

## Aligned planar-wire zero-index metamaterial for terahertz frequency range

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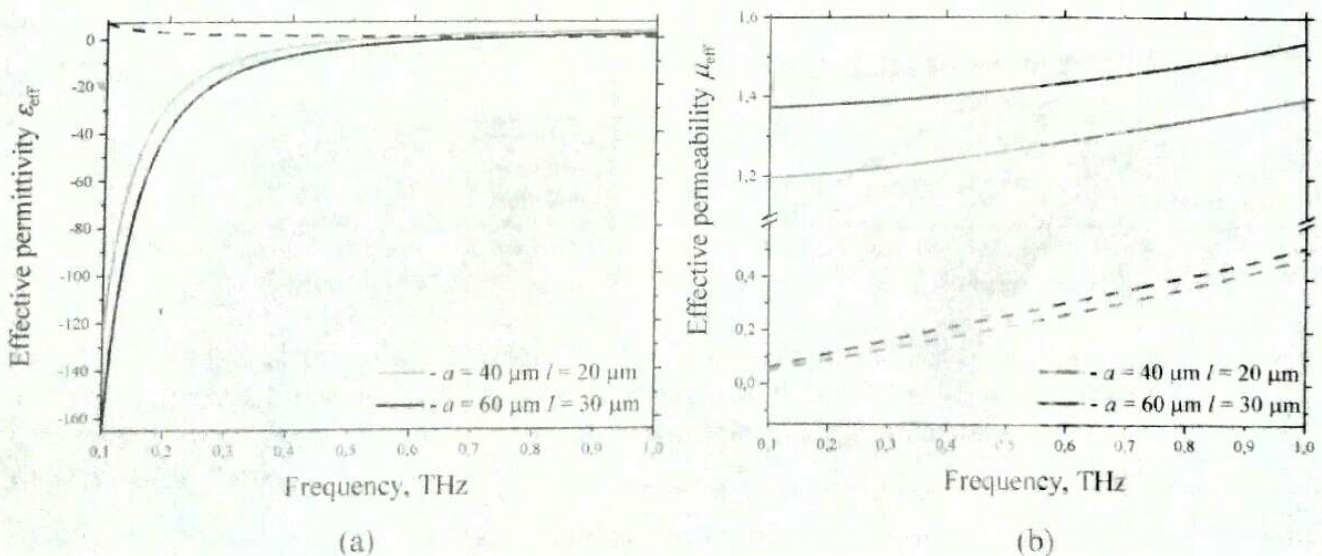
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**Abstract.** Demonstrations of specific class of materials with extremely small (near zero) values of permittivity have attracted attention of scientific community<sup>1</sup>. These unique materials have the refractive index equal to zero what causes almost constant spatial distribution of the electric field of the propagating wave inside these media<sup>2</sup>.

Considering its extreme properties, ENZ-material can also be used as delay line that brings no phase delay in propagating wave<sup>3</sup>, as ideal coupler between waveguides of the same diameter and can find effective application in cloaking<sup>4</sup>. It should be mentioned that ENZ-, MNZ- ("mu near zero") and LH- ("left-handed") materials can be designed using transformation optics approximation<sup>5-7</sup>. ENZ or MNZ coating may be used to radically enhance transmission through subwavelength aperture. In general, isolated subwavelength aperture cannot provide enough transfer of energy, but with ENZ coating the transfer increases by several orders of magnitude<sup>8</sup>.

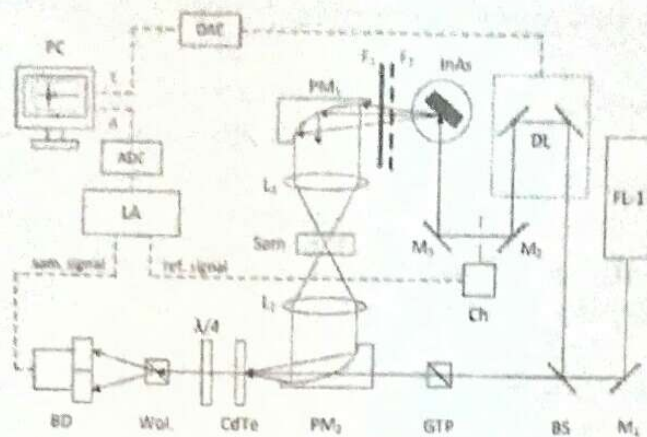
**Objective of the work.** This work is dedicated to zero-index (ZI) terahertz metamaterial designed with one-layer aligned planar aluminum wires on dielectric PET substrate and acting like epsilon-near-zero (ENZ) medium. Metal stripes on dielectric substrate can be easily manufactured. The idea is that metal stripes may have permittivity described by Drude model in terahertz frequency range which gives the opportunity to design ENZ-material.

**Results.** To prove that such structure can act like ENZ-material, number of numerical simulations has been done with the periodic boundary conditions. Simulations have been also done also in two steps: the first is for the unit cell and the second is for the one-layered structure.



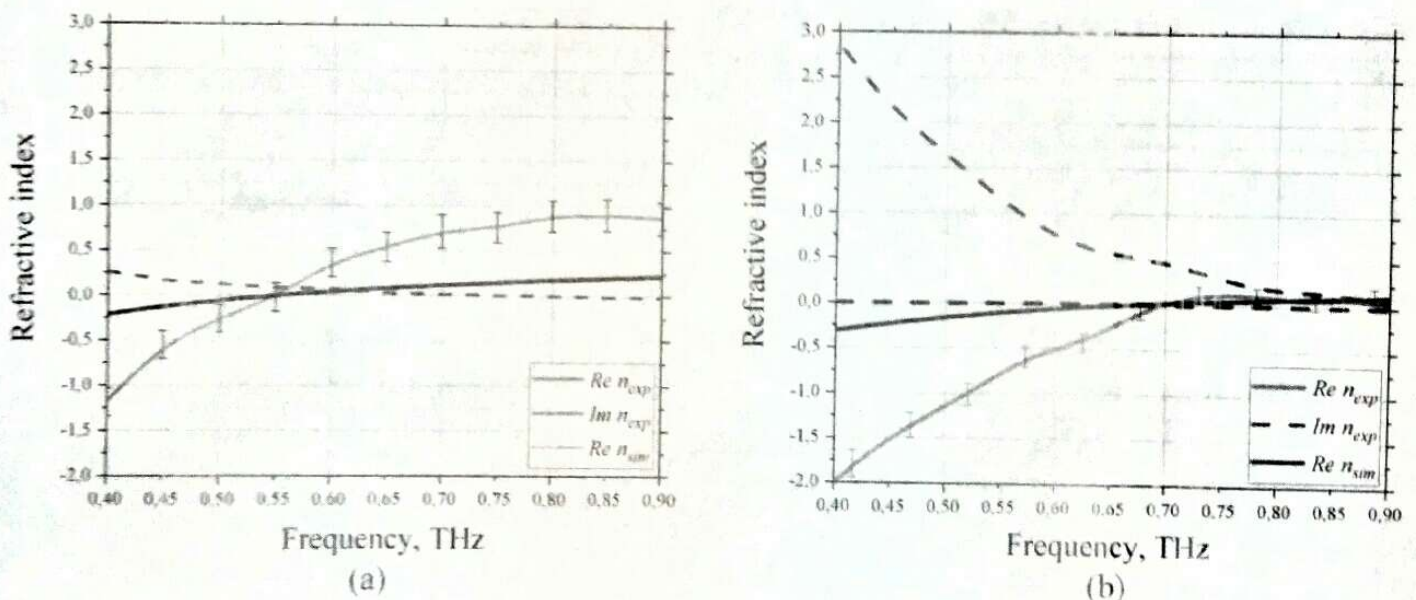
**Fig. 1.** The investigated structure: dielectric PET (Polyethylene terephthalate) substrate and parallel aluminum stripes. Results of numerical simulations of the striped metamaterial ( $a$  is the lattice constant,  $l$  is the width of the stripe). 'Electric' plasma frequency for  $l = 20 \mu\text{m}$  is 0,641 THz and for  $l = 30 \mu\text{m}$  is 0,562 THz.

The material was made by laser ablation method using LaserGraver LG2500 SP47. Two samples were used for the experiment: ones with  $l = 20 \mu\text{m}$   $a = 40 \mu\text{m}$  and  $l = 30 \mu\text{m}$   $a = 60 \mu\text{m}$ . Examined samples were measured using time-domain terahertz spectroscopy in 0,1-1 THz frequency range in transmission mode.



**Fig. 2.** Experimental THz TDS setup<sup>9</sup> in transmission mode (FL-1 – femtosecond laser based on potassium-yttrium tungstate crystal activated with ytterbium (Yb: KYW), generating femtosecond pulses; F1,2 – teflon filters for IR wavelength range cutting off, BS – beamsplitter, DL – optical delay line, M1,2,3 – mirrors, Sam – investigated sample, Wol. – Wollaston prism, CdTe – electro-optical cadmium-telluric crystal, BD – balanced detector, LA – lock-in amplifier, PC – personal computer, GTP – Glan-Taylor prism, PM1,2 – parabolic mirrors, Ch – chopper, DAC – digital to analog converter, ADC – analog to digital converter)

The experiment has showed that samples have the dispersion of refractive index according to Drude model (Figure 8). In a little area near plasma frequencies samples behave as ENZ-material. It should be mentioned that below plasma frequencies medium shows left-handed properties in materials previously designed<sup>10,11</sup>.



**Fig. 3.** Experimental (blue) and calculated (cyan) effective permittivity and permeability of two striped metamaterial samples. (a) is the data on s sample with  $l = 20 \mu\text{m}$   $a = 40 \mu\text{m}$  and (b) is the data on sample with  $l = 30 \mu\text{m}$   $a = 60 \mu\text{m}$ . Plasma frequencies are approximately 0,556 THz for (a) and 0,648 THz for (b).

**Conclusion.** This research has demonstrated the possibility of designing ZI-materials for terahertz frequency range using one-layered copper wire or aluminum stripe lattices. Copper-wired medium can be manufactured using electrochemical etching or electron-beam lithography. Aluminum-striped material has been made from metallized PET substrate using laser ablation. ENZ properties of metal-striped materials have been showed using numerical simulation and verified experimentally. Two


striped-material samples have effective plasma frequency in terahertz frequency range and left-handed properties below the plasma frequency.

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« 07 » марта 2019

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