Two Dimensional Polarization Independent All-dielectric Left-handed Metamaterial in Free Space

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Abstract— In this paper, we proposed a type of all-dielectric metamaterial(ADM) with quasi-continuous structure, which can inspire quasi-continuous electric and magnetic responses to acquire left-handed properties in free space. The proposed model utilizing dielectric rods and cubes as sub-wavelength inclusions. A two dimensional polarization independent left-handedness can be achieved with the frequencies at C band. The rods resonant under characteristic modes can generate negative permittivity and permeability, whereas the cubes are used in the non-resonant modes to assure the continuity of the displacement currents in dielectric inclusions. The simultaneously double negative properties can be interpreted by electric and magnetic fields distributions of the dielectric inclusions near 7.6 GHz under normal incidence with polarization angle 45°. The further study on transmission spectra and effective refractive indexes of the model with different polarization angles shows that the left-handed property is insensitive to different polarization angles due to the $\pi/2$ rotation symmetry of the ADM. The proposed ADM can be easily realized at infrared and optical frequencies with dielectric inclusions.

1. INTRODUCTION

The realization of isotropic negative refractive index in two- or three-dimensional left-handed metamaterials has attracted much attention [1–5] due to the demands of realizing perfect lens [6] and other applications. Shelby et al. [1] investigated a two-dimensional isotropic left-handed metamaterial by placing SRR/wire in a square lattice. This LHM is insensitive to incident angles, but sensitive to polarization angles. Koschny et al. [2] proposed a three-dimensional left-handed metamaterials which is insensitive to incident angles, as well as insensitive to polarization angles. However, the conducting wires using in these models should have a contact on the side-walls of the waveguide or should be continuous. These features bring about difficulties in fabricating, and limit their applications in free space. On the other hand, the Ohmic losses in metallic inclusions are increased with frequency notably at the optical frequencies, where the left-handed properties will be eliminated [7].

The similarity of the conduction currents and displacement currents indicated that dielectric structures can replace metallic patterns to realize left-handed properties. Thus, an alternative way to fabricate isotropic metamaterial is proposed by using dielectric materials with high permittivity and low loss. A number of authors proposed new types of LHMs by employing dielectric materials [8–15]. Zhao et al. [9] reported that the combination of dielectric cubes and metallic wires can produce a left-handed transmission. Peng et al. [10] reported that dielectric rods contacting side-walls of a waveguide can generate negative permittivity and negative permeability simultaneously.

In this paper, we proposed a quasi-continuous structure, which can inspire quasi-continuous electric and magnetic responses to acquire left-handed properties in free space. Numerical simulations were carried out to verify the polarization insensitivity properties of the all-dielectric left-handed metamaterial (ADM) with a normal incidence of the TE wave.

2. MODEL AND SIMULATION

The proposed model is shown in Figure 1. Figure 1(a) shows the schematic of the two-dimensional polarization-free all-dielectric left-handed metamaterial (ADM). The ADM consists of a matrix ($\varepsilon = 2.65$, $\tan\delta = 0.0015$) with composite cubes/rods regularly embedded within it to form a quasi-continuous network structure. The cubes and rods are made of BST ceramic, which has a permittivity of 110 and a loss of 0.0011. Figure 1(b) shows the unit cell of the ADM. The scale of the unit cell is 10 mm. The thickness of the ADM is 5 mm. The gap between the cube and rod is 0.25 mm. The numerical study of the ADM is carried out by a full-wave finite-element method simulator (Ansoft HFSS). Floquet ports and master-slave boundaries are employed to simulate free space.

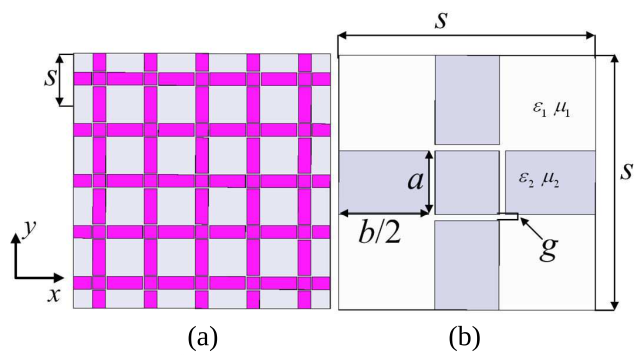

Figure 1: (a) Two-dimensional polarization-free ADM. (b) Unit cell of the 2D ADM. a is 2.5 mm, b is 7 mm, g is 0.25 mm, and S is 10 mm.

3. RESULTS AND ANALYSIS

Figure 2 shows the simulated transmission spectra and effective refractive indexes of the model subject to normal incidences with different polarization angles. The simulated transmission spectra and effective refractive indexes are stable when polarization angle changes. Note that the model has $\pi/2$ rotation symmetry; the ADM we proposed is polarization insensitive at any incident polarization angle. Figure 3(a) shows that there are three transmission peaks at 7.6, 8, and 9.5 GHz, which demonstrate three pass-bands. The investigations are focused on these three pass-bands.

The simulated scattering parameters and the retrieved effective electromagnetic parameters of the ADM are shown in Figure 3. The polarization angle of the incident TE wave is 45°. Figure 3(a) shows that there are three transmission peaks at 7.6, 8, and 9.5 GHz. Figures 3(c) and 3(d) show that negative effective permittivity and permeability are simultaneously realized at 7.6, 8, and 9.5 GHz, which demonstrate that the three pass-bands are left-handed pass-bands. The FOM (figure of merit) at 7.62 GHz is calculated to be 85.41. At this frequency, the real part of refractive index n is -3.16, with the imaginary part 0.037. The FOM at 8 GHz is 36.27, with the refractive index $n = -2.539 - 0.07i$. The FOM at 9.5 GHz is 19.23, with the refractive index $n = -1.538 - 0.08i$. The left-handed bands are in the range of 7.56∼7.76, 7.96∼8.08, and 9.46∼9.62 GHz, respectively. Both the magnetic resonance and electric resonance in these bands are Lorentz-type, which indicate Lorentz resonances. These resonances are generated by the rod-type dielectric resonators.

Figure 4 shows the electric and magnetic fields distributions for dielectric inclusions at 7.6 GHz. Figure 4(a) shows the distributions of the electric vector fields on the front side of the dielectric inclusions. Figure 4(b) shows the distributions of the electric vector fields on the back side of the dielectric inclusions. The resonant mode of the y-axis aligned rods is $\mathrm{TE}^{x}_{\delta 11}$ mode, while the resonant mode of the x-axis aligned rods is $\mathrm{TE}^{y}_{1\delta 1}$ mode. Note that the displacement current distributions for dielectric inclusions are similar to the electric field distributions. The displacement currents on the front side of the dielectric inclusions are in the same direction to the applied electric field, whereas the displacement currents on the back side of the dielectric inclusions are in the opposite direction to the applied electric field. The displacement currents in the dielectric inclusions are composed to a quasi-continuous contra-directional current pair, which can yield negative permittivity via

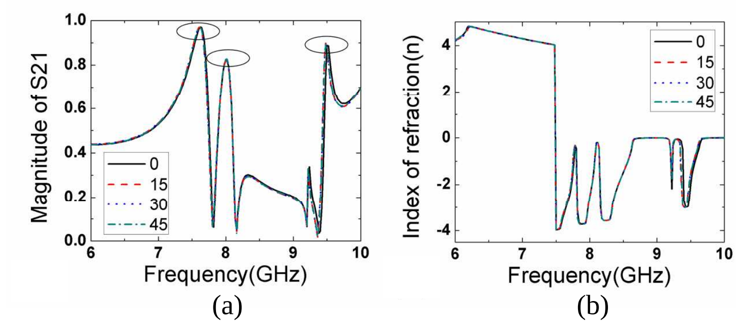

Figure 2: The simulated transmission spectra and effective refractive indexes of the model with different polarization angles. (a) Magnitude of the simulated S_{21}. (b) Real part of the retrieved refractive index.

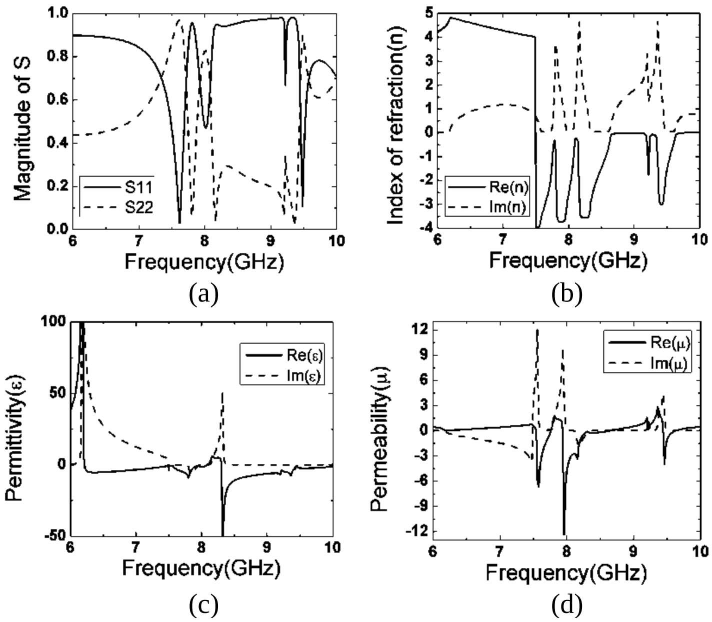

Figure 3: The simulated transmission spectra and effective parameters for the proposed model (polarization angle 45°). (a) Magnitude of the simulated S parameters. (b) Retrieved refractive index. (c) Effective permittivity. (d) Effective permeability.

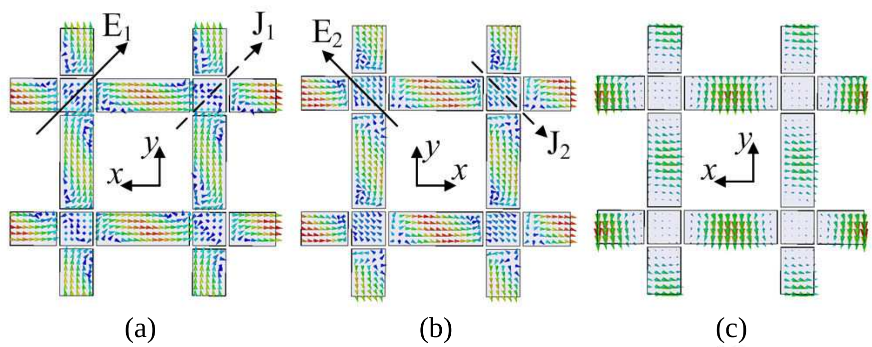

Figure 4: Electric and magnetic fields distributions of the dielectric inclusions at 7.6 GHz under normal incidence (polarization angle 45°). (a) Surface electric field distribution on the front side. (b) Surface electric field distribution on the back side. (c) Volumetric magnetic field distribution.

resonant behavior. Figure 4(c) shows the distributions of magnetic vector field of the dielectric inclusions. The combined magnetic fields, joint by the magnetic fields emerged in each rods, are equivalent to a magnetic dipole, which is oriented to the direction of the applied magnetic field. The resonant magnetic dipole can generate negative permeability. Thus, the left-handed properties can be achieved by combining a quasi-continuous contra-directional current pair and a resonant magnetic dipole.

4. CONCLUSIONS

In summary, we have proposed a method to realize 2D polarization-independent all-dielectric left-handed metamaterial in free space. The model we introduced possess $\pi/2$ rotation symmetry, which made the left-handed properties of the ADM insensitive to different polarization angles. Three left-handed pass-bands were achieved in the vicinity of 7.6, 8, and 9.5 GHz, respectively. The resonant displacement currents emerged in the high dielectric inclusions can generate negative permittivity and permeability simultaneously. The proposed ADM can be easily realized at infrared and optical frequencies with proper dielectric inclusions.

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