Antiferromagnetic response of dielectric nanoparticles coupled to split-ring resonators

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Abstract

We analyze optically-induced antiferromagnetic response of a novel hybrid metal/dielectric structure consisting of a silicon nanoparticle coupled to multilayer stacks of split-ring resonators, and observe a strong antiferromagnetic resonance with a staggered pattern of the induced magnetization field. A periodic array of such elements will support a novel type of spin waves.

1. Introduction

Metamaterials offer new possibilities to manipulate and control the propagation of electromagnetic waves. Typical metamaterials are created by systems of resonant subwavelength elements, for which electric and magnetic responses can be changed independently. During last decade there were many efforts to achieve the artificial magnetism at high frequencies exploiting the inductive response of normal metals. The idea was successfully implemented in arrays of split-ring resonators (SRRs) [1] and mesh-like metal-dielectric fishnet structures [2]. In many of such cases the ferromagnetic response of the whole structures was utilized, based on the induced magnetization of constituent elements [3-6].

In this work, we demonstrate that the manipulation of the magnetic response can be taken one step further, and predict that by combining the magnetic resonances of silicon nanoparticles and split-ring resonators would allow for a strong antiferromagnetic response by placing them in a close proximity. We expect that one-dimensional periodic arrays of such elements will support a novel type of spin waves. This approach opens up a new way for manipulating magnetic response in the visible range.

2. Magnetic response of a single Si nanoparticle

According to the Mie theory, the scattering of electromagnetic waves by a small dielectric particle with high permittivity may exhibit a strong magnetic resonance [7]. The induced magnetic response is connected to the excitation of the localized modes of a dielectric particle for which the radial component of the magnetic field does not vanish. In this case, a dielectric particle can be considered as a *magnetic dipole scatterer* of an incident electromagnetic wave at the resonant wavelength. This resonance results in an increased magnetic field in the near-field region around the particle. Recently, it was demonstrated that a silicon nanoparticle with the radius in the range of R=40–100 nm can have a magnetic resonance located in the visible spectrum [8]. It makes such particles the best candidate to have low-loss magnetic response at high frequencies.

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3. Hybrid structures consisting of dielectric nanoparticles and split-ring resonators

We consider a small silicon nanoparticle of the radius R = 150 nm placed between two multilayer stacks of copper split-ring resonators of the radii R_1 = 70nm and R_2 = 75nm, thickness d =5 nm, and gap width g = 10nm [see Fig.1(a) for more details]. For given parameters, the decoupled nanoparticle and split-ring resonators have very close magnetic resonances f_{Si} = 268 THz and f_{SRR} = 250THz, respectively. By placing them in a close proximity, we may expect an effective magnetic coupling between the elements of different origin. To enhance the magnetic response, we use two multilayer stacks of split-ring resonators with 5 layers each, placed symmetrically around the spherical silicon nanoparticle. Our numerical simulations made by means of CST Microwave Studio confirm the existence of the induced strong magnetic coupling in such a hybrid structure. We find that, in addition to the standard ferromagnetic response where both magnetizations of the nanoparticle and split-ring resonators are parallel, there exist an antiferromagnetic response with *anti-parallel magnetization* of both the elements [see Fig.1(b)].

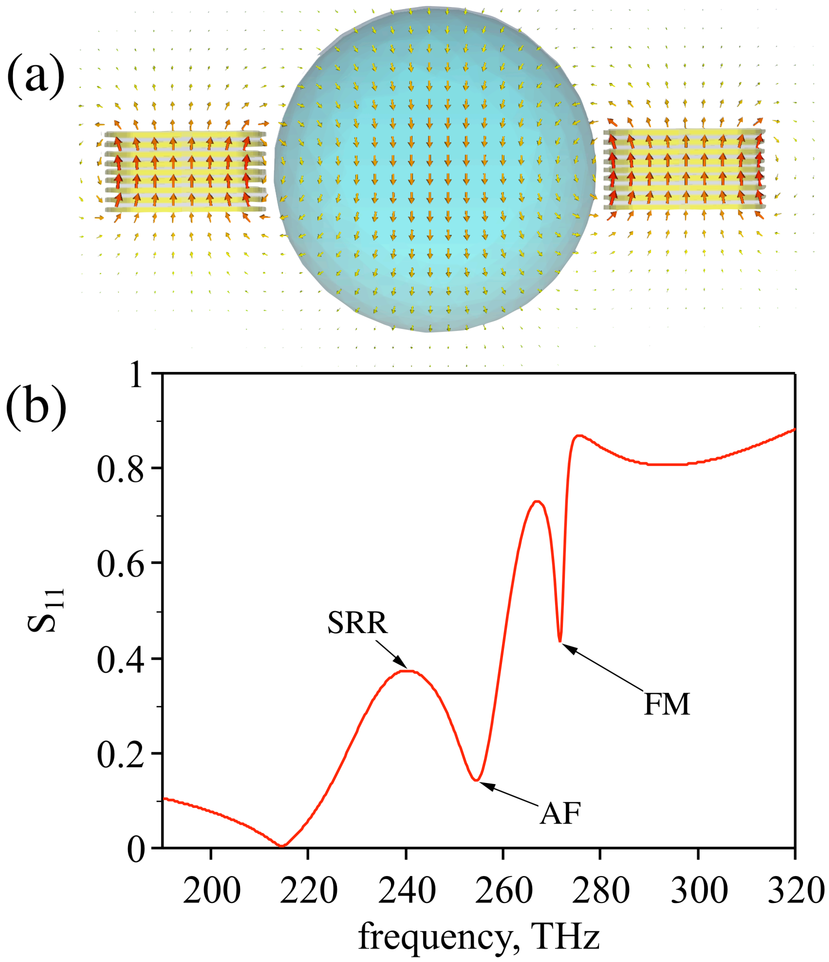

Fig. 1. Antiferromagnetic response of a hybrid structure. (a) Schematic view of the silicon nanoparticle coupled to two stacks of split-ring resonators (SRRs). Arrows indicate the induced magnetic field at the antiferromagnetic resonance; (b) Spectral properties of the hybrid structure with marked positions of SRR magnetic resonance, as well as ferromagnetic (FM) and antiferromagnetic (AF) resonances of the hybrid structure.

As the next step, we consider a one-dimensional array of the hybrid elements. In such a structure we observe the formation of antiferromagnetic coupling between silicon nanoparticles. Coupled split-ring resonators play an essential role in the control of the induced coupling, which can be changed from the ferromagnetic type to the antiferromagnetic type by changing the position of the gap of individual split-ring resonators. We also study the excitation of spin in such structures.

4. Summary and conclusion

We have studied the magnetic response of hybrid metal/dielectric structures consisting of dielectric nanoparticles and multilayer stacks of metallic split-ring resonators. Each of these elements can exhibit a magnetic response in the THz frequency range. By coupling these two different elements together, we have been able to achieve the magnetic interaction between the nanoparticles and split-ring resonators. We have found that the strongest induced magnetic coupling can be of two types – ferromagnetic, with the same direction of magnetization of both elements, and antiferromagnetic, with a staggered magnetization pattern

By arranging these elements into a one-dimensional array we have been able to induced magnetic interaction between dielectric nanoparticles and demonstrate the propagation of spin waves. We have demonstrated that the interparticle magnetic interaction can be effectively controlled by changing the gap of split-ring resonators. We believe this approach opens new possibilities for the manipulation and control of the artificial magnetism at optical frequencies.

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