3$ CRYSTAL

The scheme of the LiNbO$_3$ crystal with the SPM is represented in Figure 2. The beam of femtosecond laser propagates parallel to the *x*-axis and one is polarized along the optical *z*-axis of the crystal. Each layer of the crystal (along the propagation direction of the laser beam) radiates the terahertz pulses under the Cherenkov angle. With the proper selection of the SPM parameters, the terahertz pulses will reach the output surface of the crystal at the same time.

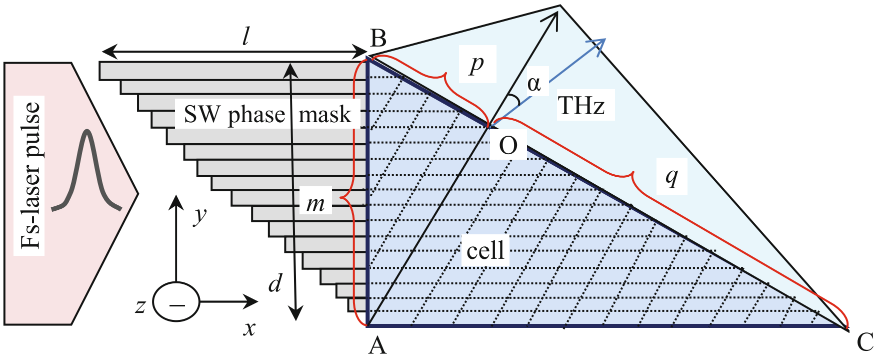

Fig. 2. The schematic representation of the LiNbO$_3$ crystal with the SPM for the efficient generation of broadband terahertz pulses.

The SPM parameters should be chosen based on the following considerations. To ensure the propagation of laser beam in the SPM without diffraction, the size of mask step should be essentially larger than the wavelength of laser radiation. However, to ensure the constructive interference for all radiated terahertz pulses from the different layers of the crystal, the step size of the SPM cannot be chosen greater than the half-wavelength of terahertz radiation [7].

Taking into account the losses of terahertz radiation in the nonlinear crystal, there is no sense to use the laser beams with the transverse dimensions greater than 1/β (β is the absorption coefficient). Therefore, it is reasonable to restrict also the lateral dimension d of the nonlinear crystal ($d_{\max} \approx 1/\beta$). Using as the SPM material the crystalline quartz with $d = 1$ mm size, we obtain for the mask length $l \approx 8$ mm. To avoid the diffraction distortions caused by the exciting laser pulses, the mask layers may be separated from each other by the thin mirror coatings.

4. ANGULAR DEPENDENCE OF SPECTRUM AND TEMPORAL FORM OF TERAHERTZ PULSES IN THE WAVE ZONE

With proper selection of the SPM parameters, the different parts of the output surface of the crystal will radiate terahertz pulses simultaneously. However, the amplitudes of pulses radiated from different parts of the crystal surface will differ from each other.

The terahertz field will be distributed on the output surface of the nonlinear crystal as follows:

$$E(t) = kS_1(t), \tag{3}$$

where $S_1(t)$ is the terahertz field, radiated from the single cell of the nonlinear crystal under the Cherenkov angle (Fig. 2), and k the number of cells (layers) from the bottom end to the output surface of the crystal. If the SPM has m steps, the number of inphase-radiating sections at the output surface of the crystal also will be equal to m.

It is not difficult to understand that for the number of the first p sections the k number of cells increases according to the law $k = i\,[q/p]$ with the increase in the number of steps i (starting from the point B in Fig. 2), and for further q sections one decreases by the law $k = m - i$ with the increase in the steps i. Note that $p + q = m$ and $q = [m\sin^2\theta_{\mathrm{Ch}}]$.

Thus, we obtain for the distribution of terahertz field on the output surface of the nonlinear crystal as function of i

$$E_i(t) = \begin{cases} \left(\dfrac{iq}{p}\right) S_1(t),\ i \le p \\ (m-i) S_1(t),\ i > p. \end{cases} \tag{4}$$

To ensure the synchronism for the total spectrum the amplitude of the all spectral components of terahertz pulse on the output surface of the nonlinear crystal will be distributed in the same way:

$$E_i(f) = \begin{cases} (iq/p) S_1(f),\ i \le p \\ (m-i) S_1(f),\ i > p. \end{cases} \tag{5}$$

To obtain the angular distribution of spectral components of terahertz radiation in the wave zone it is necessary to sum the field radiated from the entire output surface of the crystal taking into account the phase delays

$$E(\alpha, f) = S(f)\left(\sum_{j=1}^{p}(jq/p)\cos\left[j\varphi(f,\alpha)\right] + \sum_{j=p+1}^{m}(m-j)\cos\left[j\varphi(f,\alpha)\right]\right), \tag{6}$$

where α is the angle between the normal to the output surface of the crystal and the direction of observation, $\varphi(f,\alpha) = 2\pi f b \sin\alpha / (cm\cos\theta_{\mathrm{Ch}})$ the elementary phase delay (between the neighboring radiating sections) of the spectral component with the frequency f under the observation angle α and c the velocity of light in free space.

Figure 3a shows the angular distribution of spectral components of the terahertz pulse in the wave zone at the Gaussian shape of spectrum of the terahertz pulse $\left(S(f) = \exp(f-0.5)^2\right)$ centered at 0.5 THz and radiated from one elementary cell of the crystal, when the transverse dimension of the phase mask is $d = 1$ mm, and the number of the SPM steps is $m = 40$.

With the help of the inverse Fourier transform, it is not difficult to find the temporal shape and the angular distribution of terahertz pulses

$$\begin{aligned} E(\alpha, t) &= \int_{\Delta f} S(f)\cos(2\pi f t) \\ &\times \left(\sum_{j=1}^{p}(jq/p)\cos\left[j\varphi(f,\alpha)\right] + \sum_{j=p+1}^{m}(m-j)\cos\left[j\varphi(f,\alpha)\right]\right) df. \end{aligned} \tag{7}$$

As can be seen from Figure 3a, the high-frequency spectral components of the terahertz pulse are concentrated around the normal to the output surface of the crystal. The width of radiation pattern for the spectral component with the frequency $f = 1$ THz at the 0.5 level (of power) is approximately equal to 5° (~0.085 rad), and the low-frequency components are radiated with the greater aperture. For the spectral components with the $f = 0.1$ THz the aperture is equal almost 60° (~1 rad). Such angular distribution distorts the temporal shape of the terahertz pulse, depending on the direction of radiation (Fig. 3b). The undistorted pulses are radiated only along the direction, of the normal to the output surface of the nonlinear crystal ($\alpha = 0$).

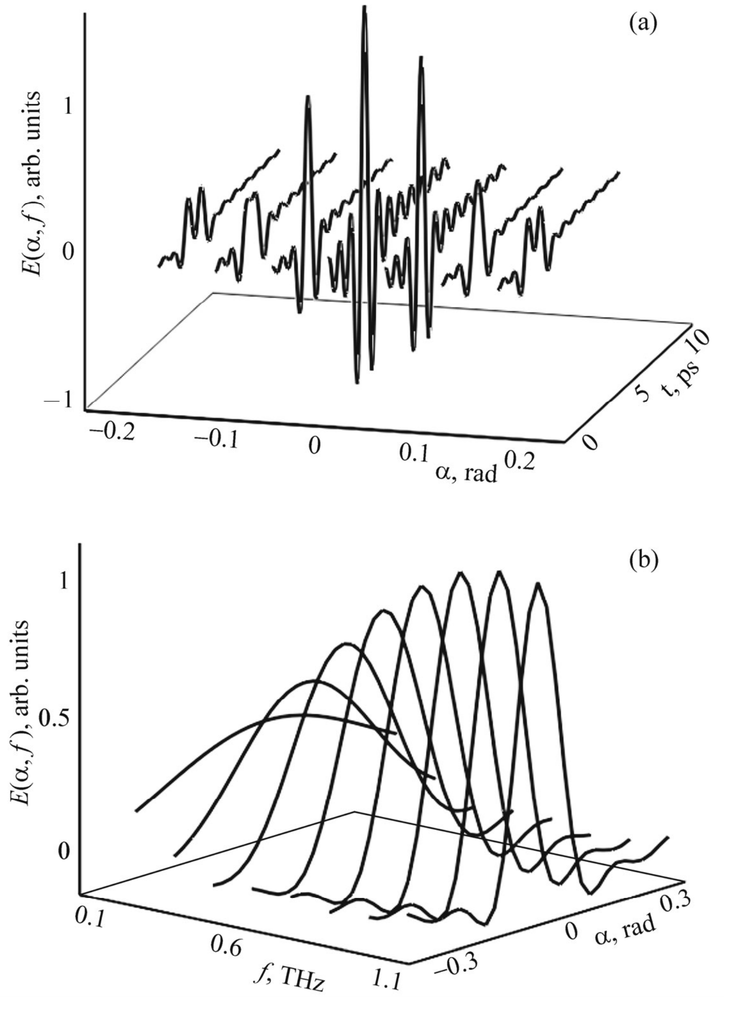

Fig. 3. (a) Angular distribution of spectral components of the broadband THz radiation. (b) Dependence of the temporal shape of THz pulse on the direction of radiation.

5. CONCLUSION

The generation of broadband terahertz radiation via optical rectification of femtosecond laser pulses in the single-domain crystal of lithium niobate equipped with the SPM is investigated. It is shown that using the SPM one may provide the phase matching of all the spectral components of terahertz pulse, thereby ensuring the efficient conversion of laser radiation in the terahertz range. The angular distribution of spectral components of the broadband terahertz radiation is calculated, as well as the temporal forms of terahertz pulse.

Thus, using the stepped phase mask one may generate the highly directional and sufficiently broadband terahertz radiation that can be used to visualize the hidden objects, in the time-domain spectroscopy, and others.

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