Optical Negative Refraction in Ferrofluids with Magnetocontrollability

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Introduction

In 1968, Veselago theoretically investigated the electrodynamic consequences of a medium with simultaneously negative permittivity and permeability. He predicted that such a medium possesses a negative (phase) index, which can result in a reversed Snell’s law, i.e., negative refraction. People have realized negative refraction of optical waves or microwaves in different systems, including metamaterials, photonic crystals, plasmonic waveguides, chiral media, and super conductor ferromagnet superlattices. The significant application of negative refraction is the concept of a superlens, which can lead to subwavelength imaging beyond the diffraction limit.

However, almost all the existing methods for achieving negative refraction were proposed or established in the realm of solid materials, in contrast to soft materials with the specific characteristic “softness”. Literally softness might offer an extra freedom of tailoring physical properties, hence, it encourages us to investigate optical refraction in certain soft materials. As a result, we reveal, for the first time, a new class of all magnetic field H, and super conductor ferromagnet superlattices. The underlying mechanism arises from assembly metallic chain or column structures induced by an external dc magnetic field H. This work paves a new way for designing tunable, active metamaterials.

Theoretical analysis

We can utilize the anisotropic form of the effective medium approximation (EMA) to calculate the effective permittivity tensor $\epsilon$.

\[ p \epsilon_1 - \frac{\epsilon_{xx,zz}}{\epsilon_{xx,zz}} + (1 - p) \epsilon_2 = 0. \]

The equivalent permittivity of the coated nanoparticle can be calculated by,

\[ \epsilon = \epsilon_0 \left( \frac{1}{p} + \frac{1}{1 - p} \right) \epsilon_{xx,zz}. \]

Shape factor along H can be approximately written as,

\[ g_z = \frac{1}{n^2} + \frac{n}{(n^2 - 1)^{3/2}} \ln \left[ n + \sqrt{n^2 - 1} \right]. \]

For the TM waves with the magnetic field component polarized in the y axis and the electric field component $\text{average Poynting vector}$, the dispersion relation for the wave propagating in a general anisotropic medium is,

\[ \frac{k_x^2}{\epsilon_{xx}} + \frac{k_z^2}{\epsilon_{zz}} = \mu_y \mu_0. \]

The x and z components of the time-averaged Poynting vector $S$ are given by,

\[ S_x = \frac{k_x}{\epsilon_{xx}} \frac{H_x^2}{\omega \epsilon_0} \quad \text{and} \quad S_z = \frac{k_z}{\epsilon_{zz}} \frac{H_z^2}{\omega \epsilon_0}. \]

The angles of refraction for the wave vector $k$ and Poynting vector $S$ are given by,

\[ \theta_{r,x} = \tan^{-1} \left( \frac{k_x}{k_z} \right) \quad \text{and} \quad \theta_{r,z} = \tan^{-1} \left( \frac{k_z}{k_x} \right). \]

The effective refractive index can be defined as,

\[ n_{\text{eff}} = \sin \theta_{r,z}/ \sin \theta_x. \]

Simulation results

Conclusions

In summary, we have demonstrated that magnetocontrollable all-angle broadband negative refraction at optical frequencies can be realized in aqueous ferrofluids, which are made of Fe$_{3}$O$_{4}$ nanoparticles coated by an Ag shell. The proposed soft optical metamaterials can offer us an extra freedom to control the properties of the materials by external electric or magnetic fields, because the structures of such soft materials can be changed by changing the external fields.

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References