Magnetic response of split-ring resonators in the far-infrared frequency regime

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We report on the fabrication, through photolithography techniques, and the detailed characterization, through direct transmission measurements, of a periodic system composed of five layers of photolithographically aligned micrometer-sized Ag split-ring resonators (SRRs). The measured transmission spectra for propagation perpendicular to the SRRs plane show a gap around 6 THz for one of the two possible polarizations of the incident electric field; this indicates the existence of a magnetic resonance, which is verified by detailed theoretical analysis. To our knowledge this is the first time that a system of more than one layer of micrometer-sized SRRs has been fabricated. The measured optical spectra of the Ag microstructure are in very good agreement with the corresponding theoretical calculations. © 2005 Optical Society of America

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In 1968, Veselago[1] pointed out that materials exhibiting negative permittivity, ϵ, and negative permeability, μ, over a common frequency range exhibit novel and unique electromagnetic (EM) properties, such as the left-handed (LH) nature of the triad $\mathbf{k},\mathbf{E},\mathbf{H}$ (thus the term LH materials proposed by Veselago and adopted by most researchers in the field), an opposite running phase and energy flux, a negative index of refraction, n, a reversal of Doppler effect, flat lens focusing, etc. Pendry *et al.* proposed a design of such a material, employing thin metallic wires[2] and split-ring resonators (SRRs).[3] The former lead to $\epsilon(\omega)<0$ for ω smaller than a cutoff frequency, ω_p, while the latter give $\mu(\omega)<0$, for $\omega_m<\omega<\omega'_m$, where ω_m is a resonance frequency similar in nature to that appearing in a capacitor–inductor circuit (ω'_m is the upper limit of the negative μ regime, which follows the resonance frequency). Smith *et al.* were the first to construct the design proposed by Pendry *et al.* and to demonstrate negative n in the gigahertz range.[4] Following this original experiment, several composite metamaterials composed of SRRs and wires were fabricated that exhibited a passband in the gigahertz range that was thought to be LH,[5,6] since it was lying within the stop bands of the SRRs-only structure and of the wires-only structure. However, the situation is more complicated, because the SRRs exhibit a resonant electric response, similar to that of cut wires, that shifts ω_p to $\omega'_p<\omega_p$.[7] Nevertheless, metamaterials were designed and fabricated that exhibited real LH transmission bands, in some cases with very high transmittance [peak values up to −1.2 dB (Ref. 8)].

Gay-Balmaz and Martin showed[9] that, besides a magnetic field normal to the SRR [see the orientations of Figs. 1(a) and 1(b)], an electric field parallel to the gap-bearing sides of the SRR [as in the orientations of Figs. 1(b) and 1(d)] can couple to the SRR, exciting the oscillating resonant current around it. The effect of this coupling is a resonance of ϵ at $\omega \approx \omega_m$. This electric excitation of the magnetic resonance (EEMR) was verified also by Katsarakis *et al.* in an experimental and theoretical study of the propagation of EM waves for the four possible orientations of the SRR [shown in Figs. 1(a)–1(d)].[10] The origin of this effect is the nonzero average polarization induced by the asymmetry of the SRR relative to the external $\mathbf{E}$.

The EEMR effect provides new opportunities for miniaturization of the SRR and wire metamaterials, since it seems to allow excitation of the magnetic resonance for propagation even normal to the SRR plane. O'Brien *et al.* presented[11] numerical calculations of the effective permittivity and permeability of a photonic crystal metamaterial consisting of SRRs structured on a nanometric scale. They showed that metallic resonators could provide a means to obtain a negative effective permeability at up to telecommunications wavelengths. Moreover, Yen *et al.* showed[12] that SRRs could indeed exhibit a magnetic response at terahertz frequencies. They performed ellipsometry measurements at 30° for one SRR layer and observed a resonant peak, centered at ~1.25 THz, in the ratio of reflectances of the two possible magnetic field polarizations, which they attributed to the magnetic response of the constituent SRRs. Very recently Linden *et al.*[13] demonstrated experimentally a magnetic resonance response at 100 THz.

We report here that we managed to fabricate, for what is to our knowledge the first time, a micrometer-scale metamaterial consisting of five lay-

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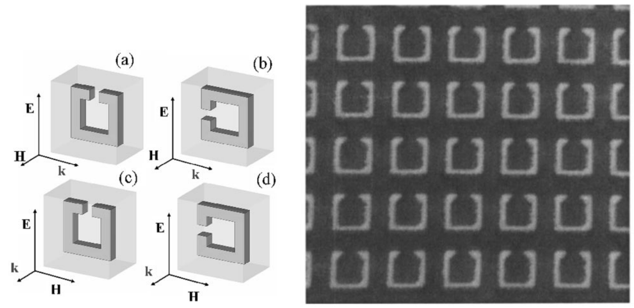

Fig. 1. Left, single unit cell of the SRR geometry studied, in all possible EM field propagation directions and polarizations [(a)–(d)]. Right, top view photograph of the SRR metamaterial fabricated by a microlithography process.

ers of single-ring SRRs (a photograph is shown at the right of Fig. 1) and operating around 6 THz. Furthermore, we were able to demonstrate conclusively by direct transmission measurements of a normally incident beam of both polarizations [see Figs. 1(c) and 1(d)] the excitation of the magnetic resonance at 6 THz by the EEMR effect only in the configuration in Fig. 1(d). Our interpretation of the experimental results is reinforced theoretically, by use of both transmission calculations for the configurations in Figs. 1(a), 1(c), and 1(d) and determination of the effective parameters ϵ and μ. The conventional configuration [Fig. 1(a)], which allows direct excitation of the magnetic resonance, was included in our theoretical calculations as a further check of our interpretation.

The SRR metallic structures are fabricated in a layer-by-layer fashion, alternating layers of polyimide and silver. We used a standard spin-on polyimide (DuPont Pyralin SP series PI-2525) with a dielectric constant of 2.5. The sequence of layers starts by spinning and curing a 5-μm-thick layer of polyimide on a Si substrate. A 1-μm-thick silver film is deposited on top and patterned by use of standard lift-off techniques. Another layer of polyimide is spun on over the metallic SRR and cured. The thickness of this polyimide layer is 5 μm. Another metal layer is deposited and patterned, with this second layer of SRRs aligned directly over the first. The sequencing of layers continues with another thick polyimide layer followed by a third metallic SRR pattern and so on. The layer-to-layer alignment was done with a Karl Suss MA6 aligner and UV photolithography. The alignment accuracy is of the order of 0.5 μm. After the fabrication, the polyimide-encapsulated metallic SRR structure is removed from the Si substrate.

Because the polyimide has two absorption bands centred about 15 and 30 μm, we chose the dimensions of the periodic SRRs to have a resonance frequency near 6 THz (wavelength of 50 μm), safely below the absorption bands. The unit cell of the structure has dimensions of 7 $\mu\mathrm{m} \times 7$ μm in the SRR plane and 5 μm in the perpendicular direction; the SRR side length is 5 μm, and the other characteristic lengths (ring width, ring depth, gap) are all 1 μm. The total metamaterial has an area of 25 mm $\times 25$ mm. A photograph of the metamaterial is presented on the right-hand side of Fig. 1.

The transmission measurements were taken with a Bruker IFS 66 v/S Fourier-transform infrared spectrometer (with a collimated beam) and a polarizer at a frequency range of 3–10 THz. The results are presented in Fig. 2. One can readily observe that for polarization (d), with the electric field parallel to the gap-bearing SRR sides, the transmission spectrum shows a gap at approximately 5–8 THz [curve (d) of Fig. 2], which we claim to be due to the EEMR effect. This interpretation is further supported by the absence of this gap for the other polarization [curve (c)], where the SRR is symmetric relative to the incident **E**. In orientation (c) we observe only a cutoff frequency at ~8 THz, corresponding to the electric cutwire SRR response [for orientation (d) this response is observed in slightly higher frequencies].

To conclusively verify the origin of the gap at ~6 THz and thus the existence of EEMR in this regime, we studied this system theoretically as well. First we reproduced the experimental data by use of transmission and reflection calculations, and then we inverted these data to obtain the effective parameters ϵ and μ of the metamaterial.

In Fig. 3 we show the calculated transmission for the cases presented in Fig. 2 as well as for the orientation in Fig. 1(a). The transmission was calculated with the finite integration technique (employed through Microwave Studio commercial software) and treating the metal as a dispersive medium following the Drude dispersion model [$\epsilon = 1-\omega_{pm}{}^2/(\omega^2+i\omega\gamma)$, with $\omega_{pm}=13.66\times10^{15}\ \mathrm{s}^{-1}$ and $\gamma=2.73\times10^{13}\ \mathrm{s}^{-1}$ (Ref. 14)]. For the polyimide background we used dielectric constant $\epsilon_b=2.5$ and loss parameter $\tan\delta=0.03$. Comparing Fig. 3 with Fig. 2, one can see that the agreement between theory and experiment is very good, adding credibility to our interpretation. Moreover, we obtained theoretically a transmission dip around 6 THz for the orientation in Fig. 1(a), where the excitation of the resonance at ω_m is purely magnetic, thus verifying the existence of a magnetic resonance associated with a negative μ in this regime. Closing the SRRs for the configuration of Fig. 1(a), thus destroying the oscillating behavior at ω_m,[7,15] the dip at ~6 THz disappears, as expected.

To offer further and definite proof of the existence of negative magnetic response in our metamaterial around 6 THz, we employed a retrieval procedure[16] to

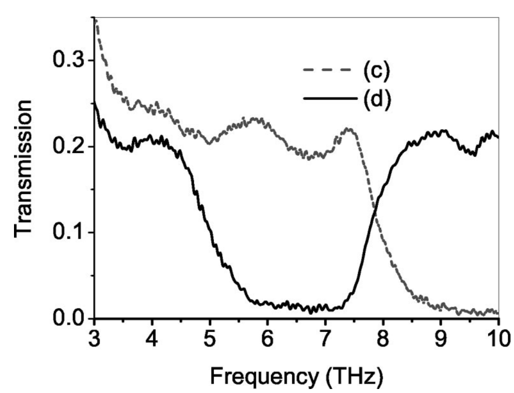

Fig. 2. Measured transmission spectra for the configurations shown in Figs. 1(c) and 1(d).

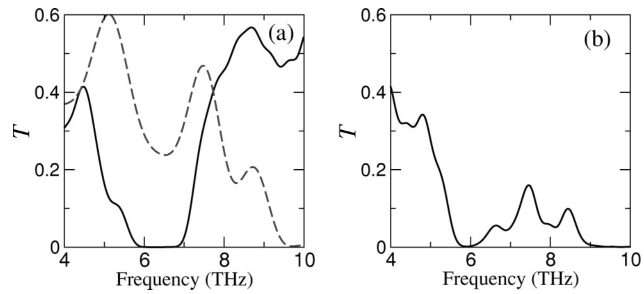

Fig. 3. (a) Calculated transmission versus frequency for the configurations shown in Figs. 1(c) (dashed curve) and 1(d) (solid curve). (b) Calculated transmission for the configuration in Fig. 1(a).

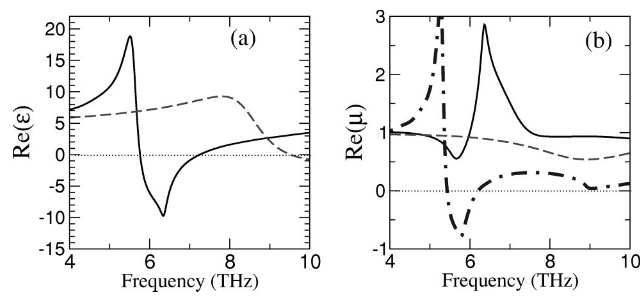

Fig. 4. (a) Real part of the effective permittivity of the SRR metamaterial shown in Fig. 1, for propagation direction and EM field polarization those of Fig. 1(d) (solid curve) and Fig. 1(c) (dashed curve). (b) Real part of the effective permeability of the SRR metamaterial for the orientations of Fig. 1(d) (solid curve), Fig. 1(c) (dashed curve), and Fig. 1(a) (dashed–dotted curve).

extract the effective ϵ and μ from the theoretical reflection–transmission results, considering our metamaterial as a homogeneous effective medium. Since, for a propagation direction perpendicular to the SRR plane, the magnetic resonance can be exhibited only through the permittivity $\epsilon(\omega)$, we inverted the scattering data also for the orientation in Fig. 1(a), where the magnetic resonance of the SRR appears only in $\mu(\omega)$. The inversion results concern only one unit cell of the metamaterial and are shown in Fig. 4. Figure 4(a) shows effective ϵ (real part) for the orientations in Figs. 1(c) and 1(d) [notice the negative ϵ around 6 THz for Fig. 1(d)], while Fig. 4(b) shows μ (real part) for the orientations in Figs. 1(c) and 1(d) as well as Fig. 1(a); clearly, the solid curve in Fig. 4(a) and the thick dashed–dotted line in Fig. 4(b) exhibit the same strong resonance at the same frequency, providing one more direct verification of the EEMR effect.

In conclusion, we have microfabricated a mechanically flexible periodic structure consisting of alternating dielectric and SRR metallic layers. By direct transmission measurements, supported by theoretical results, we have demonstrated a magnetic resonance response at 6 THz through the EEMR effect. The magnetic resonance response is of particular importance to THz optics and their applications.

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