Terahertz Waves Propagation in a $LiNbO_3$ Wedge Antenna

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The terahertz (THz) wave propagation in $LiNbO_3$ wedge crystal was investigated. In order to study the THz wave propagation in the crystal, located within a free space, a simulation by the finite-element method was performed. The THz pulses were generated via optical rectification of femtosecond pulses of a Ti: Sapphire laser in the nonlinear optical wedge crystal. In order to analyze experimental results - the propagation of the most intense spectral lines of the THz pulse (in the range of 270 GHz - 1016 GHz) was modeled by means of COMSOL Multiphysics software.

I. Introduction

Terahertz waves have been found in a wide range of applications in science and engineering such as in the fields of time domain spectroscopy, medical diagnosis, imaging of concealed items, security, biological sensing, defense, space science, space instrumentation, etc. Terahertz waves offer a lot of benefits for radar applications, such as 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 without changing the frequency of operation.

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). The dielectric antenna is a promising technique which unlike the tip method, demonstrates a greater power efficiency. 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 these 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 wedge shape allows to concentrate the THz field in a nonlinear crystal, 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 $LiNbO_3$ wedge antenna 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.

II. THz Waves Propagation in a $LiNbO_3$ Wedge Antenna

The THz pulses were generated via optical rectification of femtosecond pulses of a Ti: Sapphire laser, a central wavelength λ=800 nm, in a wedge crystal, Fig.1. A schematic diagram of the experimental setup, demonstrating the principles of THz pulse generation and detection, to obtain THz spectral data is shown in Fig.2. The linear tapered broad band dielectric antenna, has been fabricated from $LiNbO_3$ nonlinear crystal. The optical field strength **E** and nonlinear polarization **P** vectors, 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} ($P_z = d_{33}E_zE_z^*$).

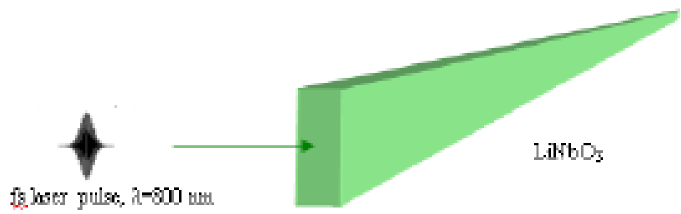

Fig.1. Laser-driven LiNbO3 wedge THz broadband antenna

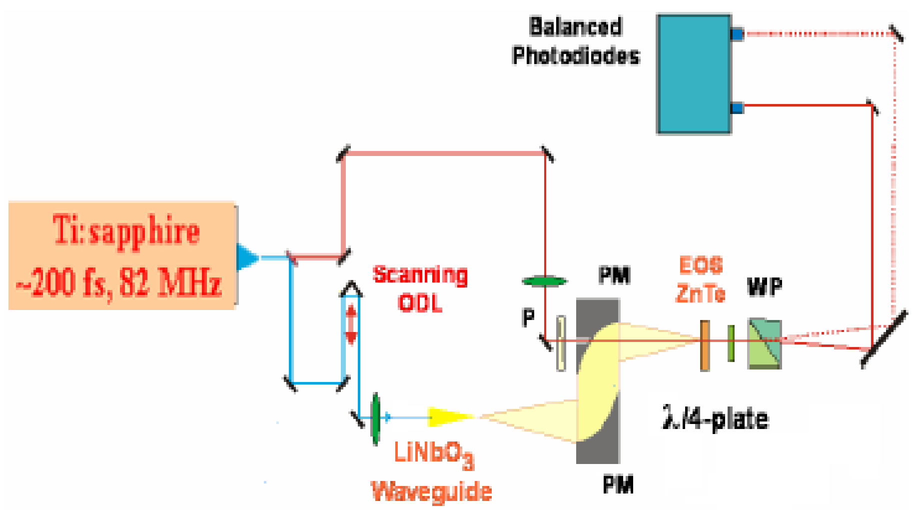

Fig.2. Schematic diagram demonstrating the principles of THz pulse generation and detection

The propagation of THz waves in $LiNbO_3$ crystal with frequencies equal to the most intense spectral lines in THz pulse spectra [9] (at: 270 GHz, 290 GHz, 330 GHz, 409 GHz, 451 GHz, 500 GHz, 644 GHz, 760 GHz, 802 GHz, 1000 GHz and 1016 GHz) were investigated.

To simulate the THz wave propagation in the $LiNbO_3$ wedged crystal located within a free space, the software 'COMSOL Multiphysics' was used. A domain of simulation is a 3D space. In order to provide good convergence for the solution the mesh has been built from tetrahedral cells the maximum size of which has been taken to be λ/10 Fig.3(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 then 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 of 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.3, Fig.4, as the THz field passes from the single mode Ex_{11} to multimode regime and vice versa. The THz 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.3 and Fig.4 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.4. 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.

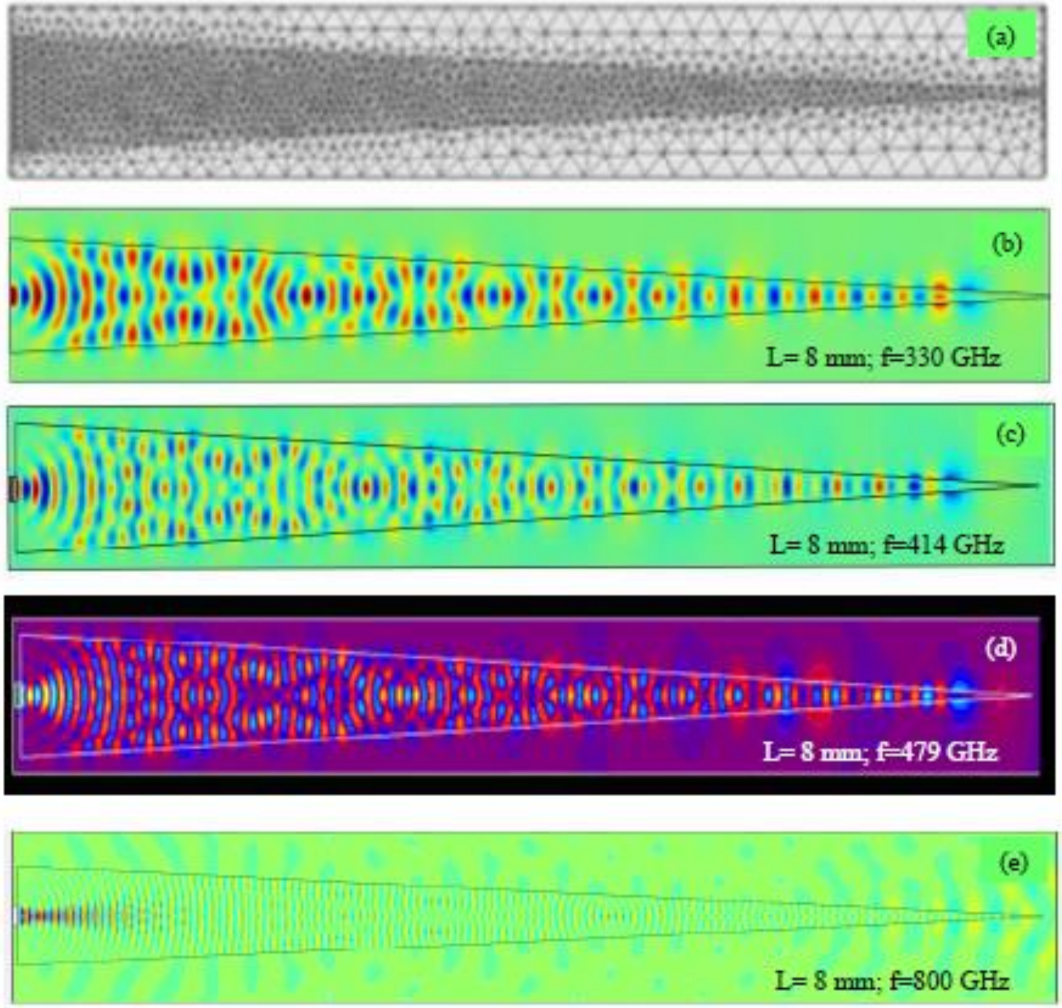

Fig.3. The spatial distribution of the E_x (z) components of the THz electric field during propagation along the *z* axis at frequency of 330 GHz, 414 GHz, 479 GHz, 800 GHz: (a) lateral view in (xz) plane, L = 8 mm.

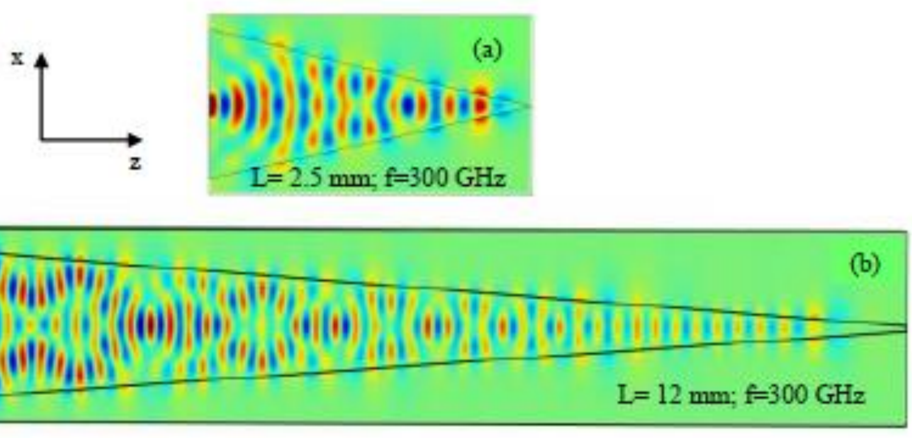

Fig.4. The spatial distribution E_x(z)-component of the THz electric field at 300 GHz frequency, axb = 0.27 x 0.8 mm^2, L = 2.5mm and L = 12 mm.

III CONCLUSION

The relatively infrequent use of dielectric antennas 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 antennas. Only recently the simulation of electromagnetic fields in arbitrarily shaped dielectric antennas has become available.

The finite-element method was employed to model and simulate the THz wave propagation in a wedge antenna in order to analyze the experimental results [9]. Excitation of THz radiation in the wedge 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

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