ELECTROMAGNETIC RESPONSE OF A STRUCTURED DRUDE MATERIAL; A NUMERICAL STUDY

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Abstract *In this work we have numerically investigated the electromagnetic response of a 2-dimensional nanostructured material with a Drude dispersive dielectric constant. The system consists in a square lattice of rings with a small positive dielectric constant realized in a material with negative permittivity. For certain frequencies of the exciting electromagnetic field, the nanostructured system presents a resonance which leads to a Lorentz type response. By performing finite difference time domain (FDTD) simulations and S-parameter calculations we have calculated the effective permittivity and permeability for this system.*

1. INTRODUCTION

Metamaterials are periodic systems of electric and magnetic resonant scatterers with size scales much smaller then the wavelength of the probing electromagnetic fields [1, 2, 3]. The interplay between the resonant properties of the scatterers allows the emergence of novel electromagnetic properties without counterpart in nature like, for instance, negative permeability or negative refractive index.

While the most investigated scatterer giving a strong magnetic response is the split ring resonator (SRR), other routes for obtaining metamaterials with artificially controlled properties. Among them one can mention the Mie resonances appearing in scatterers with high electric permittivity [4, 5], transmission line systems[6], plasmonic systems [7] and complementary split ring resonators (CSSR), the complementary screen of the SRR configuration [8]. The latter system investigated in the context of metasurfaces [9, 10] has been also proposed as a possibility for realizing an epsilon near zero (ENZ) metamaterial with applications in waveguiding and tunneling [11].

In this work a complementary metamaterial has been numerically investigated utilizing a combination of FDTD computations and the S-parameter retrieval formalism. The metamaterial consists in a square array of air filled infinitely long rings configured in a material with its bulk permittivity described by a Drude–like behavior. We have numerically shown that for wavelengths larger than the wavelength corresponding to the plasma frequency, where the bulk material does not allow propagating modes, the structured system developes resonating modes which lead to an effective positive dielectric constant.

2. NUMERICAL ANALYSIS

The schematic diagram of the investigated metamaterial is shown in Fig. 1. The bulk material in which the air filled rings are configured, posses a plasma frequency of 8×10^{11} rad/s corresponding to a wavelength of approximately 3mm, and the Drude scattering rate of 8×10^{9} rad/s. A material with this controlled Drude behavior in the microwave spectral domain can be easily realized using the conducting thin wires array configuration [1]. The geometrical characteristics of the metamaterial are the following: lattice constant a=1mm, ring diameter D=0.6 mm and the thicknes of the rings w=0.1 mm.

The polarization of the incident electromagnetic field is TM such that the magnetic component is parallel to the rings.

In order to investigate the electromagnetic response of this metamaterial, the reflection – transmission power spectra have been numerically computed by FDTD method using the commercially available software OptiFDTD [13].

The results shown in Fig. 2 indicate that for wavelengths larger than 3 mm (plasma wavelength), two bands of propagating modes are present suggesting that the system presents electric resonances giving rise to a collective dielectric response described by a Lorentz – like behavior.

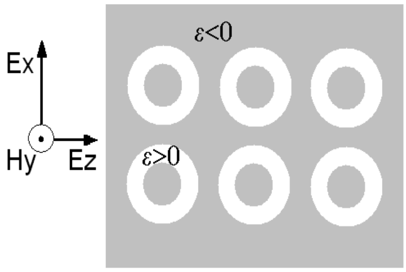

Fig. 1. A square lattice of rings with positive permittivity patterned in a material with negative permittivity. The polarization of the incident field is TM.

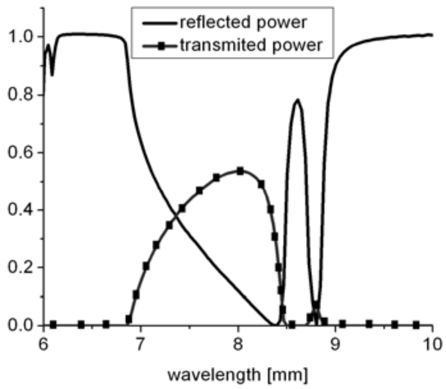

Fig. 2. The reflected (black line) and transmitted (black line with squares) power in a slab of rings patterned in a material with negative permittivity.

In order to ascertain the nature of the resonating modes developed in metamaterial the S–parameter formalism have been applied.

The simulated systems consisted in thin metamaterial slabs one unit cell thick probed with an incident Gaussian modulated electromagnetic wave, centered at the wavelength λ = 6mm with a half width of 8×10^{-11} s. The boundary conditions were perfect matching layers for the *x* lines normal to the wave propagation direction *z*, and periodic boundary conditions for the *z* lines parallel to the wave propagation direction.

For finding the effective material constants, we apply the S–parameter method [12] which relates the complex refractive index *n* and the complex surface impedance *Z* by the complex reflection coefficient *r** and complex transmission coefficient *t'** through the following expressions.

$$Z = \pm\sqrt{\frac{(1+r^*)^2 - t^{*2}}{(1-r^*)^2 - t^{*2}}}$$

$$n = \frac{1}{kd}\arccos\left(\frac{1}{2r^*}\left(1 - r^{*2} + t^{*2}\right)\right) + \frac{m\pi}{kd}$$

where $t^* = t'^*\exp(-ikd)$, *k* is the wavevector, *d* is the thickness of the slab and m is an integer corresponding to the branch point chosen for the n calculation. The permittivity ε and the permeability μ are related to *n* and *Z* through the following standard formulas: $\mu = nZ$ and $\varepsilon = n/Z$.

The results are shown in Fig. 3 – Fig. 6. In Fig. 3 the complex refractive index is shown. One can see that in the range of wavelengths 7-9 mm the real part of the refractive index is positive varying monotonically from n=3.5 at the wavelength of 7 mm to almost zero at 8.8 mm. The imaginary part of the refractive index is practically zero in this wavelength interval showing that the metamaterial is transparent.

The complex surface impedance Z is shown in Fig. 4. It is noteworthy that in the transparency the imaginary part of Z is also zero, while the real part increases from zero at λ=7mm to 3.5 at λ=8.5 mm. The ratio between the wavelength and the lattice constant ranges between 7 and 9 showing that in this case the approximation of effective medium is valid such that the electric permittivity and magnetic permeability are meaningful quantities.

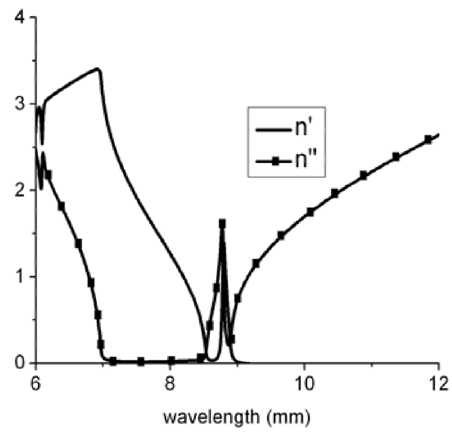

Fig. 3. The real (black line) and the imaginary (black line with squares) of the refractive index.

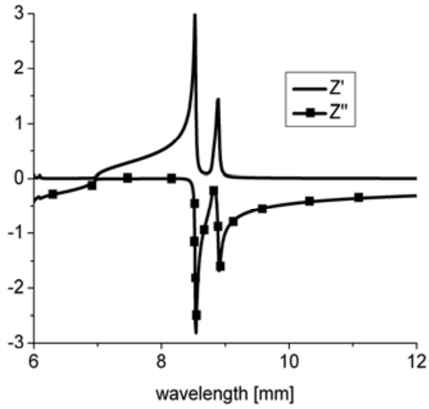

Fig. 4. The real (black line) and the imaginary (black line with squares) of the surface impedance Z.

Fig 5 depicts the complex dielectric permittivity. It can be seen that at $\lambda = 7$ mm the system presents a sharp dielectric resonance where the real and imaginary parts of the permittivity becomes very large showing in the normal dispersion region a Lorentz – like behavior. At the upper edge of the band $\lambda = 8.8$ mm, one can see another Lorentz – type resonance. In this case the real part of the permittivity is small and it crosses twice the zero axis.

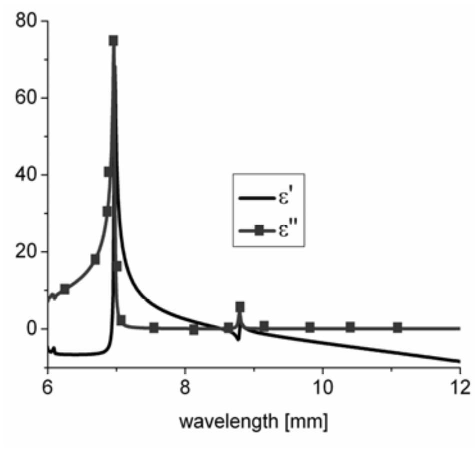

Fig. 5. The real (black line) and the imaginary (black line with squares) of the electric permittivity.

The behavior of the complex magnetic permeability shown in Fig. 6. is interesting. The real part is positive in the entire range of wavelengths increasing monotonically from zero at the 7 mm resonance to unity at the larger wavelengths where the system does not respond magnetically. The imaginary part of the permeability is negative presenting a sharp antiresonating peak at 8.8 mm and a large negative feature for wavelengths smaller than 7 mm. This behavior is a manifestation of the spatial dispersion present in periodic systems.

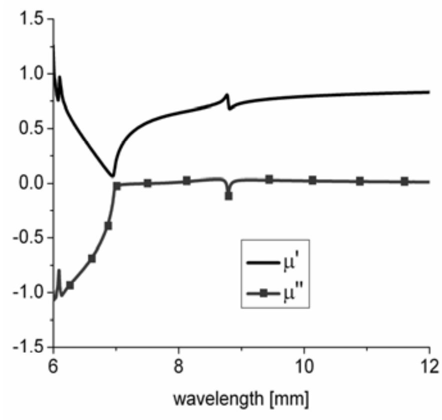

Fig. 6. The real (black line) and the imaginary (black line with squares) of the electric permeability.

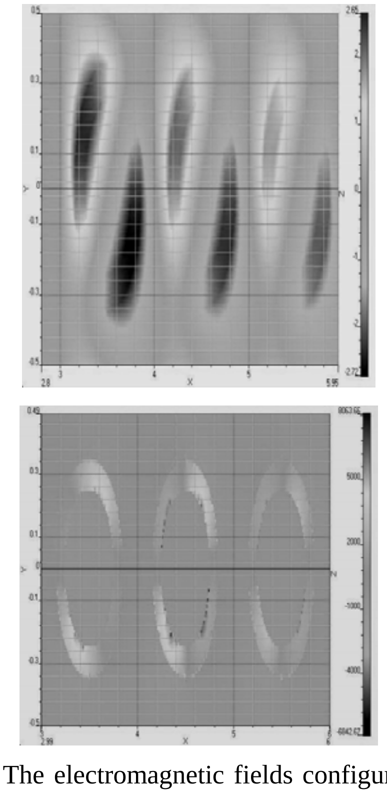

Fig. 7. The electromagnetic fields configuration in the system consisting in an array of rings patterned in a Drude material; left panel represents the magnetic field Hy, the right panel represents the electric field Ex.

Finally, we perform continuous wave FDTD simulations for a wavelength of the incident electromagnetic field located in the middle of the transparency band. The configuration of the electromagnetic fields is displayed in Fig. 7. One can see that the both magnetic Hy and electric Ex components are localized inside the unit cell. The electric component is strongly localized in the air filled rings suggesting the existence of a plasmonic mode. A theoretical description of this resonating modes is currently under investigation.

3. CONCLUSIONS

In this work we have numerically demonstrated that a structured Drude – like material develops resonating modes behaving like a Lorentz – type excitations, which lead to a transparency band where propagating modes exist even for wavelengths larger than the plasma wavelength. The metamaterial investigated in this work operates in the millimeter spectral domain. The possibility to increase the response frequency to infrared as well as the waveguiding properties of a 3-dimensional system based on this configuration is under investigation.

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