Organic Millimeterwave Fishnet Metamaterial Structures under Oblique incidence of Plane Electromagnetic Waves

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Abstract

A two-layer fishnet metamaterial consists of a dielectric plate cladded on both sides with a conducting fishnet structure. The use of planar organic conductive films or the fishnet structures allows to control the sheet resistance in a wide range. In this work we investigate the propagation of TE and TM waves with oblique incidence through lossy two-layer fishnet metamaterials. The frequency dependence of the refractive index is computed numerically for different values of the sheet resistance.

1 Introduction

Metamaterials are artificial materials, not occurring in nature, with inhomogeneous, usually periodic sub-wavelength structure. At microwave and millimeterwave frequency bands negative refraction index metamaterials, also called left-handed metamaterials have received considerable attention, especially for imaging, cloaking, circuit, and antenna applications [1, 2]. Planar multilayer metamaterial structures allow cost-effective fabrication [3]. A special kind of planar multilayer metamaterials are the so-called fishnet metamaterials which consist of two or more metallic fishnet grids spaced by an insulating layers [4]. Fishnet metamaterials can be fabricated cost-effectively on the basis of printing technologies. Fishnet metamaterials with cell sizes in the order of a few millimeters exhibiting a negative refractive index at microwave frequencies were presented in [5]. Fishnet structures exhibit negative refractive index for waves incident within a cone with axis perpendicular to the fishnet planes. An analytic theory of the wave propagation through fishnet materials was presented in [6], and an equivalent circuit model was given in [7]. Wave propagation in perfectly conducting fishnet structures was analyzed for toblique incidence and TE and TM polarization [8, 9].

It has been shown in literature that the negative refractive index bandwidth increases for lossy metamaterials [10]. In [11, 12] we investigated left-handed organic fishnet metamaterial structures based on films with carbon nanotube pigments. The use of planar organic conductive films allows to control the sheet resistance in a wide range. In this work we investigate the propagation of TE and TM waves with oblique incidence in lossy two-layer fishnet metamaterials.

2 The Fishnet Metamaterial Structure

Figure 1a shows a 2D-fishnet metamaterial consisting of two fishnet layers separated by a dielectric plate. An electromagnetic plane wave with wave vector $\mathbf{k}$ is incident under an angle θ. Normally incident plane waves are TEM waves. For plane waves with oblique incidence the polarization of the plane wave may either be transverse electric (TE) or transverse magnetic (TM). Waves with other polarizations can be understood as superposition of TE and TM waves. Figure 1b shows an elementary 2D-fishnet metamaterial cell. We have modeled 2D-fishnet metamaterial structures with the dimensions $a = 3.8$ mm, $b = 1.8$ mm, $p = 1.1$ mm. As the dielectric substrate we have assumed glass with a refractive index $n = 5.1$.

Each fishnet can be considered as a mesh of inductors. Vertically the fishnet layers are capacitively coupled. For a wave incident in direction normal to the fishnet planes the inductors are in transversal direction and the capacitors are in normal direction. Therefore a normally incident wave sees a negative refractive index metamaterial.

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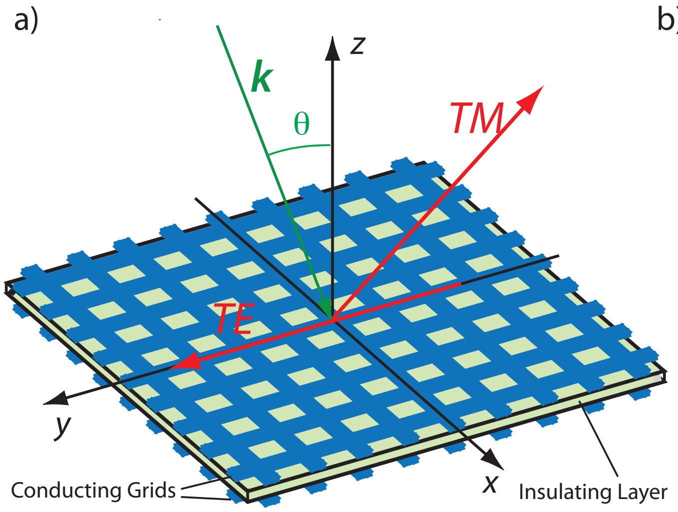

Figure 1: Fishnet metamaterial structure: a) 2D-fishnet metamaterial with two fishnet layers separated by a dielectric plate, b) elementary fishnet cell.

3 Modeling of Organic Fishnet Structures

The modeling of the fishnet plane wave structures has been performed using HFSS using the Floquet port feature [?]. This feature allows to use so-called Floquet modes, i.e. plane waves with propagation direction set by the frequency, phasing and geometry of the periodic structure to be investigated. By this way, the computational effort can be reduced considerably since only a single metamaterial cell as depicted in Fig. 1 needs to be modeled.

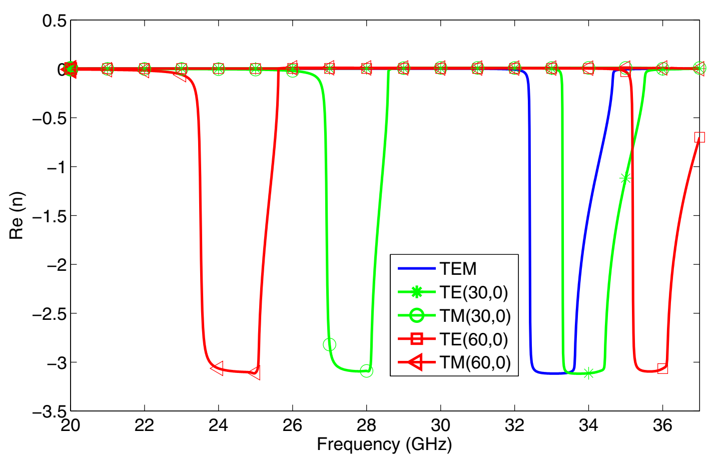

Figure 2: Real part of the refractive index n for perfectly conducting fishnet for normally incident TEM waves, and for TE and TM waves with variable angle of incidence $\theta = 30°$ and $\theta = 60°$.

Figures 2- 5 show the real part of the refractive index n for fishnet metamaterials for normally incident TEM waves and for the TE and TM cases of plane waves with oblique incidence. Figures 2 shows the parameters for perfectly conducting fishnet structures, whereas Figures 3, 4, and 5 show the cases of fishnet films with surface impedances of 3Ω, 30Ω, and 300Ω, respectivelyy

The curve show negative refractive index bands with width in the order of 5 GHz. The position of the

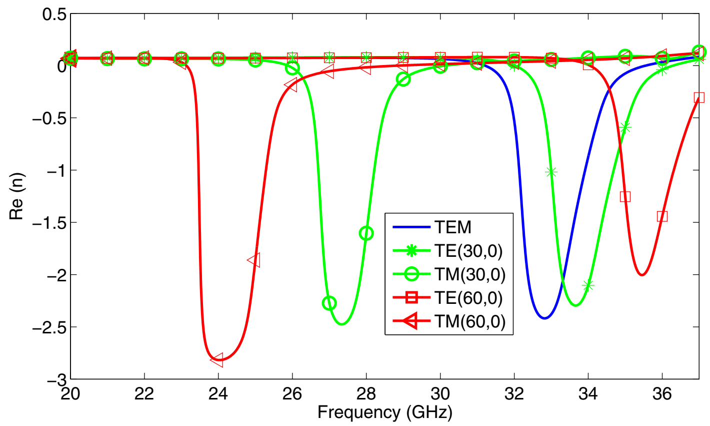

Figure 3: Real part of the refractive index n for fishnet made from 3 Ω surface impedance CNT films for normally incident TEM waves, and for TE and TM waves with variable angle of incidence $\theta = 30°$ and $\theta = 60°$.

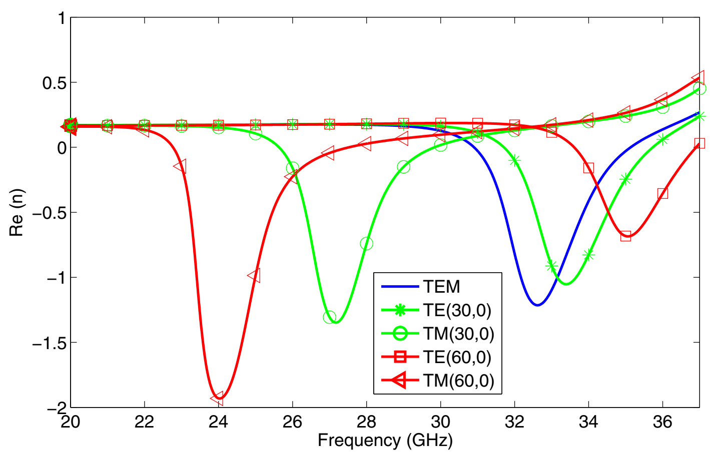

Figure 4: Real part of the refractive index n for fishnet made from 30 Ω surface impedance CNT films for normally incident TEM waves, and for TE and TM waves with variable angle of incidence $\theta = 30°$ and $\theta = 60°$.

negative refractive index band s shift with increasing angle of incidentce in the TE case to higher feequencies and in the TM case to lower frequencies. The magnitude of the negative resistance bands decrease with increasing surface resistance of the mesh films.

4 Conclusion

In this work we have investigated the propagation of planar electromagnetic waves through lossy two-layer fishnet metamaterials. We have considered normal as wells oblique incidence. For oblique incidence we have distinguished the TE and TM cases.

The frequency dependence of the real part of the refractive index show negative refractive index bands with widths in the order of 5 GHz. The position of the negative refractive index band s shift with increasing angle of incidentce in the TE case to higher feequencies and in the TM case to lower frequencies. The

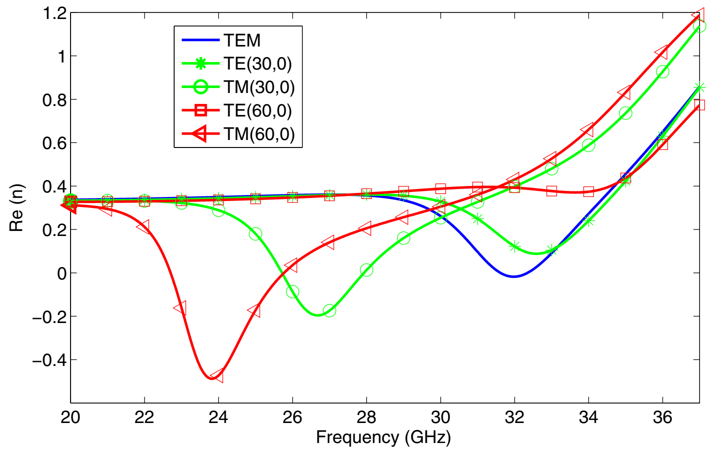

Figure 5: Real part of the refractive index n for fishnet made from 300 Ω surface impedance CNT films for normally incident TEM waves, and for TE and TM waves with variable angle of incidence $\theta = 30°$ and $\theta = 60°$.

magnitude of the negative resistance bands decrease with increasing surface resistance of the mesh films. In the TM case the magnitude of the negative refraction index increases with increasing angle of incidence whereas in the TE case the magnitude of the negative refraction index decreases with increasing angle of incidence. For the fishnet material with the highest considered surface resistance of 300Ω negative refractive index occurs only for oblique wave incidence and only in the TM case.

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