Epsilon-Near-Zero metal-dielectric composite for terahertz frequency range

E A Litvinov, A V Vozianova and M K Khodzitsky
Terahertz Biomedicine Laboratory, *ITMO University*, 3b, Kadetskaya line VO, Saint-Petersburg 199034, Russia
E-mail: litviegor@yandex.ru

**Abstract.** Recent demonstrations of the specific class of materials such as Epsilon-Near-Zero - materials (ENZ) cause a big interest because of their potential application for manipulation and control of the propagation of the radiation on subwavelength level. The latest experiments on these materials were realized in microwave, far-infrared and visible spectral range, but there were not any demonstrations in terahertz frequency range. In this paper, we present the research of ENZ wired metal-dielectric composites with effective permittivity ranging from 0 to 1 that was designed for application as a phase compensator in terahertz frequency range. Numerical simulation of the composites was calculated by the Finite-difference time-domain method (FDTD).

**Introduction**

Current success in studies and development of optical metamaterials attracts special attention of the research community considering their unique properties that are not occurred in ordinary materials. Metamaterials are extremely attractive in the view of photonics. Specific effects, that are predicted in optical metamaterials permit to create not only new devices and gadgets, but to replace old ones. In particular, it is supposed to use metamaterials to manufacture both effective and exotic optical elements. One engaging type of optical metamaterials is ENZ-material («Epsilon-Near-Zero»). ENZ is the artificial material with extremely low value of the dielectric permittivity, which was studied in microwave spectral range, where ENZ properties have been predicted theoretically [1–3] and demonstrated experimentally [4–8]. ENZ materials correspond with phenomena like squeezing electromagnetic energy [3], supercoupling [9] and tunneling [2]. It can be used to obtain the images with high resolution in visible and near-infrared spectra, control of heat radiation with the purpose to avoid thermal losses or increase the efficiency of thermophotovoltaic conversion (TRV) [10]. Such new artificial media may find application in waveform shaping [1,13], obtaining tunnel effect [2], the control of spontaneous emission enhancement and superradiance [14]. This kind of metamaterial allows constructing some outstanding devices. Indeed, ENZ-media could be used for designing materials with high transmission or high reflection [11,12]. Devices based on ENZ give the opportunity to create materials that can change their properties from dielectric to metallic with the slight alteration of material parameters [15]. It was shown that ENZ can be applied in dielectric sensors [16], nanocircuits [17], Fourier transform [18] and beamspliding [19]. It was suggested to use ENZ for creating EO-modulators, nanoresonators [20] and beam splitters [21].
In recent years, terahertz (THz) technology has made great advance in the fields of biological samples analysis, THz image, high-speed wireless communication and so on. To the further development of THz technology, there is also a high demand for the tunable functional devices [22-25]. In this work we present and analyse the metal wires-dielectric composites with the effective dielectric permittivity ranged from -1 to 1 for THz frequency range.

Theory

The development of the metal-dielectric composite media was made using the effective medium theory (EMT). This theory is simple mathematically and represents us the method which allows getting the information about effective properties of the metal-dielectric composites quickly [26]. There are two approximations in EMT:

- a composite of metallic and dielectric inclusions is the homogeneous medium, which can be described from the terms of self-consistency;
- either metallic or dielectric inclusions have the same form.

In theory, composite has to be structure with period $d$ and definite dispersion of dielectric permittivity in the frequency range 0.1-1 THz. In this work the plastic VisiJet M3 with $\varepsilon_b = 2.76$ is used for basis of the structure. With the approximation in EMT the composite based on material with permittivity $\varepsilon_b$ with metal inclusions (wires) the dispersion can be calculated by (1):

$$
\varepsilon_{\text{eff}} = \varepsilon_b - \frac{\omega_p^2}{\omega(\omega + i\gamma)},
$$

where $\omega_p = \frac{2\pi c^2}{d^2 \ln \frac{2d}{d_a}}$ is the plasma frequency, $\gamma = \frac{4\varepsilon_0 d^2 \omega_p^2}{\pi d_a^3 \sigma}$, $\sigma$ is the conductivity of metal inclusions, $d_a$ is diameter of wires in the structure, $c$ is the speed of light in vacuum.

**Figure 1.** The geometry of simulated wired metal-dielectric structure. It is composed of unit cells with cylindrical copper wires with diameter $d_a = 300 \, \mu m$. 
It was necessary to change the concentration of the metal cylinders with the same diameter \( d_a \) in different samples in order to make the composites with different effective permittivity based on plastic-photopolymer VisiJet M3. Hence, it was necessary to change the period of structure \( d \) (figure 1) which has the limit of manufacturing for 3D printing (30 \( \mu m \)).

**Numerical Simulation**

Simulations of the composite were calculated by the Finite-difference time-domain method (FDTD) using CST Microwave Studio. It was demanded that the electrical field of the incident wave was codirected with the orientation of wires in order to show anisotropic properties of the composite.

![Image](image.png)

**Figure 2.** Pulses with bipolar profile through the air layer (black dotted line) and the composite with the period of unit cell 450 \( \mu m \) (blue line).

It was needed to obtain negative phase delay which provides designed material to work as phase compensator. The phase delay is meant as the ‘air’ pulse (propagated through the air) shifts relative to ‘composite’ pulse (propagated through the composite).

| Dimension of the unit cell \( d (\mu m) \) | Phase Delay \( (ps) \) |
|-------------------------------------------|---------------------|
| 650                                       | -1.203              |
| 600                                       | -1.480              |
| 550                                       | -1.621              |
| 500                                       | -1.764              |
| 450                                       | -1.768              |
| 400                                       | -1.875              |
Several simulations with changing period of structure (table 1) were made both for one-layered composite and the same volume filled with the air. The phase delay was calculated using this data (table 1) by equation (2):

$$\delta t = \frac{d}{c} (n - 1),$$

where $n$ - the effective refractive index of a composite, $c$ – speed of light. Dispersion curves show exactly the borders of material working as ENZ with regard to various dimensions of the unit cell. The period of structure less than 400 μm was not considered due to closeness of technological limits.

![Figure 3](image.png)

**Figure 3.** Demonstration of ENZ-composite characteristics. Curves (a) show the dispersion of dielectric permittivity and dotted lines show the approximate borders of ENZ material. Presented results of numerical simulations (b) describe how one layer of composite can give the phase delay by decreasing the period of structure.

According to computations and simulations, phase delay of the ENZ-composite can be increased by simply reducing the period of structure.

**Conclusions**

In this work the calculation and numerical simulation of the ENZ metal-dielectric wired composite in terahertz frequency range were demonstrated. Simulations show the negative phase delay for each simulated sample with different periods of structure. It has been shown that the delay can be increased by simply decreasing the period of structure, but the limits of manufacturing must be taken into account. Experimental demonstration of this terahertz Epsilon-Near-Zero metamaterial is expected in the near future.

**References**

[1] Alù A, Silveirinha M G, Salandrino A and Engheta N 2007 *Phys. Rev. B* 75 155410
[2] Silveirinha M G and Engheta N 2006 *Phys. Rev. Lett.* 97 157403
[3] Alù A and Engheta N 2008 *Phys. Rev. B* 78 035440
[4] Engheta N and Polman A 2013 *Nature Photonics* 7 907–12
[5] Vesseur E J R, Coenen T, Caglayan H, Engheta N and Polman A 2013 *Phys. Rev. Lett.* 110 013902
[6] Adams D C, Inampudi S, Ribaudo T, Slocum D, Vangala S, Kuhta N A, Goodhue W D, Podolskiy V A and Wasserman D 2011 Phys. Rev. Lett. 107 133901
[7] Edwards B, Alù A, Silveirinha M G and Engheta N 2009 Journal of Applied Physics 105 044905
[8] Khodzitsky M K, Kharchenko A A, Strashevskiy A V, Tarapov S I 2009 Telecommunications and Radio Engineering 68(7) 561-566
[9] Silveirinha M G and Engheta N 2007 Phys Rev B 76 245109
[10] Dyachenko P N, Molesky S, Petrov A Y, Störmer M, Krekeler T, Lang S, Ritter M, Jacob Z and Eich M 2016 Nature Communications 7 11809
[11] Xu Y and Chen H 2011 Appl. Phys. Lett. 98 113501
[12] Luo J, Xu P, Chen H, Hou B, Gao L and Lai Y 2012 Appl. Phys. Lett. 100 221903
[13] Luo J, Xu P and Gao L 2012 J. Opt. Soc. Am. B 29 35–39
[14] Alù A and Engheta N 2009 Phys. Rev. Lett. 103 043902
[15] Kaipurath R M, Pietrzyk M, Caspani L, Roger T, Clerici M, Rizza C, Ciattoni A, Di Falco A and Faccio D 2016 Scientific Reports 6
[16] Alù A and Engheta N 2008 Phys Rev B 78 045102
[17] Engheta N 2007 Science 317 pp 1698–1702
[18] Navarro-Cia M, Beruete M, Sorolla M and Engheta N 2012 Phys. Rev. B 86 165130
[19] Torres V, Pacheco-Peña V, Rodriguez-Ulibarri P, Navarro-Cia M, Beruete M, Sorolla M and Engheta N 2013 Opt. Express 21 9156–9166
[20] Yao J, Yang X, Yin X, Bartal G and Zhang X 2011 Proceedings of the National Academy of Sciences 108 11327–31
[21] Gurvitz E A, Vozianova A V, Khodzitsky M K 2014 Journal of Physics: Conference Series 541(1) 012067
[22] Denisultanov A Kh, Khodzitsky M K 2013 Proceedings of SPIE - The International Society for Optical Engineering 8806 880621
[23] Girich A, Khodzitsky M, Nedukh S, Tarapov S 2011 NATO Science for Peace and Security Series B: Physics and Biophysics 159-164
[24] Tarapov S I, Khodzitsky M, Chernovtsev S V, Belozorov D, Merzlikin A M, Dorofeenko A V, Vinogradov A P, Inoue M, Granovsky A B 2010 Physics of the Solid State 52(7) 1427-1431
[25] Tarapov S I, Khodzitsky M, Chernovtsev S V, Belosorov D, Merzlikin A M, Vinogradov A P, Granovsky A B 2009 Solid State Phenomena 152-153 394-396
[26] Pendry J B, Holden A J, Robbins D J and Stewart W J 1998 Journal of Physics: Condensed Matter 10 4785