Tunable negative index liquid crystal metamaterial employing in-plane switching mode

R. Kowerdziej[1], M. Olifierczuk[2], J.Parka[3]

[1]Institute of Applied Physics
Military University of Technology
Kaliskiego Street 2, 00-908 Warsaw, Poland
Fax: + 48–6839262; email: rkowerdziej@wat.edu.pl
[2]Institute of Applied Physics
Military University of Technology
Kaliskiego Street 2, 00-908 Warsaw, Poland
Fax: + 48–6839262; email: molifierczuk@wat.edu.pl
[3]Institute of Applied Physics
Military University of Technology
Kaliskiego Street 2, 00-908 Warsaw, Poland
Fax: + 48–6839262; email: jparka@wat.edu.pl

Abstract

Authors analyze response of tunable liquid crystal metamaterial transducer in terahertz frequency range. Tunability of scattering parameters is achieving by In-Plane Switching (IPS) effect. Metamaterial (MTM) structure is based on Ω-shape resonators. A full-wave analysis technique based on the finite-difference time-domain method (FDTD) was performed using QuickWave 3D electromagnetic solver. Terahertz transmission properties of the metamaterial structure can be controlled by director of liquid crystal layer. Effective refractive index for operation frequency varies from negative to positive values. Novel approach to switching of metamaterial transducer by IPS mode is presented.

1. Introduction

In recent years, terahertz science and technology has been a significant focus of many scientists and researchers worldwide. However, compared to the well established neighboring infrared and microwave regions, the THz region is still in need of fundamental technological advances. The challenge to bring THz applications to fruition arises in large part because it is difficult to find naturally occurring materials that display a usable electronic response at THz frequencies [1-3].
Artificial materials, often called metamaterials (MTM), are artificial electromagnetic media whose physical properties are engineered by assembling microscopic and nanoscopic structures in unusual combinations. Metamaterials are easily fabricated for response in the microwave regime, including three dimensional (3-D) structures, owing to the relatively large unit cell size (~1 cm) and smallest required feature size (~1 mm). With modest effort metamaterials have been extended to THz frequencies [4]. Split ring resonators (SRRs)/wire arrays can be considered as a generic EM metamaterial [2,3], in which the SRR array exhibits negative permeability above the magnetic resonance frequency whereas the wire array behaves as a negative permittivity medium below the electric plasma frequency.
Authors present comprehensive numerical analysis of metamaterial transducers employing In-Plane Switching (IPS) mode. The structure is based on Ω-shape resonators inclusions embedded in LC. Reorientation of liquid crystal molecules is achieved by IPS effect. The simulation technique is described in detail and the beam is characterized. Tunability of effective refractive index was obtained. The simulations were performed using QuickWave 3D commercial electromagnetic solver.

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2. MTM structure based on IPS technology

In this section we describe properties of tunable MTM based on IPS technology. Figure 1 shows a general view of a periodic metamaterial transducer with reconfigurable index of refraction. The unit cell is stacked along the *x* and *y* directions with periodicity of 60 µm. Simulated tunable MTM structure was composed of liquid crystal layer with a thickness of 5µm, metallic patterns and quartz plates with a thickness of 10 µm. Metamaterial structure is composed of Ω strips which have back-to-back orientation. SRR's size is 30 to 40 microns and a width of metallization - 10 microns. Conductivity of metal was set as $5*10^{-7}$[S/m]. On top quartz plate's surface we have Ω-shape stirps which have opposite orientation to the bottom and are used as IPS electrodes. This solution is novel and very promising because allow us achieve strong resonance and on the other hand give us possibility to tune molecules of liquid crystal in simple way. In the IPS mode, the direction of the applied voltage is parallel to the substrate surface, which is produced from the interdigitized electrodes. In numerical simulations liquid crystal was characterized by the dielectric tensor and conductivity. LC director lies in the *x-z* plane. An incident beam with the electric field polarized along the *y* direction and magnetic field polarized along the *z* direction was assumed to illuminate the structure along *x* direction.

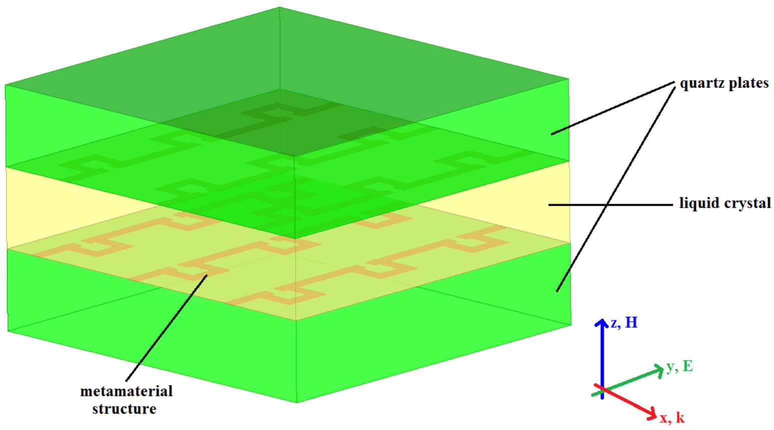

Fig. 1: 3D view of the tunable negative index metamaterial transducer employing nematic liquid crystal switching by IPS mode.

In simulation technique external field is applied to orientate the LC director from parallel x to parallel y. A permittivity tensor was used for a rigorous description of LC molecules, where $\varepsilon_e=n_e^2$ and $\varepsilon_o=n_o^2$ are the permittivities parallel and perpendicular to the molecule director, respectively. Parameters of highly birefringence nematic LC compound (1825) were set as: ε_{II} = 4,01, $\varepsilon_{\perp}$ = 2,57. Conductivities of nematic liquid crystal (1825) were set as σ_{II} = 0,384 [S/m] and $\sigma_{\perp}$ = 0,401 [S/m]. Using QuickWave software for electromagnetic design, a full wave analysis was performed to determine the scattering parameters of the structure.

3. Numerical results

Figure 2 shows the simulated frequency dependence of metamaterial on the LC reorientation. For initial case when director of LC layer is parallel to x axis, transmission is the biggest about 0.47 [THz]. When an external electrical field is applied to reorientate LC director from parallel to *x* to parallel to *z* resulting in an increase in the capacitance and a decrease in the resonant frequency to 0.42 [THz]. Importantly, such a frequency shift gives the possibility to tune effective parameters of metamaterial around resonance. As a consequence real and imaginary part of effective refractive index can be tune (Fig. 3).

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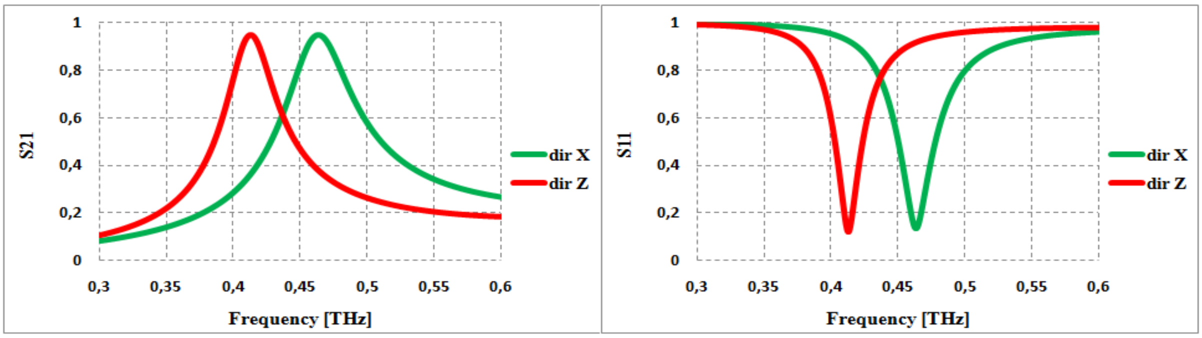

Fig. 2: Tunability of scattering parameters for x and z orientation of liquid crystals layer versus frequency.

Both real and imaginary part of effective refractive index are tunable in a wide frequency range. Numerical results show that the index of refraction for the proposed structure can be changed over the range from -4.7 to 0 for x and z alignment of LC molecules. We obtained tunability of real part of effective refractive index between 0.41 and 0.53 THz. What is more important negative values of real part of effective refractive index corresponding with low losses (n'') from 0.41 to 0.47 [THz] for z orientation of LC molecules and from 0.46 to 0.53 [THz] for x orientation, respectively. Comparing *n'* and *n''* in Fig. 4, for x and z orientations of LC over the region where $n' < 0$, one can observe a trade-off relationship between bandwidth and loss [4]. As the negative index bandwidth becomes narrower with increasing ε_{LC}, *n''* monotonically decreases over the same bandwidth.

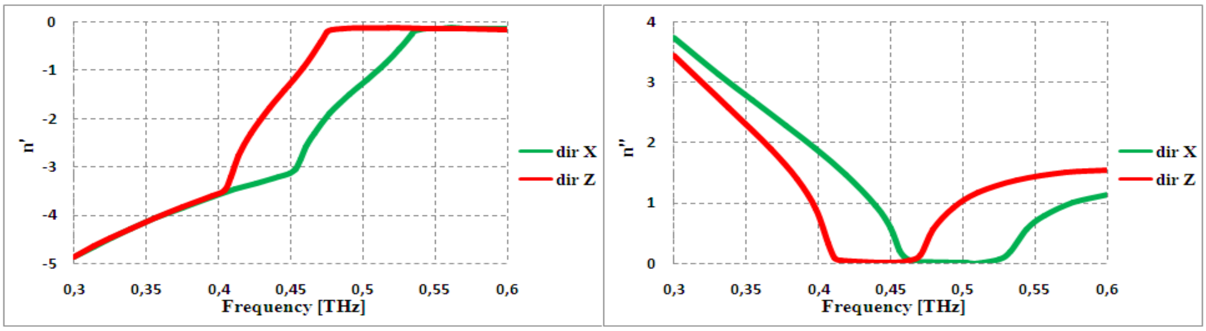

Fig. 3: Real and imaginary part of effective refractive index for x and z orientation of liquid crystals layer versus frequency.

4. Conclusions

For the first time to our knowledge, we have demonstrated metamaterial transducer with In-Plane Switching mode (IPS) for dynamically control orientation of liquid crystal at terahertz frequencies. The effective refractive index of the metamaterial structure can be readily reconfigured or tuned between negative, zero, and positive values (for higher frequencies) at a given wavelength. Tunability of presented metamaterial transducer with highly anisotropic liquid crystal is more than 9%.

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