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Original Paper

Negative Refractive Index in Nanoparticles Layer at the Visible

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Abstract

Metamaterial structure based on epoxy resin nanoparticles positioned on mica glass substrate is proposed in order to produce negative refractive index. Complex reflection and transmission coefficients (S-parameters) are computed using CST MWS, based on finite integration technique (FIT) which is equivalent to FDTD when applied to Cartesian grids in the time domain. Effective refractive index, effective permittivity and effective permeability were extracted from the simulated S-parameters by using CST MWS extraction method which is done by using template pots-processing features. The real part of the refractive index is found to be negative at wavelengths where both real parts of the permittivity and permeability are negatives without using split ring resonators and thin wires.

Keywords

Metamaterials, effective parameters, S-parameters

1. Introduction

Left handed materials or metamaterials with simultaneously negative electric permittivity and negative magnetic permeability have attracted great attention in recent years because of their unique electromagnetic behaviors which cannot be found in naturally occurring materials (Veselago, 1968; Smith, Pendry, & Wiltshire, 2004; Pendry & Smith, 2004; Shelby, Smith, & Schultz, 2001). Since the first metamaterial consisting of metallic split ring resonators (SRR) and wires was reported (Shelby, Smith, & Schultz, 2001), various investigations have been conducted both theoretically as well as experimentally to better understand such composite structures. Many techniques have been used to confirm whether or not such a proposed structure has a negative index of refraction. The effective ε and μ can be derived by averaging the electromagnetic field in a unit cell with appropriate boundary conditions (Pendry, Holden, Robbins, & Stewart, 1999; Smith, Vier, Kroll, & Schultz, 2000), while Smith et al. numerically calculated them by analyzing the scattering parameters (i.e., transmission and reflection coefficients) (Smith, Schultz, Markos, & Soukoulis, 2002). There are several diverse alternative methods to verify whether or not a structure is a metamaterial, such as Snell's law experiment (Shelby, Smith, & Schultz, 2001), flat slap imaging (Pendry, 2000), negative beam shift (Ran, Huangfu, Chen, Zhang, Chen, Grzegorczyk, & Kong, 2004), negative Goos Hanchen shift (Berman, 2002), reversal Cherenkov radiation and reversal of Doppler shift.

Metamaterial devices and design methods are continuously being imagined, simulated, designed and tested by using computational electromagnetics. The most popular methods are: finite difference time domain method, transfer matrix method, method of moments, and finite element method. CST microwave studio, ANSOFT HFSS, and COMSOL are well known as commercial software and also as electromagnetic computational tools that can present simulations in 2D and 3D. The design of MTM based on shape and geometry is the most interesting work among those used in (David Davidson, 2005; Ziolkowski, 2003).

In this paper, we investigate numerically non-metallic non-dielectric epoxy resin nanoparticles positioned on mica glass substrate as a potential candidate for optical metamaterials. Using the commercial software CST Suite Studio, the S-parameters for a unit cell are calculated and effective material parameters are extracted from S-parameters. From simulation results, the real part of the refractive index is found to be negative at wavelengths where both real parts of the permittivity and permeability are negatives.

2. Design and Simulation

The proposed MTM unit cell used in the simulation is shown in Figure 1 and Figure 2, where epoxy resin nanoparticles of 20 nm radius and permittivity $\varepsilon_r = 4$, positioned on a substrate of mica glass with effective thickness d=70 nm and permittivity $\varepsilon_r = 6.7$ at visible light wavelengths.

The structure is designed and simulated using the commercial software package CST MWS, based on the FIT method. For the simulation of the unit cell, boundary conditions of magnetic and electric walls are applied respectively according to axes x and y. The structure is excited by an electromagnetic waves with the propagation vector k in z direction. We applied magnetic fields along x-axes and electric fields along y-axes. The simulation is done in the range of frequencies 430-770 THz which covers the visible light wavelengths.

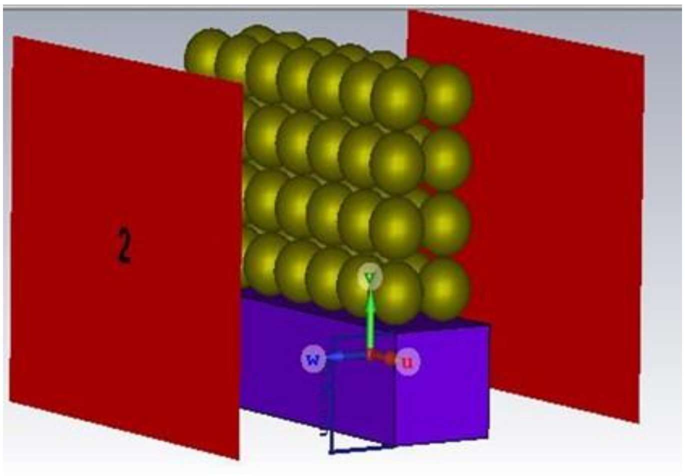

Figure 1. Full 3D Geometry of the Proposed Structure

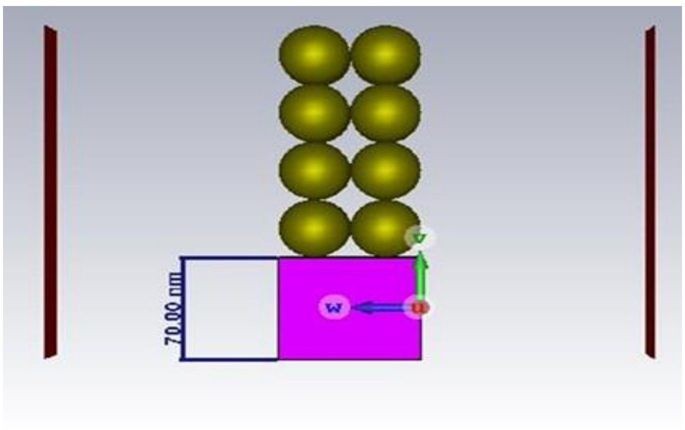

Figure 2. Side Graph of the Full 3D Geometry of the Proposed Structure

3. Results and Discussion

Scatter parameters (S-parameters) are usually use to describe the optical behavior of structures. S-parameters relate the incident light to reflected or transmitted light. The S-parameters are complex-value numbers that represent reflection and transmission coefficients. In case of metamaterials, the S-parameters are directly proportional to the electric fields. So, we simply run the simulation and look at the S-parameters as transmitted field divided by the incident field in one direction and reflected field divided by the incident field in the other direction. In Figure 3, computed results for transmission ($S_{2,1}$) and reflection ($S_{1,1}$) characteristics of the proposed metamaterial are presented. Magnitudes of ($S_{1,1}$) and ($S_{2,1}$) presented in Figure 2 show a resonant at 573.44 THz with an order of 77.376 dB and at 704.09 THz with an order of 176.96 dB. From Figure 2 we see that the refractive index has a continuous negative values in the frequency range 575.39-704.09 THz. In the proposed structure, real part of wave impedance and imaginary part of refractive index are greater than zero so that they ensure the verification of passivity for the medium as it appears in Figure 4.

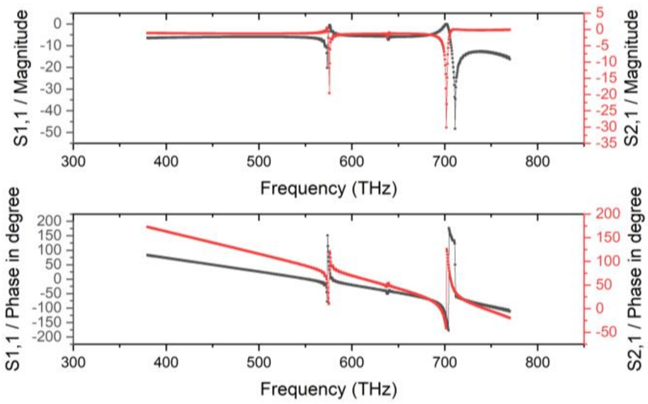

Figure 3. Single Metamaterial Structure: Magnitude Spectra of $S_{1,1}$ and $S_{2,1}$ versus Frequency, and Phase of $S_{1,1}$ versus Frequency

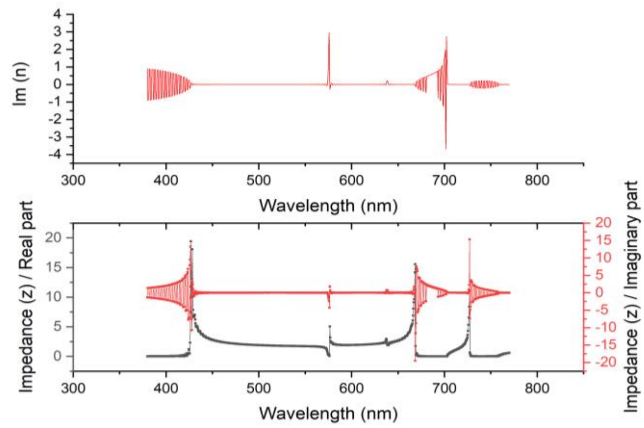

Figure 4. Single Unit Cell MTM: Imaginary Part of Refractive Index and Real and Imaginary Parts of Wave Impedance

After running the simulation and computing the S-parameters, the effective permittivity, permeability and refractive index were extracted by using the CST MWS extraction method which is done by using template pots-processing features which allows for flexible processing of 2D/3D fields, complex 1D signals, real-valued 1D signals or scalar values (0D results). The Post-Processing Templates are evaluated after every solver calculation.

Permittivity of the proposed metamaterial unit cell is resonant in real part and lies in the negative band from 380 nm to 668.57 nm (448.71 THz-789.47 THz); this permittivity agrees with Drude response. Whereas the real part of effective permeability resonates and occurs in the negative band from 424.06 nm to 702.97 nm (426.76 THz-707.44 THz), this permeability agrees with Lorentz behavior. It can be said that the wavelength regions with negative permeability and negative permittivity are relatively wide and with this realization of wide negative range of the permeability we can overcome the issue of fabricating LHMs. The negative band of the refractive index exists from 380 nm to 677.59 nm (448.71 THz-442.74 THz); it is where the permittivity and permeability are simultaneously negative. This result confirms that our MTM structure exhibits left-handed properties without using split ring resonators and thin wires. Theses parameters are presented in Figure 5.

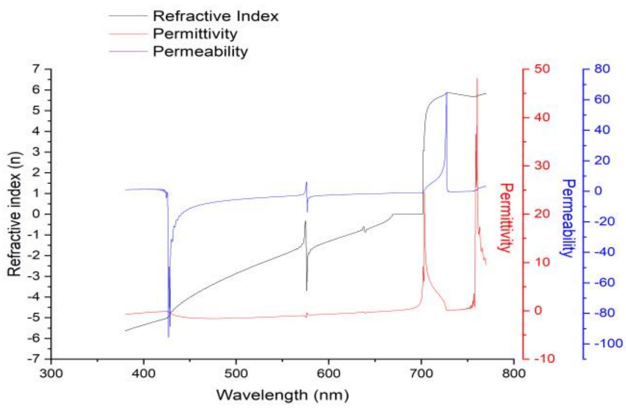

Figure 5. Single MTM Unit Cell: Real Part of the Effective Parameters along the Visible Range

4. Summary

We have studied a metamaterial structure from a unit cell of nanoparticle layer geometry of epoxy resin nanospheres and mica glass substrate. Numerical simulations were performed using CST MWS to find the S-parameters for specified nanoparticle layer geometry. From numerical simulations we used S-parameters to find the effective parameters using CST MWS extraction method. The structure shows a negative refractive index, indicating the properties of double negative material. Moreover, the results in this paper are useful for designing novel devices by utilizing the optical properties of metamaterials without using split ring resonators and thin wires.

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