Simulation of Electromagnetic Enhancement in Transition Metamaterials using COMSOL

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Introduction

Metamaterials are a new class of artificial materials, which possess various unusual properties [1]. One of these properties is a negative index of refraction produced by setting both the dielectric permittivity ε and the magnetic permeability μ of the material (or more precisely, their real parts) less than zero [2]. Unique electromagnetic phenomena occurring at the interface between negative-index materials and conventional positive-index materials have attracted significant attention during last few years [3]-[6]. In particular, recent investigations of metamaterials with μ and ε gradually changing from positive to negative values (transition metamaterials) revealed important new features of the resonant field enhancement phenomenon that was previously studied in inhomogeneous plasmas for obliquely incident electromagnetic waves [3]. When the wave vector of the TM-polarized electromagnetic wave makes an angle with respect to the permittivity gradient, the electric field anomalously increases as ε tends to zero [7]. In plasma physics, this effect is referred to as resonant absorption. In contrast to the effect observed in plasmas, resonant field enhancement in transition metamaterials occurs for both TE and TM polarizations, and the propagating waves are allowed beyond the resonant point.

Figure 1 shows a schematic of the problem. In the case of TE-wave, the anomalous enhancement occurs for the magnetic field as μ tends to zero. This effect may have potential applications in low-intensity nonlinear optics, antennas and polarization sensitive devices.

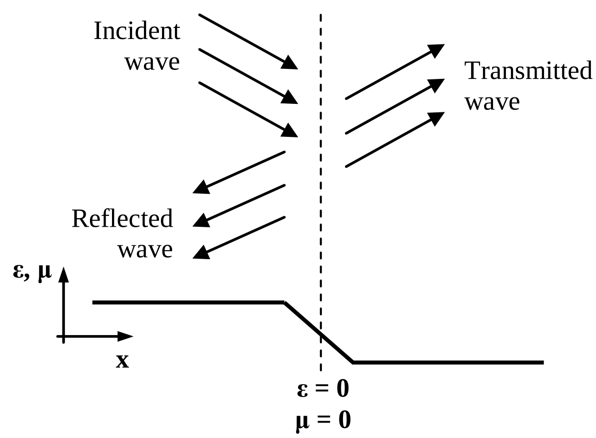


Figure 1. Schematic of the problem

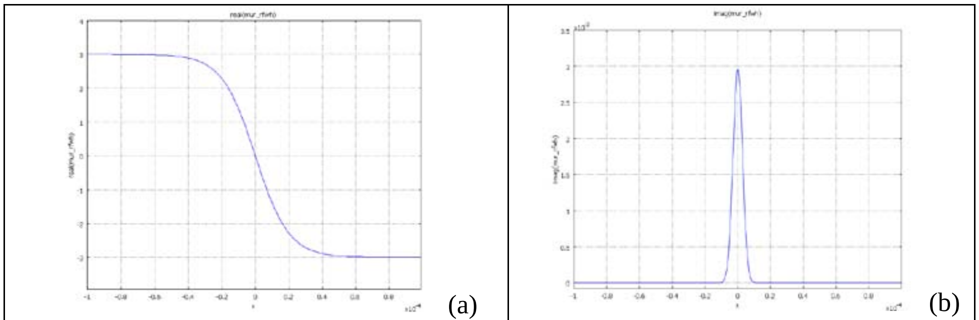
Use of COMSOL

The 2D In-Plane Waves Application Mode of the RF Module was used for simulations of transition metamaterials. We considered both TE and TM polarizations, while “Harmonic propagation” was chosen to describe propagation though the transition region. The relative dielectric permittivity and magnetic permeability were set to be complex functions of x

$$\varepsilon_r = \varepsilon_{r0}\left[-\tanh\left(\frac{x}{L}\right) + i\delta e^{-\frac{x^2}{l^2}}\right]$$

$$\mu_r = \mu_{r0}\left[-\tanh\left(\frac{x}{L}\right) + i\delta e^{-\frac{x^2}{l^2}}\right],$$

whose real parts are gradually changed from μ_{r0} and ε_{r0} to $-\mu_{r0}$ and $-\varepsilon_{r0}$. The small loss factor δ is introduced in the vicinity of the point, where the real parts approach zero, in order to avoid computation difficulties around this point. The real and imaginary parts for the magnetic permeability are shown in fig. 2.



(a) (b)

Figure 2. Real (a) and imaginary (b) parts of the magnetic permeability μ_{r0}=3, L=20µm, l=4µm

Results

Figure 3 shows the anomalous enhancement of the magnetic field in the vicinity of the zero-permeability point for the case of an obliquely incident TE wave, whose wave vector makes angle $\pi/17$ with the x-axis. The input electric field amplitude is chosen to be 1V/m, while the rest of parameters are set as shown in Fig. 2.

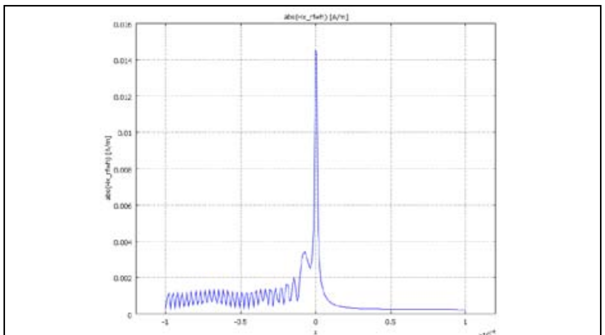


Figure 3. Absolute value of the x-component of the magnetic field as a function of x

Conclusion

Anomalous electromagnetic enhancement in transition metamaterials was demonstrated using COMSOL Multiphysics. The results obtained closely reproduce the results of numerical simulations using MATLAB for some values of input parameters. However, numerical methods currently used to solve problems of this type [3], [7], implement the Thomas Algorithm, which does not allow a straightforward description of wave propagation in inhomogeneous nanostructures plasmonic media, if considerable losses or nonlinear effects are present. At the same time, optical metamaterials are known to be significantly lossy [1]. For that reason, COMSOL may become a useful tool for performing simulations based on realistic parameters and the accurate design and optimization of new devices utilizing transition metamaterials.

This research was supported by the Army Research Office through an award# W911NF-09-1-0075.

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