Core-shell spherical particles for near-infrared isotropic negative refraction

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Abstract

In this paper we study a design solution of metamaterial composed of coated non-magnetic spheres, which possess negative refractive index in the inter-band (visible/near-infrared bound) range. The electromagnetic response of the particles was studied using an analytical theory and full-wave numerical simulations. The effect of negative refraction was confirmed by simulations of the Gaussian beam incidence on the metamaterial prism.

1. Introduction

There has been a great progress in the development of negative-index metamaterials (NIMs) in the past decade. The first NIMs operated at microwaves and consisted of thin metal wires (negative electric response) and split-ring resonators creating the resonant magnetic response [1]. The overlapping of two negative responses over the frequency axis allowed the negative refractive index. Various modifications of this design were proposed at the infrared [2, 3], though further increasing of operational frequency met technological problems. Due to further expand the range of materials with negative magnetic permeability to the visible range complicated designs were proposed which either lead to a strong anisotropy of optical properties as in [4] or to technological challenges as in [5].

We are looking towards a simple design solution for isotropic NIMs for visible or at least near-infrared range, which realization would grant the optical isotropy. The simplest isotropic geometry of particles is spherical shape. Spherical particles were proposed to obtain negative refraction previously in the literature. In [6] a NIM was performed as a photonic crystal of metal spheres operating in the visible range, and its optical properties were very anisotropic due to rather large optical sizes of constituents. An interesting approach was presented in [7], where metamaterial was made of polaritonic $LiTaO_3$ spheres covered with metallic shells. Metallic shell provided negative permittivity due to the plasmon resonance whereas the core provided negative permeability due to the magnetic Mie resonance. By tailoring the sizes these resonances were obtained in the same frequency region (within the far infrared range).

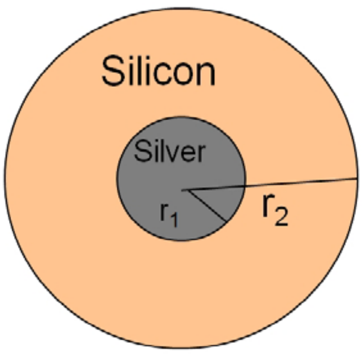

Fig. 1: A particle made of a silver core and a silicon shell

In [8] authors suggested the similar approach as in [7], however the plasmonic resonance is due to the metal core and the shell is polaritonic. The core is made of silver and the shell is made of crystalline silicon, as shown in Fig.1. This (at the 1st glance slight) modification leads to a qualitatively new result: the NIM presuma-

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bly operating in the near infrared region. In [8] authors calculated the effective material parameters using the Clausius–Mossotti formulae. However, for the composites where the particles are so densely packed and whose period is comparable with the operational wavelength Clausius–Mossotti technique is not fully reliable. Our goal is to better develop this design solution. We validate the effect of negative refraction and modify the design to shift the frequency of negative refraction closer to the visible range. We analytically calculate the electric and magnetic response of the single particle, then compare it with the results of full-wave simulations and finally numerically demonstrate the negative refraction.

2. Individual polarizabilities of a single core-shell particle and effective material parameters of the composite

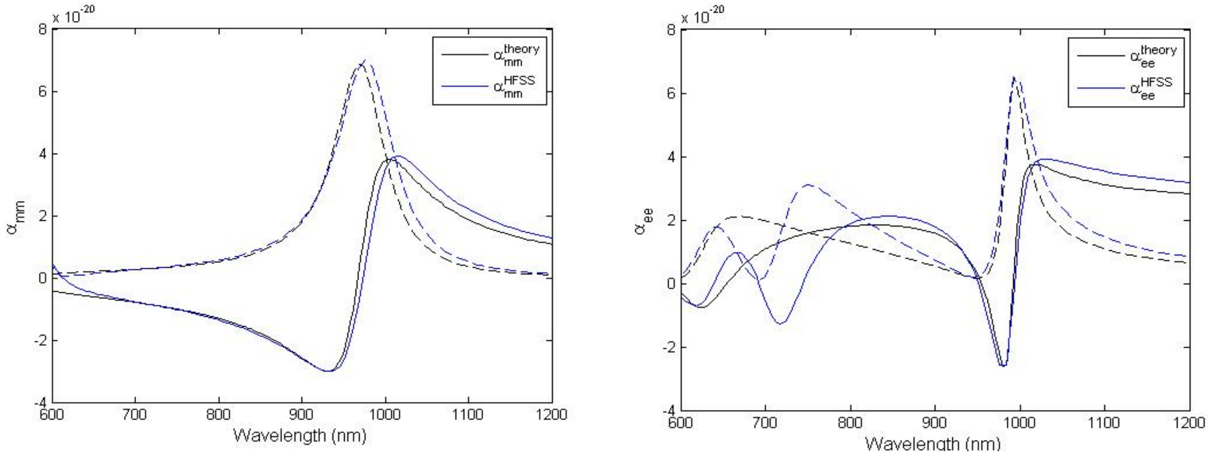

Fig. 2: (a) – dependence of the magnetic polarizability on wavelength: black – obtained from the Mie theory, blue – extracted from numerical simulations; (b) - dependence of the electric polarizability on wavelength: black – obtained from the Mie theory, blue – extracted from numerical simulations. Real and imaginary parts are shown by solid and dashed curves respectively.

Electromagnetic response of spherical particles can be analytically estimated using the Mie theory generalized for core-shell particles in work [9]. Further, we validate the analytical results extracting the individual polarizabilities of a particle from the reflection R and transmission T coefficients of the planar grid of such particles [10]. The R and T coefficients were obtained from the Ansoft HFSS full-wave simulation of a plane wave normal incidence on the planar array. Fig.2 shows the comparison of the analytical results for polarizabilities with numerical extraction data for the case r_1 = 30 nm and r_2 = 130 nm. It is clearly seen that up to approximately 850 nm wavelength two methods give very similar results. It means that for a planar array the quasi-static model is adequate until the frequency when the array period is close to one third of wavelength!

Using the individual polarizabilities of the spherical particles we calculated the effective permittivity and permeability by the Maxwell-Garnett model for a simple cubic lattice of such particles. The unit cell size in the analytically optimized structure is 270 nm, which at the combined electric-and-magnetic resonance is four times smaller than the wavelength. The Maxwell-Garnett theory gives the 50 nm-wide range of the negative refractive index. However, it is necessary to mention that quasi-static interaction model for a bulk lattice becomes inadequate at lower frequencies than for a planar array. For unit cells equal to quarter-wavelength the Maxwell Garnett theory is not accurate and the design parameters (dimensions) analytically optimized using this theory are only preliminary estimations of the needed sizes. To find parameters which reliably implement the NIM we performed numerous simulations of the refraction of a Gaussian beam on the metamaterial wedge-shaped prism (see Fig.3). At low frequencies the prism possesses a positive refractive index. Due to particles interaction the resonance is shifted and a negative refraction occurs at higher frequencies than the quasi-static model predicts. The wavelength of the negative refraction is 877 nm compared to 1350 nm obtained in [8]. The angle of negative refraction is quite low compared with that predicted by the Maxwell Garnett model for such the lattice. The dimensions leading the negative refraction are very close to those predicted by the quasi-static model, however are not exactly same.

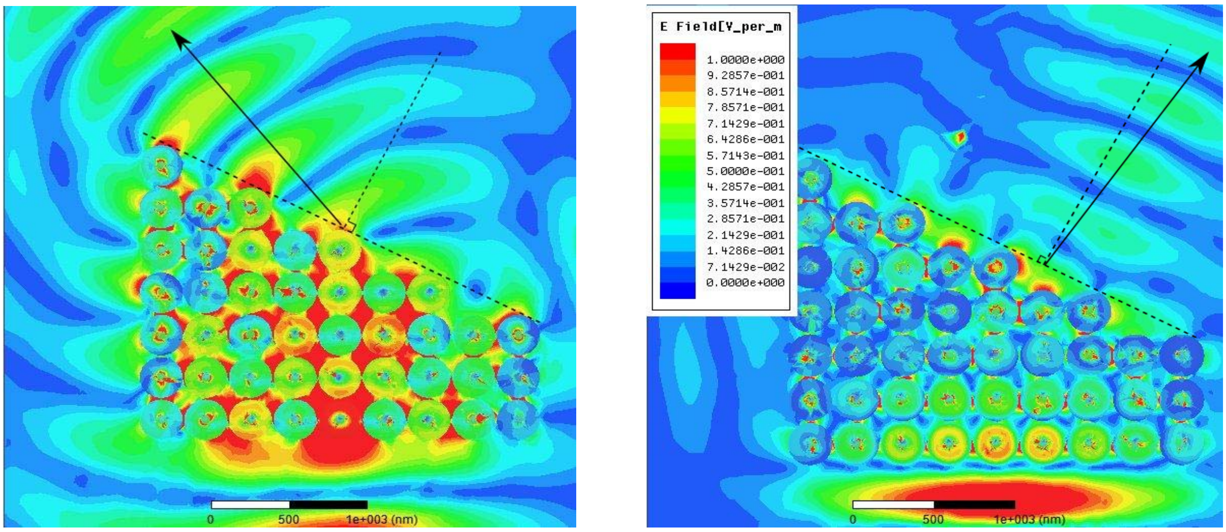

Fig. 3: Electric field distribution for the Gaussian beam excitation of the prism made of spherical core-shell particles: (a) – positive refraction at λ = 1150 nm; (b) – negative refraction at λ = 877 nm

3. Conclusion

We studied a design solution of metamaterial based on spherical particles with a silver core and a silicon shell, recently suggested in the literature. Using the Mie theory and full-wave numerical simulations we studied properties of individual particles and performed optimization of particle's dimensions to combine electric and magnetic resonances at highest possible frequency. Then, using Maxwell-Garnett model we calculated the effective material parameters of the composite and obtained the region of negative refraction in the inter-band frequency range. The results were validated by the numerical simulation of the refraction of the Gaussian beam on the metamaterial prism. Finally let us acknowledge the support of this study by the FP7 METACHEM project.

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