Magnetic excitation of magnetic resonance in metamaterials at far-infrared frequencies

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The authors experimentally demonstrated magnetically excited magnetic resonances with negative magnetic permeability in a metamaterial composed of an array of silver rod pairs. In transmission spectroscopy of the metamaterial, by employing oblique incidence, an incident-magnetic-field-dependent absorption feature was clearly observed at 18 THz. The experimental results directly prove that the rod pair structure interacted with the magnetic field of the incident light, producing magnetic resonance. The experimental results were in good agreement with a numerical simulation suggesting that the value of μ_{Re} of the silver rod pair array changes from –0.29 to 2.26 at resonance. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2785167]

Plasmonic metamaterials have recently attracted a great deal of interest from researchers because of their potential to create materials with unprecedented optical properties.[1–5] Since metamaterials are fabricated by building up subwavelength-engineered metallic structures, their effective electric permittivity (ε) and magnetic permeability (μ) are macroscopically defined not by the properties of the metal but by the internal structures. The control of μ is one of the most important functions of metamaterials; the creation of magnetically active materials at optical frequencies increasingly has great significance because μ of most natural materials in the terahertz frequency region is unity.[6]

The most common structure for realizing artificial magnetism is the split-ring resonator (SRR), whose operation is based on an *LC*-resonant circuit.[7] Although the first magnetic metamaterial at terahertz frequencies was demonstrated using SRRs,[8] SRRs are not suitable for realizing magnetic resonance at optical frequencies, because they have an inherently large capacitance, which results in a low resonant frequency. On the other hand, our recent analyses have suggested that a single-ring SRR (s-SRR) can be used to achieve magnetic resonance in the frequency region above 100 THz.[9,10] This prediction has been experimentally verified by successive demonstrations of the magnetic responses from 100 THz up to the near-infrared region.[11,12] More recently, by using an array of rod or strip pairs, which is structurally similar to the s-SRR, the operating frequency of magnetic metamaterials is now approaching the visible light region.[13–15]

SRRs, or analogous resonant structures, are composed of inductive and capacitive structures, and they can be driven by two excitation systems: magnetically or electrically excited magnetic resonances.[16] The induced resonant current reported in Refs. 11 and 12 was generated by the coupling between the incident electric field and the capacitive structure. For this electrical excitation case, however, the excited magnetic resonances never contribute to the changes of μ of the metamaterial because the magnetic field produced by the induced current is not parallel to the incident magnetic field.[17] On the other hand, for the magnetic excitation case, which is based on the magnetic coupling of the inductive structure, the magnetic field produced by the induced current is added to the incident one, changing the value of μ at resonance. As a result, in order to verify the magnetic activity of the metamaterials, we must demonstrate magnetic excitation of the magnetic resonances.

In this letter, we describe the magnetically excited magnetic resonances in a metamaterial composed of an array of silver rod pairs. To realize the magnetic excitation, we employed transmission spectroscopy with oblique incidence. By continuously changing the incident angle, which means that the magnitude of the magnetic filed interacting with the rod pair array was changed, we clearly observed an incident-magnetic-field-dependent absorption feature at 18 THz. A comparison of the transmission spectra between the rod pair array and a single (unpaired) rod array indicated that this absorption feature results from the magnetic resonances in the rod pair structure.

The magnetic metamaterial we fabricated was composed of a two-dimensional array of silver rod pairs. Figure 1(a) is a scanning electron microscope (SEM) image of the rod pair

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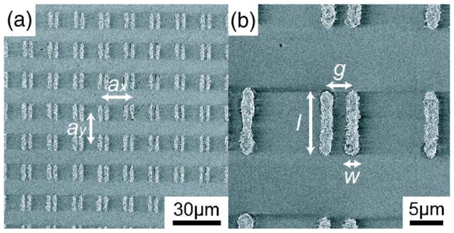

FIG. 1. (a) SEM image of silver rod pair array fabricated on a quartz substrate and (b) its magnified image. The unit-cell dimensions a_x and a_y were 15 μm, the rod length l was 10 μm, the rod width w was 1.5 μm, and the distance between two rods g was 4 μm.

array, and Fig. 1(b) shows its magnified image. The unit-cell dimensions a_x and a_y were 15 μm, the rod length l was 10 μm, the rod width w was 1.5 μm, and the distance between the two rods g was 4 μm; the total size of the sample was 3×3 mm^2. All silver structures were fabricated on a z-cut quartz substrate with a thickness of 150 μm by employing the two-photon-induced reduction of silver ions in an aqueous solution.[18,19] In addition to the rod pair array, we also measured a single (unpaired) rod array to confirm that the magnetic responses were observed only in the rod pair array. The single rod array had the same rod-filling factor as that of the rod pair array; therefore, we could compensate for the influence of the electric interactions between the structures and light by comparing the transmission spectra of the two structures.

All transmission spectra of the metamaterials were measured by using a fourier-transform infrared spectrometer (FTIR) (JASCO, FT/IR-6300FV). The measurement spectral range was from 0.9 to 20.4 THz, with a resolution of 0.1 THz. An aluminum aperture with a diameter of 3 mm was installed between the sample and the photodetector to improve the signal-to-noise ratio of the detected signal. In order to realize oblique incidence onto the sample, a rotating table was installed in the sample chamber of the FTIR, and the transmission spectra of the sample were measured by changing the incident angle (θ) of s-polarized light, as shown in Figure 2(a). When the incident light passes through the sample at the incident angle of θ, the magnetic field perpendicular to the plane including two rods is

$$H \sin \theta, \tag{1}$$

where H is the magnetic field of the incident light. As shown in Fig. 2(b), the rod pair structure has the geometrical inductance (L) and capacitance (C), which, respectively, come from the rectangular area sandwiched between two rods and the gap between two rods; it acts as an LC-resonant circuit coupled with the magnetic field. Therefore, by increasing the

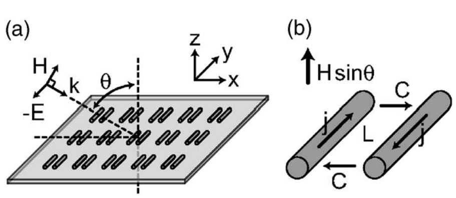

FIG. 2. (a) Optical setup for measuring the magnetically excited magnetic responses of the rod pair array by changing the incident angle (θ) of s-polarized light. (b) The rod pair structure acts as an LC-resonant circuit, and the induced current (j) is generated by the magnetic field perpendicular to the plane including two rods ($H \sin \theta$).

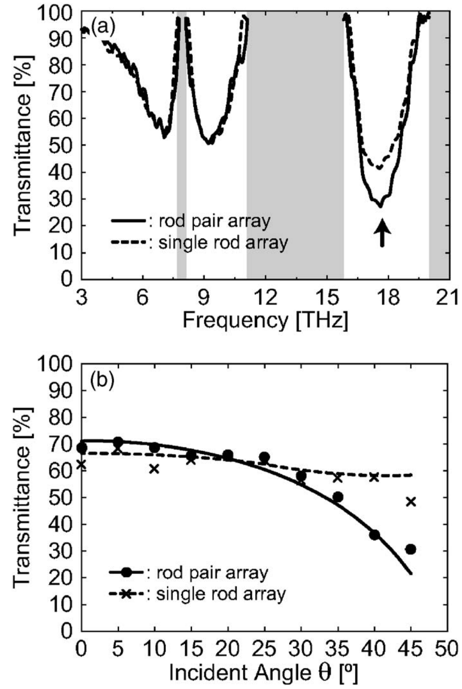

FIG. 3. (a) Transmission spectra of the rod pair array and the single (unpaired) rod array measured at θ=45°. The absorption feature indicated by the arrow is attributed to the occurrence of the magnetic resonances in the rod pair structure. In the shaded regions, no valid data were obtained because of strong absorption by the quartz substrate. (b) Incident angle dependencies of the transmittances of the rod pair array and the single rod array measured at 18 THz.

incident angle at which the large magnetic field is introduced, strong magnetic excitation of the magnetic resonances can be obtained.

Figure 3(a) shows an example of the transmission spectra of the rod pair array and the single rod array measured at θ=45°. In the shaded regions, which are irrelevant for our purpose, no valid data were obtained because of the strong absorption by the quartz substrate. The transmittances of the two structures were almost the same, except for an absorption feature centered at 18 THz, which is indicated by the arrow. We believe that this absorption feature resulted from the occurrence of the magnetic resonances in the rod pair structure for the following reasons. Figure 3(b) shows the incident angle dependencies of the transmittances of the rod pair array and the single rod array measured at 18 THz. The range of the incident angle was limited to 0°–45° because the detected light intensity passing through the aluminum aperture became weak at the large incident angle. When the incident angle increased, the transmittance of the single rod array did not change and remained almost constant at 65%, indicating that the single rod array did not interact with the magnetic field. On the other hand, the transmittance of the rod pair array uniformly decreased from 70% to 20% as the incident angle increased. Since the increase of the incident angle leads to an increase of the magnetic field that interacts with the rod pair structure, this result directly proves that magnetically excited magnetic resonances occurred in the rod pair array.

To investigate this, we also performed a corresponding numerical simulation of the magnetic responses of the rod pair array. The analytical form of the effective permeability μ_{eff} of the rod pair array can be described by[9,10]

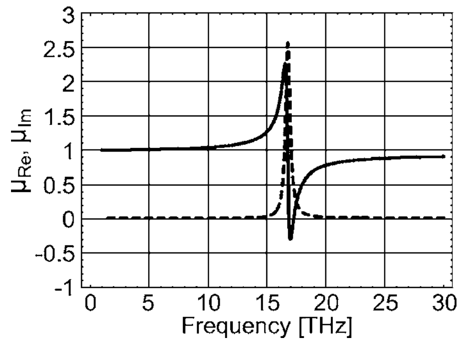

FIG. 4. Numerically simulated real and imaginary parts of the effective permeability [μ_{Re} (solid line) and μ_{Im} (dotted line)] of the silver rod pair array. The magnetic resonance response in μ is clearly observed around the resonant frequency of 16.77 THz, which was in good agreement with the experimental results.

$$\mu_{eff} = \mu_{Re} + i\mu_{Im} = 1 - \frac{F\omega^2}{\omega^2 - 1/CL + iZ(\omega)\omega/L}, \qquad (2)$$

where ω is the angular frequency, F is the filling factor, C and L are the geometrical capacitance and inductance, and $Z(\omega)$ is the metal impedance. For the rod pair array, these parameters in Eq. (2) are given by[20]

$$F = \frac{l(g-w)}{a^2}, \qquad (3)$$

$$C = \frac{l}{4}\varepsilon_0 \frac{\pi}{\ln\left(\frac{g-w/2}{w/2}\right)}, \qquad (4)$$

$$L = \mu_0 \frac{l(g-w)}{a}, \qquad (5)$$

and

$$Z(\omega) = \frac{2lZ_s(\omega)}{\pi w}, \qquad (6)$$

where ε_0 and μ_0 are the permittivity and permeability of vacuum, and $Z_s(\omega)$ is the internal impedance of the silver rods. Here, we assumed that the current flows on the surface of the rod along the axis of the rod, and $Z_s(\omega)$ was found by integrating the in-plane current along the radial direction, as follows:[10]

$$Z_s(\omega) = \frac{1}{\sigma(\omega)\int_0^{w/2} \exp\{i\omega r\sqrt{\varepsilon_0\mu_0(1 + i\sigma(\omega)/\omega\varepsilon_0)}\}dr}, \qquad (7)$$

where $\sigma(\omega)$ is the conductivity of silver derived from the Drude model.[21]

Figure 4 shows the numerically simulated real and imaginary parts of the effective permeability (μ_{Re} and μ_{Im}) of the silver rod pair array. In the calculation, the plasma frequency $\omega_p = 1.40 \times 10^{16}\ \mathrm{s}^{-1}$ and the damping constant $\gamma = 1.06 \times 10^{14}\ \mathrm{s}^{-1}$, which is 3.3 times larger than that of bulk silver ($\gamma = 3.23 \times 10^{13}\ \mathrm{s}^{-1}$), were used.[18,22] In Fig. 4, the magnetic resonance response in μ is clearly observed around the resonant frequency of 16.77 THz, and the value of μ_{Re} changes from −0.29 to 2.26. Since μ_{Im} has a finite value around the resonant frequency, the absorption of the incident light should be observed; this is in good agreement with the experimental results and the above discussion.

In conclusion, we demonstrated the magnetic excitation of magnetic resonances in a metamaterial composed of an array of silver rod pairs by employing transmission spectroscopy with oblique incidence. In this letter, we focused only on the magnetic resonances in the rod pair array. However, at the same time, the rod array also interacts electrically with the incident light, and these electric interactions are also important for the applications of the metamaterials.[23] To further investigate them, the electric responses hiding behind the magnetic responses must be rigorously extracted; this can be achieved by employing more control of the polarization of the incident light and the higher-accuracy numerical analysis.

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