Optical Negative Refraction in Ferrofluids with Magnetocontrollability

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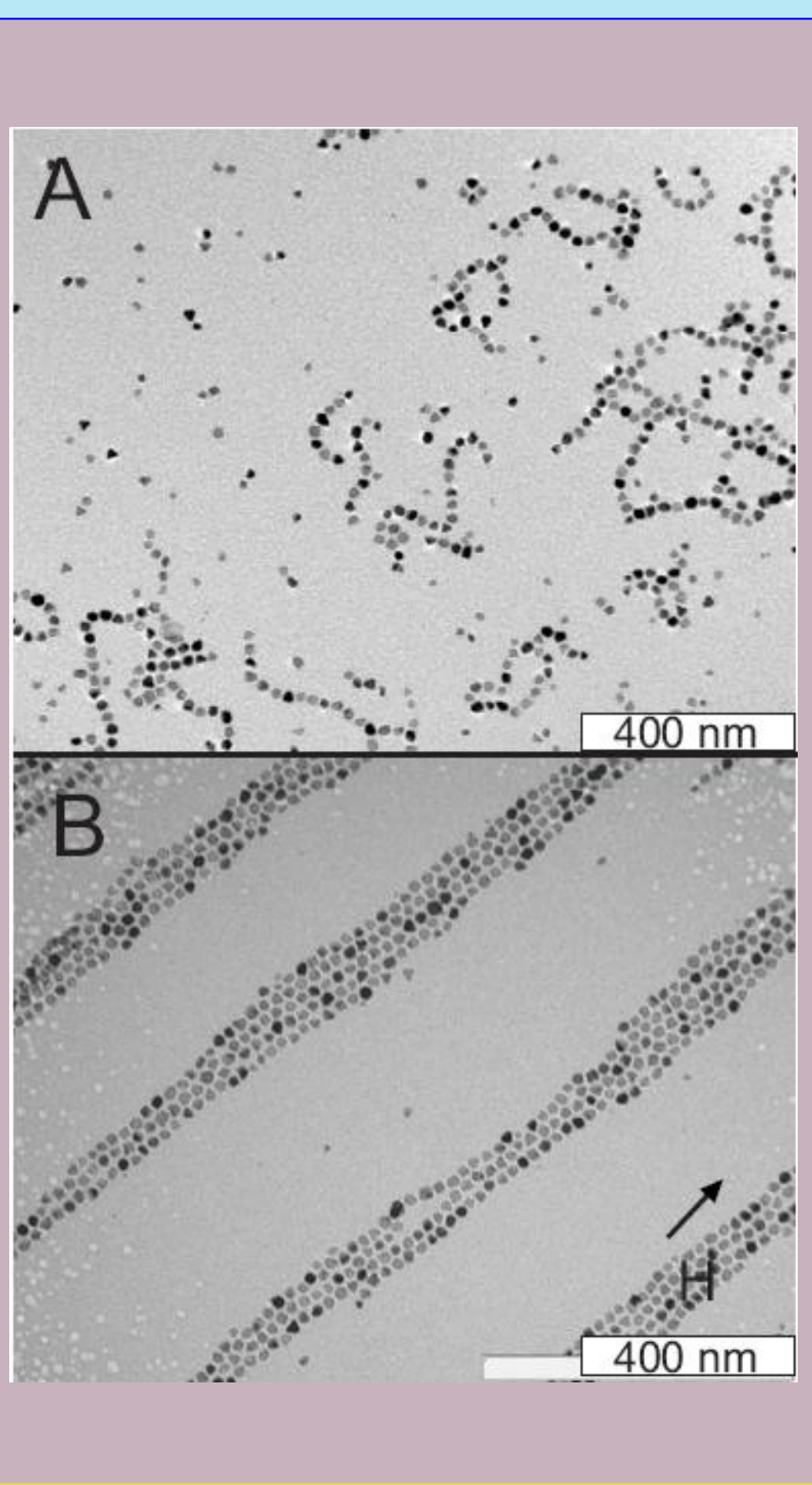
Introduction

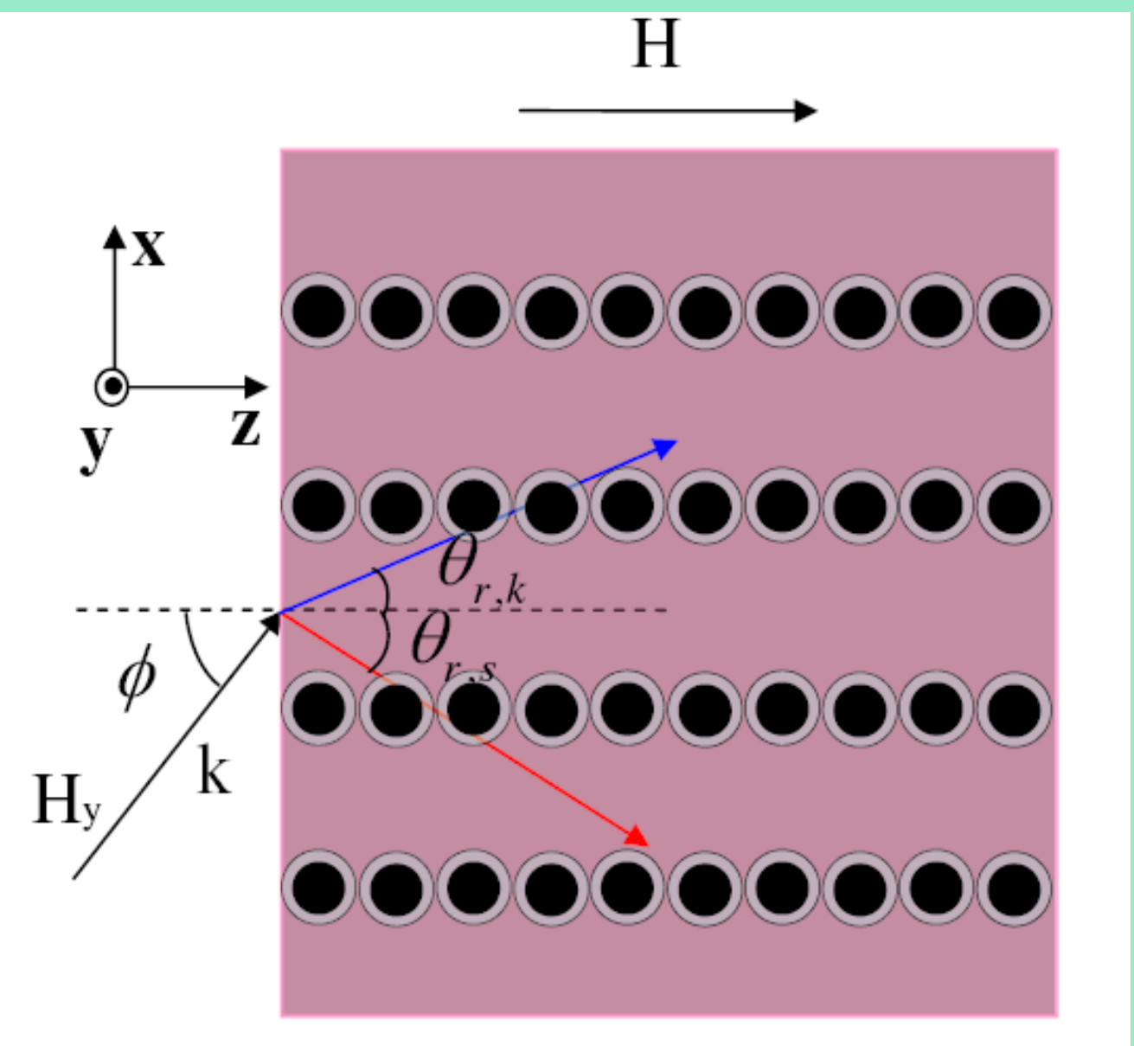
In 1968, Veselago theoretically investigated the electrodynamic consequences of a medium with simultaneously negative permittivity and permeability. He predicted that such a medium possesses a negative (phase) index, which can result in a reversed Snell's law, i.e., negative refraction. People have realized 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-angle broadband optical negative refraction in ferrofluids with magneto-controllability. Its 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.



A. TEM images of vitrified films of ferrofluids in zero field.

B. In a homogeneous magnetic field 0.2 T, a transition occurs to equal-spaced columns that exhibit hexagonal symmetry. [3]



The ferrofluids are made of Fe_3O_4 nanoparticles coated by an Ag shell dispersed in water. TM waves with the magnetic field component polarized in the y axis and the electric field component located in the xz plane.

Theoretical analysis

We can utilize the anisotropic form of the effective medium approximation (EMA) to calculate the effective permittivity tensor[1,2],

$$p\frac{\varepsilon_1-\varepsilon_{xx,zz}}{\varepsilon_1+\left(\frac{1}{g_{xx,zz}}-1\right)\varepsilon_{xx,zz}}+(1-p)\frac{\varepsilon_2-\varepsilon_{xx,zz}}{\varepsilon_2+\left(\frac{1}{g_{xx,zz}}-1\right)\varepsilon_{xx,zz}}=0\,,$$

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

$$\epsilon_1=\epsilon_a\frac{\epsilon_f(1+2\rho)+2\epsilon_a(1-\rho)}{\epsilon_f(1-\rho)+\epsilon_a(2+\rho)}\,,\qquad \rho=r^3/(r+d)^3,$$

Shape factor along H can be approximately written as,

$$g_{zz}=\frac{1}{1-n^2}+\frac{n}{(n^2-1)^{3/2}}\ln\left[n+\sqrt{n^2-1}\right]\,,$$

For the TM waves with the magnetic field component polarized in the y axis and the electric field component located in the xz plane, the dispersion relation for the wave propagating in a general anisotropic medium is,

$$\frac{k_x^2}{\varepsilon_{zz}}+\frac{k_z^2}{\varepsilon_{xx}}=\mu_{yy}k_0^2\,,$$

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

$$S_x=\frac{k_x}{\varepsilon_{zz}}\frac{H_y^2}{2\omega\varepsilon_0}\quad\text{and}\quad S_z=\frac{k_z}{\varepsilon_{xx}}\frac{H_y^2}{2\omega\varepsilon_0}.$$

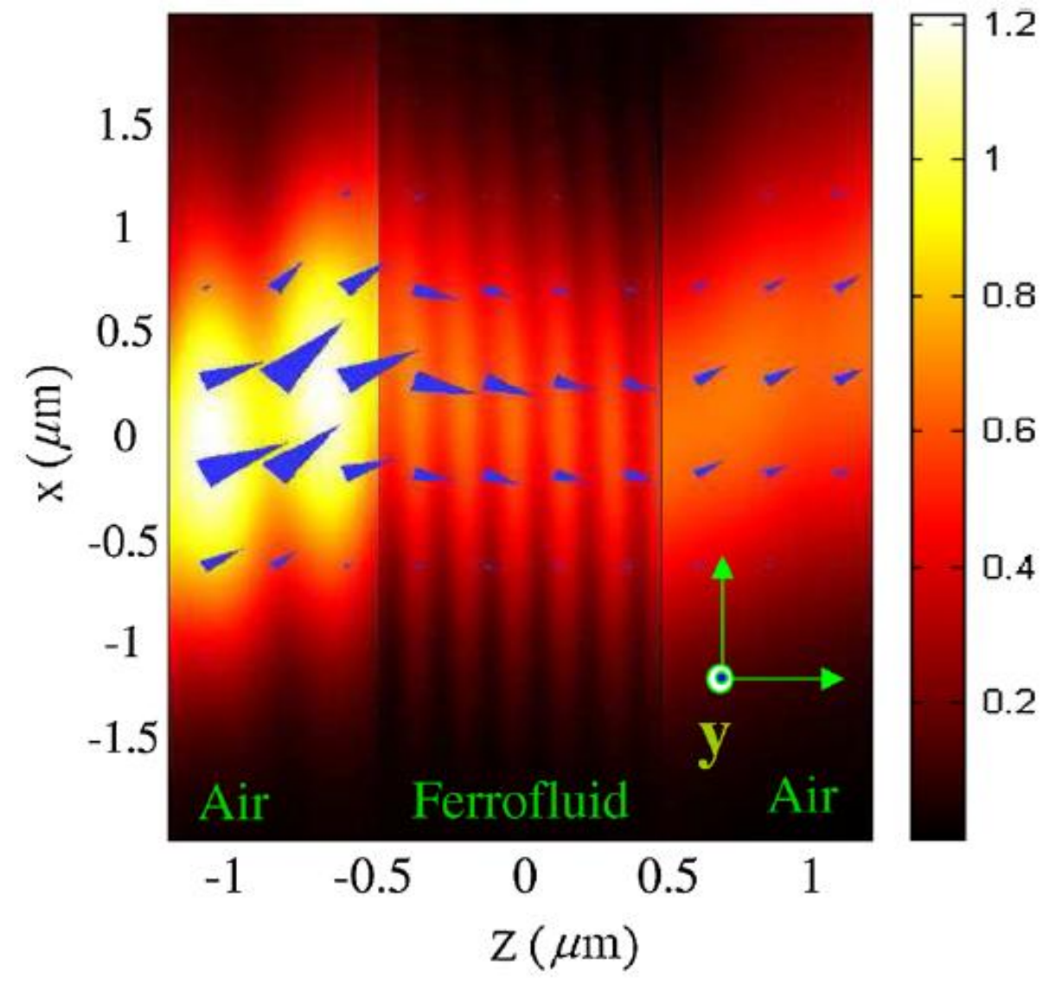
The angles of refraction for the wave vector k and Poynting vector **S** are given by,

$$\begin{aligned}\theta_{r,k}&=\tan^{-1}\left(\frac{k_x}{k_z}\right)\,,\\ \theta_{r,s}&=\tan^{-1}\left(\frac{S_x}{S_z}\right)=\tan^{-1}\left(\frac{k_x/\varepsilon_z}{k_z/\varepsilon_x}\right)\,.\end{aligned}$$

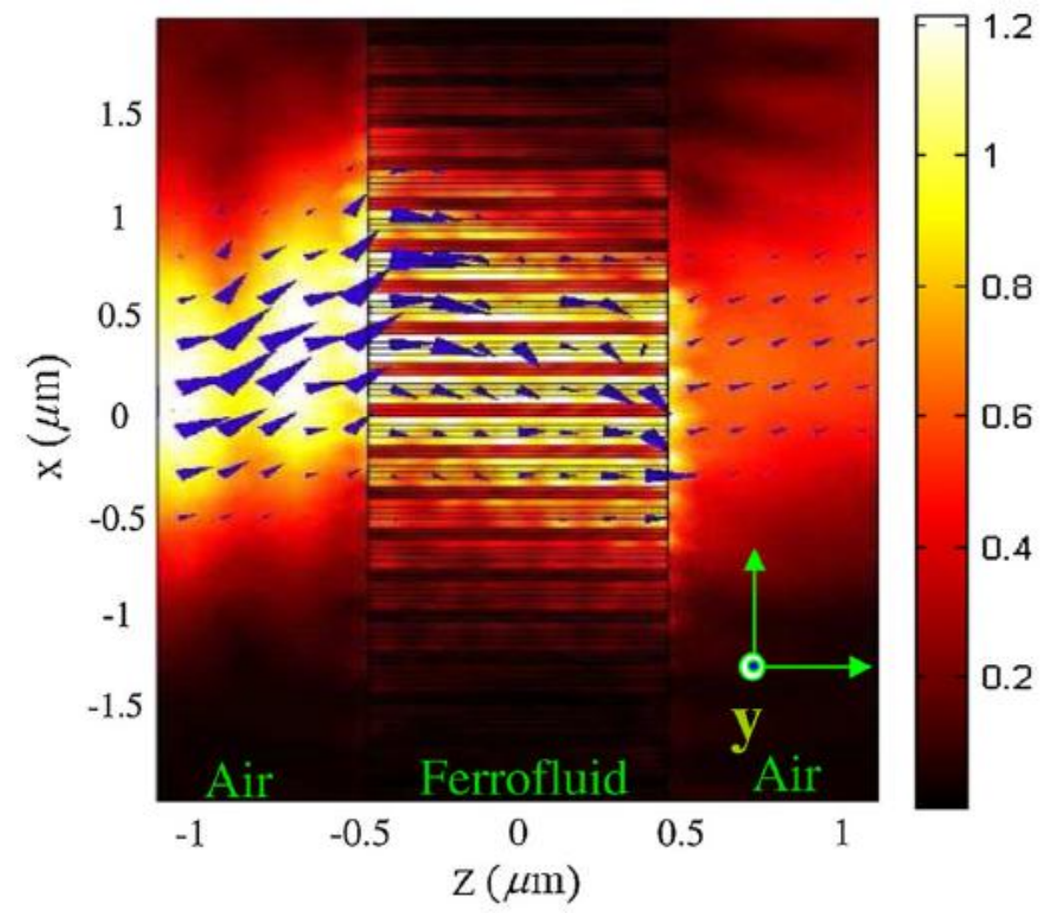
The effective refractive index can be defined as,

$$\eta=\sin\phi/\sin\theta_s$$

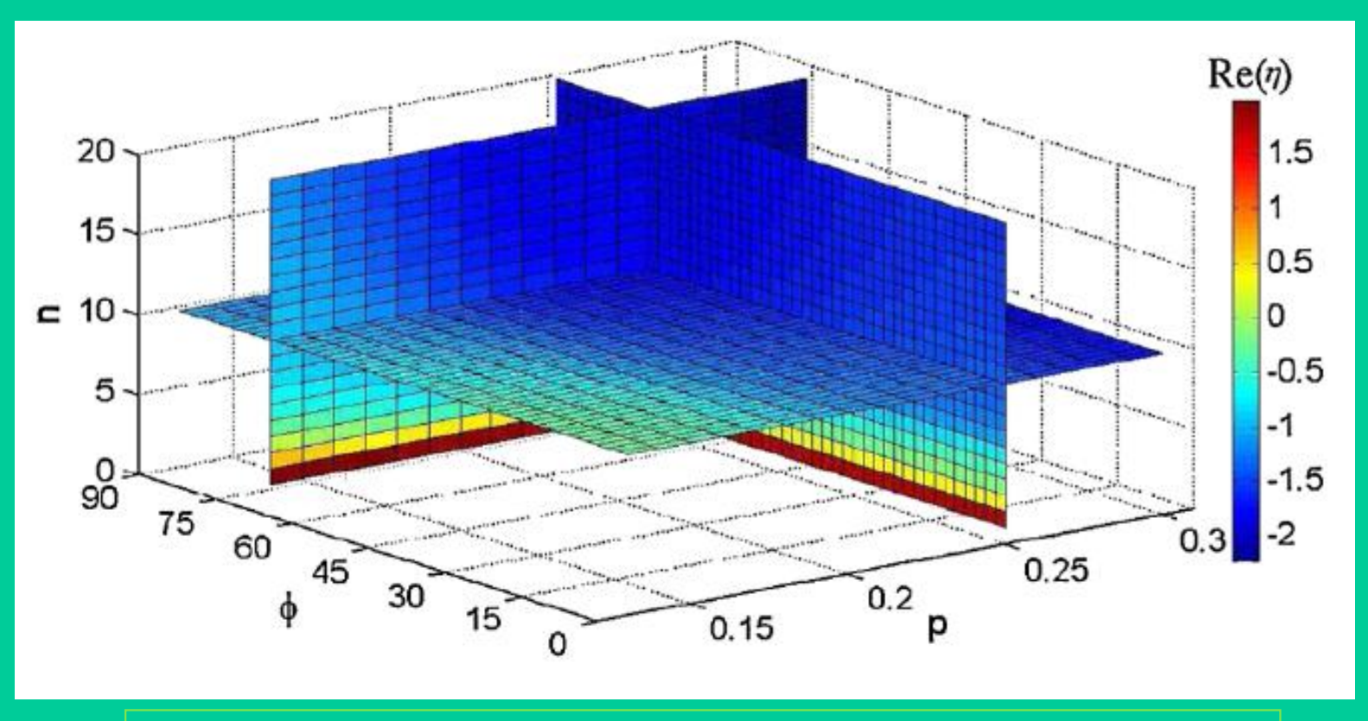
Simulation results



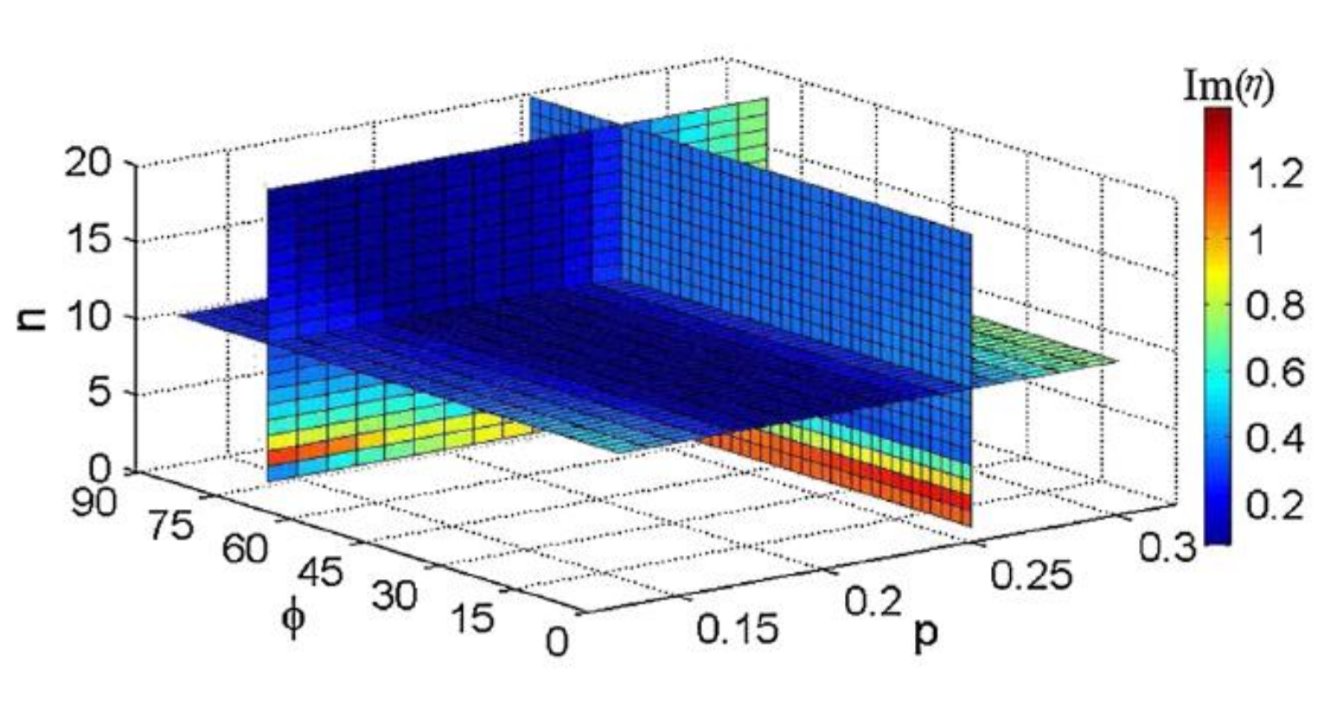
2D finite element simulations result of the distribution of the absolute value of electric field components of an incident TM wave with λ=758 nm. The ferrofluid system is replaced by an effective medium described by the parameters calculated according to EMA. The direction and size of the blue arrows indicate the direction and magnitude of the local power flow or Poynting vector.



3D finite element simulations result. For convenience we replace each column with a solid cylinder by assuming the solid cylinder to possess the same electromagnetic responses as the column. The radius of the cylinder is 30 nm, and the centerto-center separation between two adjacent cylinders is 122 nm.



Real part of the effective refractive index, λ=758 nm, n=10, p=0.25, and ϕ=70°.



Imaginary part of the effective refractive index, λ=758 nm, n=10, p=0.25, and ϕ=70°.

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_3O_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.

Acknowledgements

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References

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