# Development of 3D Anisotropic Artificial Dielectric Metamaterial for THz Frequency Range

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**Abstract**— The paper is devoted to development of 3D anisotropic dielectric artificial structure. The proposed structure was simulated by CST Microwave studio and the tensors of refractive index were obtained. The dielectric structure was made by 3D printer. The trasmission spectra were obtained using the time domain spectrometry technique and the tensors of permittivity and the refractive index dispersion were calculated. The simulation and experimental results are presented and analyzed in the frequency range of 0.1–2 THz.

## 1. INTRODUCTION

Nowadays, the metamaterials [1] and their applications challenge the customary view on the physics of optics and photonics. Since the works of Veselago, Pendry and Yablonovich [2–4] the metamaterials find their applications in the fields of satellites communications, data transfer and processing systems, solar energy technology and cloaking. It can be explained by unusual properties of artificial structures for example: negative refraction index, extremely values of permittivity and permeability, superresolution effect, invisibility, tunability of constitutive parameters [5–10].

The most important property of metamaterials is capability to scale their sizes from centimeters to nanometers. Such property allows to use the well-known effects in any frequency range. The scale factor and quality of the structure are limited only by possibility of used fabrication technology. Always, metamaterials are composite structures, which consist of unit cells. Sizes of unit cell strongly depend on wavelength, hence the sizes of unit cell are also limited by resolution of fabrication device as noted before.

The development of dielectric metamaterials can find their niche and they can fast, easy and inexpensively be done by the 3D printer technologies of the local facilities everywhere. In contrast to the metallic composite structures [11], the dielectrics metamaterials are predominantly 3D structures and, of course, they can be reduced to 2D or 1D designs [12]. However, capabilities of dielectric metamaterials are limited by resolution of 3D printing devices about hundred of micrometers. We suggest the method of fabrication of 3D anisotropic dielectric structure for terahertz frequency range.

In this paper we propose model of dielectric anisotropic metamaterial structure. The suggested model has very simple geometry parameters and it possesses anisotropy if the radiation is directed along the different sides of the model. The anisotropy of the proposed design was obtained by FDTD numerical simulation method in CST Microwave Studio and it was experimentally confirmed by the refractive index dispersion obtained from the transmission spectra by the time domain spectroscopy. The potential applications of anisotropic dielectric metamaterial are optical elements, such as polarizer, prisms, waveplates, microlenses arrays metamaterial devices such as cloaks, beam splitters and combiners, filters and etc..

## 2. SIMULATION RESULTS

At this moment, most of 3D printers work with high precision resolution, because the structures need more than ten microns resolution for terahertz frequency range. Therefore, the simple geometry of cubic structure with square holes was chosen. The projection of the structure on $XY$ plane is presented in Fig. 1(a), the upper left corner of the figure demonstrates the unit cell highlighted by red color. The full structure is shown in Fig. 1(b). For more matching of the numerical simulation model to the experimental dielectric material, the refractive index dispersion extracted from the transmission spectra Fig. 1(c) was included in the model.

The simulations were performed by the time domain solver for the pulse duration of 3.75 ps. The anisotropy of the investigated structure was shown by analysis of refractive index for the different position of radiation sources, when the wave-vector is directed along $y$ and $z$ axes.

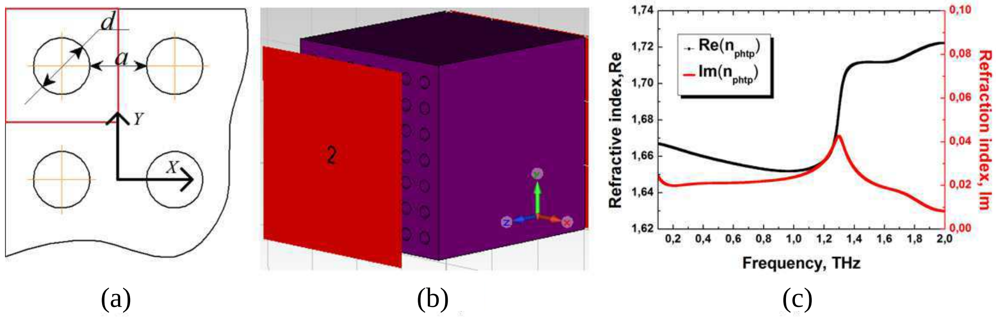


Figure 1: (a) The scheme of the structure projected on the $XY$ plane (the side of circular hole with diameter of $d = 200\,\mu\text{m}$, the period the structure of $400\,\mu\text{m}$ $(a + d)$). (b) The simulated structure with the side length of $3000\,\mu\text{m}$. (c) The dispersion of imaginary and real parts of photopolymer refractive index used for the simulation.

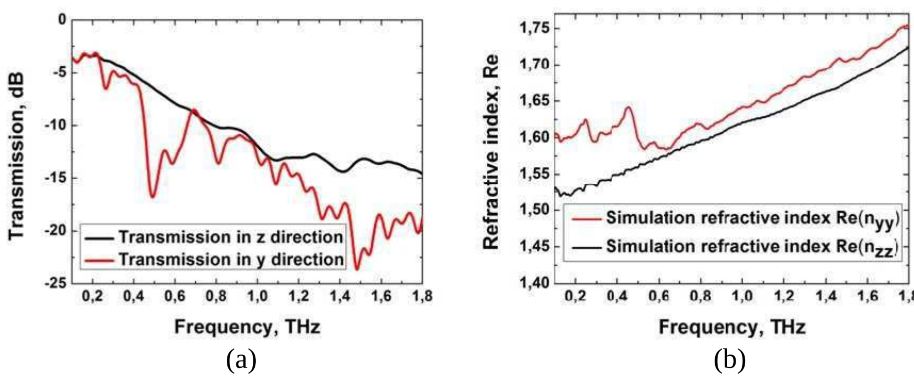


Figure 2: The transmission spectra (a) of structure along $y$ and $z$ axes. (b) The real parts of $\hat{n}_{yy}$ and $\hat{n}_{zz}$ refractive indices components extracted from the simulated transmission spectra.

The complex refractive index is presented as the diagonal matrix (1) with the following elements:

$$\hat{\mathbf{n}} = \begin{pmatrix} \hat{n}_{xx} & 0 & 0 \\ 0 & \hat{n}_{yy} & 0 \\ 0 & 0 & \hat{n}_{zz} \end{pmatrix} \tag{1}$$

The elements $\hat{n}_{xx}$ and $\hat{n}_{yy}$ are equivalent due to the tetrad symmetry of the structure, but $\hat{n}_{zz}$ element will be obvious differ from the $\hat{n}_{xx}$ and $\hat{n}_{yy}$ due to the chosen model geometry.

Let's consider the characteristic dimensions of the structure under study. It is clear that not for every frequency in the signal the proposed design will obey the model of effective medium. Since in the frequency range of 0.1–0.3 THz the wavelength inside the metamaterial is in five times larger of the unit cell size, the structure may work as effective medium. For the highest THz frequencies the anisotropic dielectric structure may be represented as photonic crystal if the radiation propagates along of $y$ or $x$ axes and therefore in the transmission spectra may be observed the stop band gaps in transmission spectrum Fig. 2(a). In the case of the THz wave propagation along of $z$ axis, the structure still works as effective medium. The real part of refraction index spectrum of the structure were extracted from the reference and sample transmission spectra using the following formula [13] and shown in Fig. 2(b):

$$n_{smpl}(f) = 1 + \frac{c}{(2\pi f d)} \left(\phi_{smpl}(f) - \phi_{ref}(f)\right), \tag{2}$$

where $n_{smpl}(f)$ is the real part of refractive index of the investigated structure, $c$ is the speed of light, $f$ is the frequency, $d$ is the sample thickness, $\phi_{smpl}$ and $\phi_{ref}$ are the phases of the complex amplitudes of the sample and the reference transmission spectra.

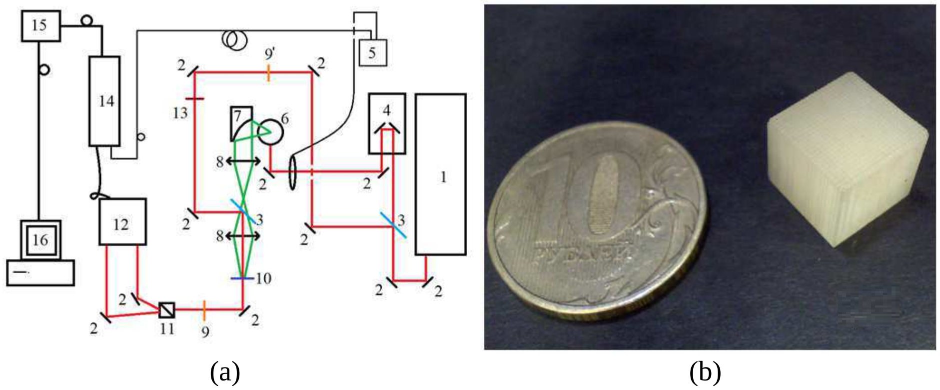


Figure 3: The experimental setup scheme (a): IR Yb:KYW laser ($\lambda = 1040\,\text{nm}$, $\tau = 200\,\text{fs}$) (1), mirrors (2), beam splitters (3), delay line (4), chopper (5), GaAs crystal of the magnetic field of 2.4 T (6), parabolic mirror (7), terahertz lenses (8), wave plates $\lambda/4$ and $\lambda/2$ (9, 9′), CdTe crystal (10), Wollaston prism (11), balance detector (12), Glan-Taylor prism (13), lock-in-amplifier (14), analog to digital converter (ADC) (15), personal computer (PC) (16) and sample (s). (b) Photo of experimental anisotropic dielectric metamaterial sample with 200 μm holes.

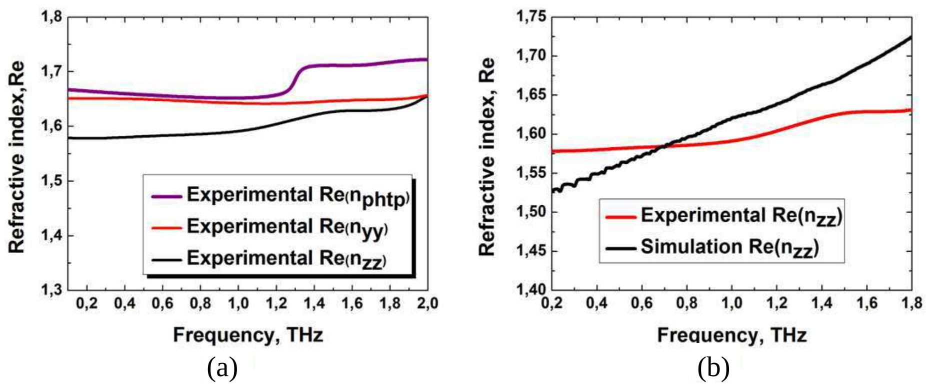


Figure 4: (a) The experimental dispersion of the refractive index components $\hat{n}_{yy}$, $\hat{n}_{zz}$ of investigated structure and the dispersion of the refractive index of the photopolymer. (b) The comparison of the experimental and the simulated $\hat{n}_{zz}$ refractive index component.

## 3. EXPERIMENTAL RESULTS

The experimental setup of THz time domain spectrometry for the experimental verification of the simulated results was used (see Fig. 3). The Yb:KYW laser pumps semiconductor crystal GaAs for THz radiation emission. Further, THz radiation is focused on the CdTe crystal and it induces the anisotropy in the crystal increasing the difference of $s$ and $p$ polarizations that can be easy detected with Wollaston prism. Changing the probe beam optical path, THz pulse is indirectly detected by balance detectors and registered by lock-in-amplifier and ADC. The sample was placed at the focus of THz lenses and the transmission spectra were obtained for two sides of the anisotropic dielectric metamaterial sample.

The components of refractive index tensor of the structure are less than photopolymer refractive index because of the holes. Thereby, the anisotropy of the refractive index dispersion was shown by the numerical simulation of the structure for the excitation pulse propagation along $y$ and $z$ axis by FDTD method in CST Microwave Studio. The obtained real parts of $\hat{n}_{zz}$ and $\hat{n}_{yy}$ refractive index components are shown in Fig. 4(a). The refractive index components of the structure are less than the photopolymer refractive index. Fig. 4(a) demonstrates the anisotropy confirmed by the experimental and the numerical simulation of the structure. As seen from the figure, the simulation and the experimental data demonstrate the same behavior.

## 4. CONCLUSIONS

The new approach of the development of anisotropic dielectric metamaterials based on 3D printer technologies was proposed for the frequency range of 0.1–2 THz. The anisotropic metamaterial model was made of the photopolymer with resolution of 25 micrometers. The dispersion of the refractive index tensor components ($\hat{n}_{xx} = \hat{n}_{yy} \neq \hat{n}_{zz}$) was shown numerically and by the time domain spectroscopy method. The experimental values of the real part ($\hat{n}_{zz}$) are changed from 1.57 to 1.656 in the frequency range of 0.1–2 THz. The experimental values of the real part $\hat{n}_{xx}$ and $\hat{n}_{yy}$ are changed from 1.570 to 1.656 in the frequency range of 0.1–2 THz. The proposed anisotropic structure can be used for development of wave plates, beam splitters, invisibility cloaks, etc. for THz frequencies.

## ACKNOWLEDGMENT

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