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Critical Wavelength in the Metal Waveguide Partially Filled with Nonlinear Crystal

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Abstract—The bandwidth in the system of the nonlinear optical crystal partially filling the cross-section of a rectangular metal waveguide is investigated. Partial filling of a metal waveguide with a nonlinear optical crystal is used to ensure the phase matching for an effective generation of THz radiation in a nonlinear crystal when it is illuminated with the femtosecond optical laser pulse. The critical wavelengths of a metal waveguide with a central symmetric arrangement of crystal plates in the waveguide are numerically calculated depending on the degree of partial filling and the dielectric permittivity of the crystal. It is shown that partial filling of the waveguide with crystal results in an expansion of the bandwidth of the fundamental mode of the odd type H_{10}, without improving the propagation conditions for the nearest higher even mode H_{20}, but on the contrary, at a certain degree of filling with the crystal excludes its occurrence.

Keywords: terahertz waveguide, frequency bandwidth, waveguide modes, metallic rectangular waveguide partially filled with a nonlinear crystal

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1. INTRODUCTION

Sources and detectors of the THz range (based on various physical processes) have found application in the last decade in such fields as telecommunications, bio-sensing, high-resolution medical imaging, biotechnology, military security, radio astronomy [1–6]. Astronomical observations in the THz range [7] are becoming more and more important in scientific research – space projects SMA, ALMA, and HERSCHEL. The importance of various applications has stimulated the research and development of the THz waveguides that direct the radiation from compact THz antennas to detectors. The THz transmission lines are also the key components of the THz systems and devices, in particular, the THz time-domain spectroscope (THz-TDS). To solve the problem, various terahertz guiding structures have been proposed and experimentally investigated [8–13], including a waveguide with parallel plates [11–13]. However, the efficient THz waveguide (with low dispersion and loss, ultra-wideband) is still a problem because of the high losses and finite conductivity of metals in this frequency region, and the high absorption coefficient of dielectric materials.

In [12], dispersionless propagation in a waveguide with parallel plates was reported. However, in this case, the distribution of the electromagnetic field fills the entire cross-sectional area of the waveguide, causing unacceptably high radiation losses.

To suppress unwanted radiation losses (at the breaks of the dielectric waveguide), a nonradiative dielectric (NRD) waveguide was developed – a dielectric is placed between parallel metal plates which maintain low losses [13].

Dielectric-filled waveguides are promising for millimeter and THz waveguides [13–15]. The advantage of the partial filling of the waveguide with a dielectric is the possibility of ensuring phase synchronism of the optical wave with the terahertz one for efficient generation of THz radiation, the reduction of losses in the walls of a metal waveguide, and a dielectric [15], as well as the losses for mode matching. In the case of generation and detection of THz radiation outside the waveguide during the input of THz radiation into and out of the waveguide, the losses arise when the mode of the THz emitter is matched with the funda-

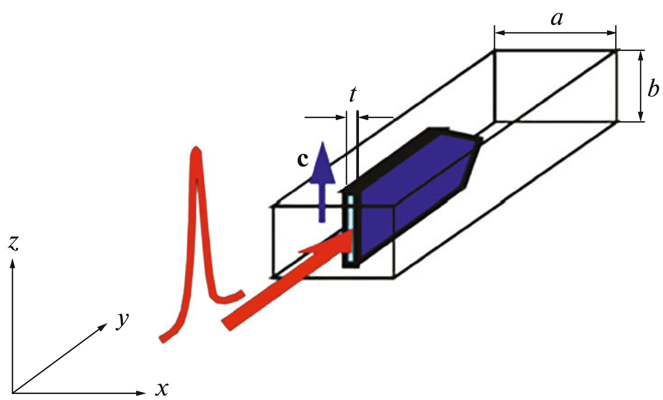

Fig. 1. Generation of the THz radiation in a nonlinear $LiNbO_3$ crystal partially filling a rectangular waveguide under illumination by a femtosecond laser pulse. The optical axis of the crystal is c, and is parallel to the wide wall of the waveguide b to ensure the generation of the THz radiation with linear polarization, because of the largest component of the nonlinear susceptibility tensor of the $LiNbO_3$ crystal – χ_{33}, the nonlinear polarization is $P_z = \chi_{33} E_z E_z^*$ [8, 14].

mental mode of the H_{10} waveguide [8, 16]. In the case of generation and detection of broadband THz radiation inside the waveguide [17–19], there are no mode matching losses.

Below, we investigate the bandwidth in the system ‘nonlinear optical crystal partially filling the cross-section of a rectangular metal waveguide’. The partial filling of a metal waveguide with a nonlinear optical crystal is used to ensure the phase matching, that is, for efficient generation of THz radiation during optical rectification of a femtosecond optical laser pulse in a nonlinear crystal in the waveguide itself. The degree of filling the waveguide with a crystal, and the thickness of the crystal, is determined numerically from the dispersion equation.

2. CRITICAL WAVELENGTH H_{10} OF A WAVEGUIDE PARTIALLY FILLED WITH A CRYSTAL

The equations for determining the critical wavelengths in a waveguide partially filled with a crystal (Fig. 1) are the transcendental equations. The numerical determination of the roots of the transcendental equation – the determination of the critical wavelengths of the H_{10} and H_{20} types, was carried out using the MATHCAD program. The cases when the waveguide is partially filled with a nonlinear-optical crystal are considered $LiNbO_3$ ($\varepsilon = 26.5$), DAST ($\varepsilon = 10$), or ZnTe ($\varepsilon = 5.2$).

The equations for determining the critical wavelengths are obtained by assuming the deceleration coefficient $m = n_{\text{eff}}$ to be zero in the dispersion equations (1, 2). In the case of a centrally symmetric arrangement of the crystal plate in the waveguide, the dispersion equation for even and odd TE types of waveguide waves has the form [14]:

$$\sqrt{n_{\text{eff}}^2 - 1}\tan\left(\pi k_1 k_2 \sqrt{\varepsilon - n_{\text{eff}}^2}\right) = \sqrt{\varepsilon - n_{\text{eff}}^2}\tanh\left(\pi(1 - k_1)k_2\sqrt{n_{\text{eff}}^2 - 1}\right), \quad (1)$$

$$\sqrt{n_{\text{eff}}^2 - 1}\cot\left(\pi k_1 k_2 \sqrt{\varepsilon - n_{\text{eff}}^2}\right) = \sqrt{\varepsilon - n_{\text{eff}}^2}\tanh\left(\pi(1 - k_1)k_2\sqrt{n_{\text{eff}}^2 - 1}\right), \quad (2)$$

where ε is the dielectric constant of the THz wave, $k_1 = 2t/a$ is the crystal thickness normalized to the width of the waveguide; $k_2 = a/\lambda_{10}$ is the waveguide width normalized to the critical wavelength of the first odd type of oscillations H_{10}; $n_{\text{eff}}(\lambda_{\text{DFR}}) = c/\upsilon_{\text{p}}(\lambda_{\text{DFR}}) = m$ is the coefficient of the THz wave deceleration or effective refractive index of the “crystal-waveguide”structure. The critical wavelength of the fundamental odd type of oscillation H_{10} for various dielectric constants is determined from the equation (3):

$$\cot\left(\pi k_1 k_2 \sqrt{\varepsilon}\right) = \sqrt{\varepsilon}\tan\left[\pi k_1(1 - k_2)\right]. \quad (3)$$

Figure 2 shows the graphs of the dependences of the waveguide width normalized to the critical wavelength for the first odd type of oscillation on the filling value. It follows from the graphs that with an increase in the value of the dielectric constant, the value of the critical wavelength for the THz wave of the H_{10} type in the “crystal plus waveguide” system increases. An increase in the critical wavelength is signif-

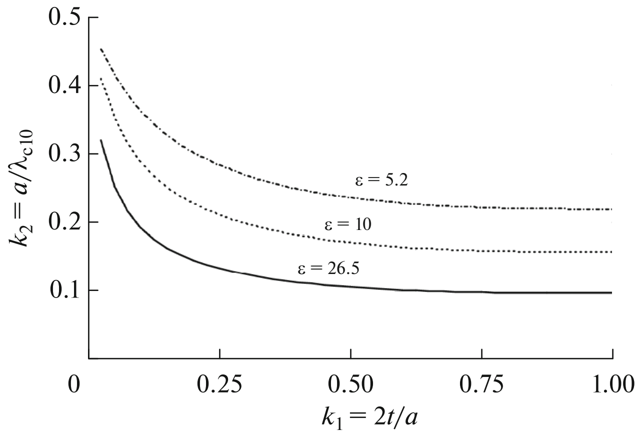

Fig. 2. Dependence of the waveguide width normalized to the critical wavelength of the first odd type of vibration k_2, from $k_1 = 2t/a$ the crystal thickness normalized to the waveguide width.

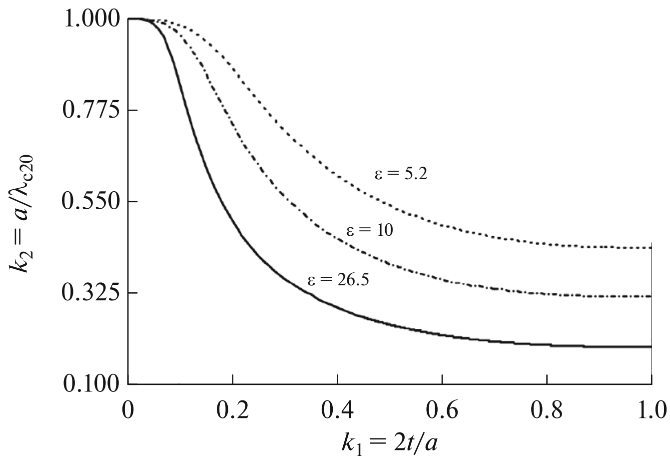

Fig. 3. Critical wavelength H_{20} of a waveguide partially filled with a crystal.

icant for such a partial filling of the waveguide by the crystal when $k_1 \leq 0.2$. With an increase in the value of k_1, the critical wavelength slowly changes, and when approaching the case of complete filling of the waveguide by the crystal, it almost does not change.

With a centrally symmetric arrangement of a thin crystal in the waveguide, an increase in the critical wavelength of the H_{10} type is caused by the fact that the crystal is located in the place of maximum electric field strength, where the effect of field concentration by the dielectric is more revealed. In the case of complete filling of the waveguide by the crystal, $k_1 = 1$, the entire field is completely enclosed in the dielectric.

3. CRITICAL WAVELENGTH H_{20} OF A WAVEGUIDE PARTIALLY FILLED WITH A CRYSTAL

To determine the bandwidth of the basic wave in the system “nonlinear optical crystal partially filling the cross-section of a rectangular metal waveguide”, it is also necessary to know the critical wavelength of the even mode of oscillation H_{20}, which is the nearest to the basic wave H_{10}. The equation for determining the critical wavelengths of even types of oscillations, obtained from equation (2), has the form:

$$\sqrt{\varepsilon}\tan\left[\pi k_1(1-k_2)\right] = -\tan\left(\pi k_1 k_2\sqrt{\varepsilon}\right). \tag{4}$$

Figure 3 shows the dependence of the root of equation (4) a/λ_{20} of the H_{20} wave on the crystal thickness, normalized to the waveguide width $k_1 = 2t/a$, at the value of the dielectric constant of the $LiNbO_3$ crystal filling the waveguide ($\varepsilon = 26.5$). From a comparison of Fig. 1 and Fig. 2, it follows that the critical wavelength of the H_{20} type changes more slowly from the filling value at $k_1 \leq 0.2$. This is because, for even types of oscillations, a node of the electric field strength is located in the center of the waveguide if the crystal is thin. As a result, the field concentration is revealed weakly. With an increase in the crystal thickness $2t/a$. the field concentration increases.

Thus, the dielectric plate expands the passband of the fundamental H_{10} wave into the low-frequency region, while it does not improve the propagation of the nearest higher wave-type H_{20} in the high-frequency region, but rather interferes with its origination.

4. RESULTS AND ITS DISCUSSION

It follows from the results obtained that if, with air filling of a waveguide with a wide wall $a = 2.4$ mm, the critical frequency of the fundamental wave is $f_{c10} = 62.5$ GHz, then in a waveguide partially filled with a $LiNbO_3$ crystal, $f_{c10} = 25$ GHz (from Fig. 2 it follows that the value $t/a = 0.1$ corresponds to $a/\lambda_{c10} = 0.2$). For the H_{20} wave in an empty waveguide $f_{c20} = 125$ GHz. In a waveguide partially filled with a $LiNbO_3$ crystal, $f_{c20} = 107$ GHz, because the value $t/a = 0.1$ corresponds to $a/\lambda_{c20} = 0.858$ (Fig. 3). In a waveguide filled with the $LiNbO_3$ crystal, $f_{c10} = 12$ GHz and $f_{c20} = 24.3$ GHz. Consequently, in a waveguide partially filled with a crystal, the bandwidth $f = f_{20} - f_{10} = 107$ GHz – 25 GHz = 82 GHz increases by a factor of ~7 as compared to the bandwidth of a waveguide filled with a crystal ~12 GHz. The increased bandwidth is another advantage of a partially filled waveguide (with a central symmetrically positioned crystal plate) as compared to a filled nonlinear crystal waveguide. It should be noted that it was experimentally shown in [14] that in a waveguide partially filled with a $LiNbO_3$ crystal, a THz pulse is generated in the 25 GHz–3 THz band. Earlier, it was shown in [9] that the propagation of a THz pulse through a waveguide is more than 98% single-mode propagation of the H_{10} type, with linear polarization of radiation.

5. CONCLUSION

The bandwidth is investigated in the system "the nonlinear optical crystal partially filling the cross-section of a rectangular metal waveguide". Crystals $LiNbO_3$, DAST, and ZnTe are considered because of their highly efficient nonlinear conversion of the optical pulse to the THz range. Crystals have an effective second-order nonlinear susceptibility and have different permittivities, for which the phase-matching condition is satisfied at a certain crystal thickness. It is shown that at a small crystal thickness ($2t/a < 0.2$) the value λ_{10} of the fundamental odd wave of the H_{10} type increases in comparison with the empty waveguide. Due to this, the bandwidth of the fundamental wave is expanded to the low-frequency region. A slow change in the value of λ_{20} in the high-frequency region does not improve the propagation conditions for the higher even type of wave H_{20}, which is closest to H_{10}, but, on the contrary, prevents its formation. The results obtained show that the partial filling of the waveguide with a crystal leads to a significant expansion of the passband of the basic odd-type vibration H_{10}, in comparison with the filled.

Thus, to ensure the efficient and broadband generation of THz radiation in a waveguide, it is advisable to use a waveguide partially but not completely be filled with a nonlinear crystal. A waveguide partially filled with a nonlinear crystal is simultaneously both a promising source of generation of broadband THz radiation and its guiding medium, which is necessary for various applications of THz radiation: as telecommunications, defense, security, medicine, and the development of high-speed integrated waveguide devices with low losses [20].

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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