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Simulation of the THz radiation in the tapered waveguide

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ABSTRACT

The finite-element method was employed to model and simulate the terahertz (THz) wave propagation in a tapered waveguide. The relatively infrequent use of dielectric waveguides and antennas is due to the lack of analysis tools. Maxwell's equations have an analytical solution only for a rectangular shape crystal. Lack of analysis tools inhibits antenna development because physicist must resort to cut-and-try methods. It is only recently that simulation of electromagnetic fields in arbitrarily shaped media has become fast and practical.Numerical simulation results showed changes in the mode structure of the THz radiation along the length of the crystal, the concentration of the THz field inside the crystal and the radiation structure from the crystal-air interface. Excitation of THz radiation in the tapered waveguide with the help of an optical laser pulse permits the resolution of problems connected with input/output coupling - mode matching and single mode propagation. THz energy concentration by dielectric wedge antenna improves the spatial resolution and increases the signal/noise ratio (SNR) for the THz imaging and spectroscopy.

Keyword: terahertz radiation, tapered waveguide, finite-element method, numerical simulation

I. INTRODUCTION

Terahertz waves have found wide range of applications in science and engineering such as in the fieldsof time domain spectroscopy, medical diagnosis, imaging of concealed items, security, biological sensing, defense, space science, space instrumentation, etc.The benefits of the THz waves utilization in the radar applications are line-of-sight propagation and a higher imaging resolution. It is known that by reducing the cross-section of the dielectric antenna, a high resolution image can be obtained at the fixed operation frequency.

Recently, in most near-field microwave-imaging systems sharp metallic tips [1] or rectangular waveguides (aperture based method) are used as probes. The spatial resolution of the images is inversely proportional to the waveguide's cross-section area and the size of the tip.A probe using a metallic aperture was demonstrated in the Ref [2] for obtaining a resolution of 7 μm (λ/86). In Ref [3] the waveguide (made out of a low loss dielectric material) with pyramidal sharpened tip has been proposed to reach a resolution of about 20 μm (λ/200). Another similar tip method with a resolution of 150 nm (λ/1000) is presented in Ref [4, 5], and a resolution of 10 nm is presented in [6]. In all of the above mentioned works, the THz radiation was supplied to the probes. A substantial part of the THz radiation was lost as a result of its coupling with the input surface of the probe. In order to avoid this kind of losses of the THz radiation in Ref [6-10] generation of THz radiation has been experimentally investigated in nonlinear wedge crystal. The dielectric antenna is promising technique which unlike the tip method demonstrates a greater power efficiency. The wedge shape allows to concentrate the THz field in a nonlinear crystal, to reduce the undesirable effects of the diffraction, as well as to get most part of the energy at the exit of the crystal. In the case of a laser-driven THz rectangular $LiNbO_3$ nonlinear crystal antenna, about 46% of the THz radiation reflects from the exit surface of the crystal due to the crystal's high reflection factor [11].

The finite-element method was employed to model and simulate the THz wave propagation (of the most intense spectral lines of THz pulse) in a $LiNbO_3$ tapered crystal in order to analyze experimental results [9]; and to visualize how the form of the crystal influences on the THz radiation both inside and outside the crystal in the near-field zone.

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II. THZ WAVES PROPAGATION IN A LINBO3TAPERED WAVEGUIDE

The THz pulses were generated via optical rectification of femtosecond pulses of a Ti: Sapphire laser, a central wavelength λ=800 nm, in a tapered crystal, Fig.1. The linear tapered broad band dielectric antenna, has been fabricated from $LiNbO_3$ nonlinear crystal. The optical field strength **E** and nonlinear polarization **P** vector, as well as the optical axis of the crystal, were parallel to the height of the wedge crystal. In this case, the linearly polarized THz radiation is generated due to the largest second-order nonlinear tensor element d_{33} ($P_z = d_{33}E_zE_z^*$).

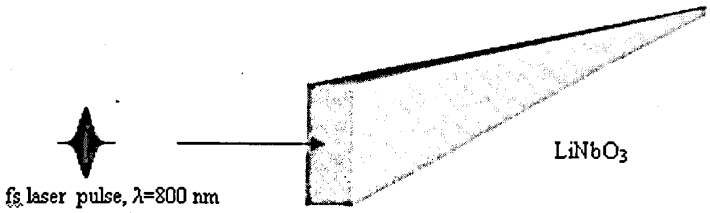


Fig.1. Laser-driven $LiNbO_3$ tapered THz broadband antenna

The propagation of THz waves in $LiNbO_3$ crystal with frequencies equal to the most intense spectral lines in THz pulse spectra [9] (at: 330 GHz, 414 GHz, 479GHz, 800 GHz, see Fig.3) were studied.

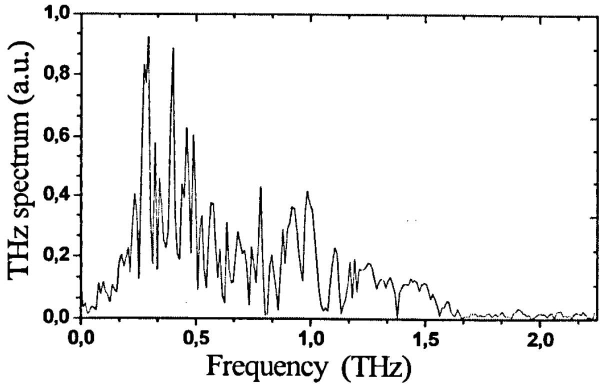
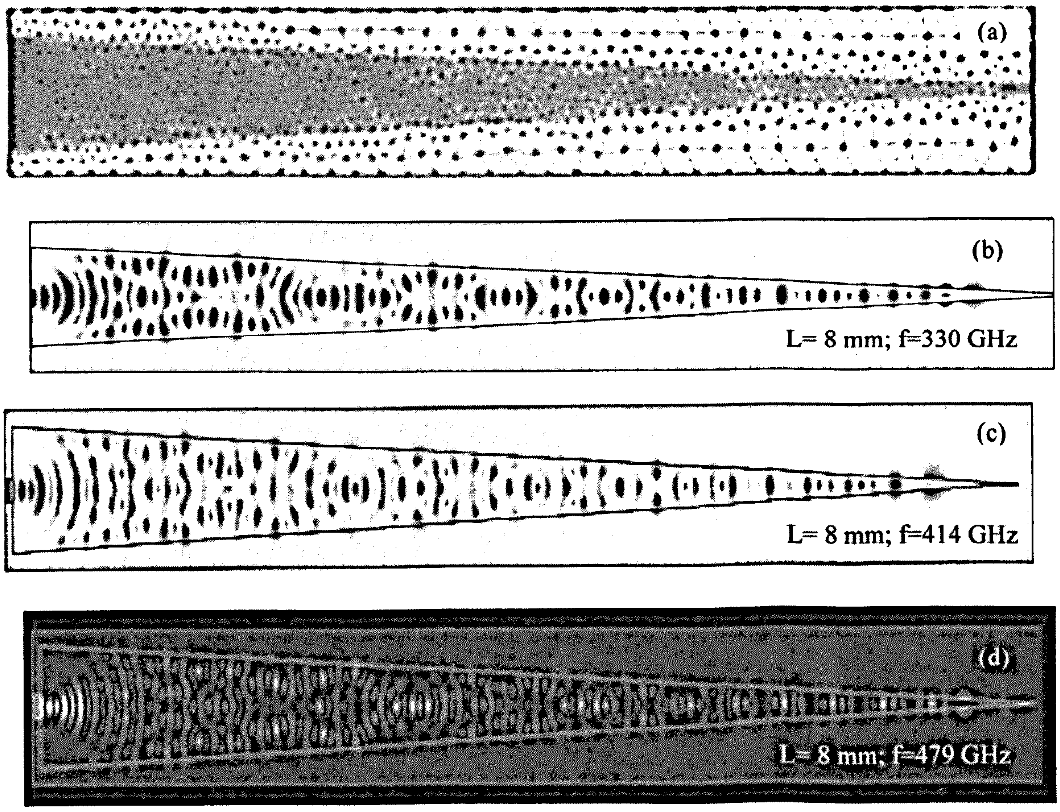


Fig.3. Frequency dependence of THz field (the spectrum of pulse after fast Fourier transform) when the tapered $LiNbO_3$crystal is placed in free space (FS), axbxL = 0.27x0.8x8 mm.

To simulate the THz wave propagation in the $LiNbO_3$ tapered crystal located within a free space, the software 'COMSOL Multiphysics' was used. A model has been built in frame of the 3D geometry. In order to provide good convergence of the solution the mesh has been built by tetrahedral cells the maximum size of which has been taken to be $\lambda/10$ Fig.4(a). All elements of the system with the physical parameters and boundary conditions are described by a set the partial differential equations. To solve correctly the equation system which describes the distribution of the THz wave field, the largest size of the cell should not be greater than one third of the wave length. In our case it was 3 times smaller to get more accuracy. The following values were input into the program: the real and the imaginary parts of the dielectric function and the power for the given THz extraordinary wave. The values n and α calculated through the formula given in [11].

It is shown that the mode structure and phase velocity of the THz radiation are changing during its propagation through the wedge crystal, Fig.4, Fig.5, as theTHz field passes from the single mode E^x_{11} to multi mode regime and vice versa. TheTHz field has been focused.The full energy of the THz radiation propagating along straight lines parallel to the Z-axis of the wedge crystal is distributed between both – external (outside of the plate) and internal fields. The red color in Fig.4 and Fig.5 indicates positive values and blue indicates negative values of the THz electric field.

The distribution of THz electric field E_z component for the wedge crystal lengths of 2.5 mm and 12 mm respectively, is shown in Fig.5. The cross-sectional area of the crystal was $0.27x1\ mm^2$.As the length of the wedge increases, the beam-width decreases, namely, the directional diagram becomes sharper and the relative gain of the antenna increases.



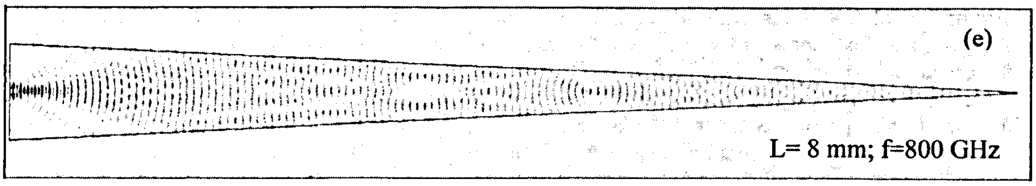


Fig.4. The spatial distribution of the E_x (z) components of the THz electric field during propagation along the *z* axis at frequency of 330 GHz(b), 414 GHz(c), 479 GHz(d), 800 GHz(e), lateral view in (xz) plane, L = 8 mm.

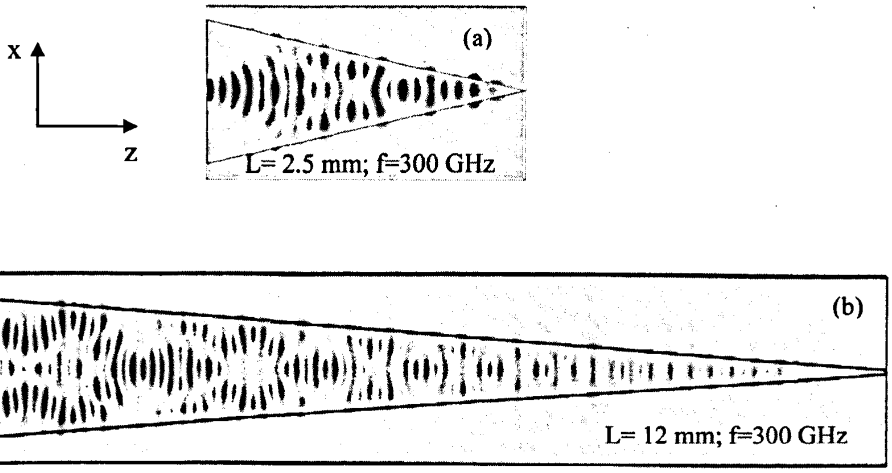


Fig.5. The spatial distribution $E_x(z)$ component of the THz electric field at 300 GHz frequency, axb = 0.27 x 0.8 mm^2, L = 2.5mm and L = 12 mm.

CONCLUSION

The relatively infrequent use of dielectric waveguide is due to the lack of analysis tools. Maxwell's equations have an analytical solution only for a rectangular shape crystal. This inhibited the development and application of arbitrarily shaped dielectric waveguides. Only recently the simulation of electromagnetic fields in arbitrarily shaped dielectric waveguides and antennas has become available.

The finite-element method was employed to model and simulate the THz wave propagation in a linearly tapered waveguide in order to analyze the experimental results [9]. Excitation of THz radiation in the linearly tapered waveguide antenna (made from nonlinear optical crystal $LiNbO_3$) by an optical laser pulse permits the solution of problems connected with coupling of electromagnetic waves at the input and output of the crystal – mode matching and single mode propagation.

Numerical simulation results showed changes in the mode structure of the THz radiation along the length of the crystal, the concentration of the THz field inside the crystal (Fig.3, Fig.4) and the radiation structure from the crystal-air interface. THz energy concentration by dielectric wedge antenna improves the spatial resolution and increases the signal/noise ratio (SNR) for the THz imaging and spectroscopy. The wedge THz antenna may be applied in other areas, in particular, in ultra-high-speed electronic integrated circuit and terahertz-wave communications.

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