Experimental demonstration of negative magnetic permeability in the far-infrared frequency regime

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Using transmission and reflection measurements in a five layer micrometer-scale split-ring resonator (SRR) system, fabricated by a photolithography procedure, the authors demonstrate the occurrence of a negative magnetic permeability regime in that system at ~6 THz. The transmission and reflection were measured using oblique incidence, resulting to a magnetic field component perpendicular to the SRR plane, which excites the resonant circular currents constituting the magnetic resonance. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2335955]

Left-handed metamaterials (LHMs), i.e., composite materials with effective electrical permittivity ε and magnetic permeability μ, both negative over a common frequency band,[1,2] have received recently an extremely increasing attention, not only due to their interesting physics but also due to the capabilities that they offer for the manipulation of electromagnetic waves (evanescent wave amplification, perfect lensing,[3] etc.). The current most common realization of such materials involves periodic systems of wires, providing the negative ε, combined with periodic systems of split-ring resonators (SRRs), i.e., metallic rings with gaps (see Fig. 1), which provide the negative μ, under the presence of a magnetic field perpendicular to their plane [SRRs act as capacitor-inductor (LC) circuits, exhibiting a resonance response, at $\omega_m = 1/(LC)^{1/2}$, corresponding to resonant circular currents in the rings].[4–10]

While the existence of LHMs in the gigahertz regime (1–100 GHz) has been definitely proven, the demonstration of negative μ and left-handed (LH) behavior in the infrared and optical wavelengths is still a target of intensive research. There are claims for the achievement of LH behavior at 1–2.7 THz (Ref. 11) and at 2 μm,[12] as well as reports which experimentally demonstrate the occurrence of a magnetic resonance in SRR systems at ~1.25 THz,[13] ~6 THz,[14] 100 THz,[15] and 1.5 μm.[16] The demonstration of the magnetic resonance in Refs. 14–16 was done through transmission measurements for propagation normal to the SRR plane and was based on the effect of electric excitation of the magnetic resonance (EEMR), i.e., excitation of the resonant circular currents in the SRR by the incident electric field **E**. The EEMR effect occurs when the SRR has not mirror symmetry with respect to **E** [see configuration (b) of Fig. 1] and is possible also for propagation normal to the SRR plane. In the normal incidence case though, the magnetic resonance, manifested as a dip in the transmission spectrum (and a peak in the reflection spectrum), appears not as a resonance in μ (since the induced magnetic field by the excited resonant circular currents is along the propagation direction, and thus does not add to the incident field $B = \mu H$) but as a resonance in ε (coming from the nonzero average polarization due to the charges accumulated at the gap sides). In Refs. 14–16 the occurrence of negative μ at the magnetic resonance, i.e., the diamagnetic behavior of the system at the magnetic resonance, was shown only through associated theoretical calculations, involving determination of the effective μ from transmission and reflection calculations.

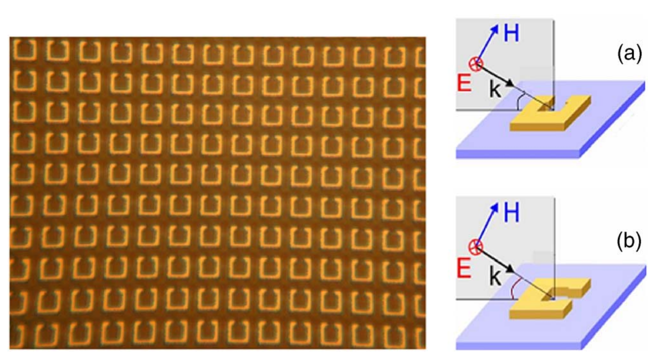

FIG. 1. (Color online) (Left) Photo of the structure studied. (Right) SRR and external magnetic field configurations studied; (a) electric field (**E**) parallel to the SRR sides with no gap and (b) **E** parallel to the SRR sides with the gap.

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To demonstrate directly that a SRR metamaterial behaves as a negative μ material, one has to introduce an external magnetic field perpendicular to the SRR plane. In principle, one way to achieve this is by employing a propagation vector **k** parallel to this plane; this is practically impossible for very thin structures. A possible solution to the problem is to employ *oblique incidence*, producing a **k** component at the SRR plane, $\mathbf{k}_{\parallel}$. For oblique incidence one can achieve an **H** component perpendicular to the SRR plane, $\mathbf{H}_{\perp}$. $\mathbf{H}_{\perp}$ induces a circular current flow inside the SRRs, which in turn produces just above the resonance frequency a large magnetic dipole moment antiparallel to $\mathbf{H}_{\perp}$, leading thus to a negative μ.

Here, we present transmission and reflection measurements at oblique incidence on a five layer micrometer-scale SRR metamaterial. These measurements confirm the occurrence of a SRR resonance at ~6 THz, add further proof to the argument that EEMR allows the excitation of this resonance for propagation even normal to the SRR plane, and demonstrate conclusively the existence of negative permeability in the ~6 THz regime.

Our SRR metamaterial (a photo is shown in the left-hand side of Fig. 1) is composed of single-ring silver SRRs, fabricated in polyimide. The fabrication has been done by UV photolithography and is described in detail in Ref. 14. The unit cell dimensions of the metamaterial are $7\times 7\ \mu\mathrm{m}^2$ in the SRR plane and 5 μm in the perpendicular direction; the SRR side length is 5 μm while the other characteristic lengths (ring width, ring depth, gap) are all of 1 μm. The total area of each sample is $25\times 25\ \mathrm{mm}^2$.

The transmission/reflection measurements have been taken using a Bruker IFS 66v/S fourier transform infrared spectrometer (with a collimated beam) and a polarizer, at the frequency range of 3–10 THz. Starting from normal incidence ($\mathbf{H}_{\perp}=0$, corresponding to $\varphi=90°$, where φ is the angle between the propagation vector **k** and the SRR plane) in configurations (a) and (b) of Fig. 1 and changing φ, we produce a gradually increasing $\mathbf{H}_{\perp}$ and we observe the evolution of the transmission and reflection spectra resulting from the interaction of SRRs with $\mathbf{H}_{\perp}$.

In Fig. 2(a) we present the reflection spectra of the SRR metamaterial at oblique ($\varphi=77°$, 70°, 60°, 50°) incidence, for configuration (a) of Fig. 1 (**E** parallel to the no-gap sides of the SRRs). At the minimum obliqueness case ($\varphi=77°$), the reflection (R) spectrum ~6 THz shows a weak peak at around 6 THz [dashed curve in Fig. 2(a)], which for growing obliqueness (decreasing φ) strengthens and broadens (~5.5–7.5 THz). For configuration (a), coupling of the incident **E** to the magnetic resonance of the SRRs (EEMR) cannot occur, since SRRs are symmetric with respect to **E**.[17] Thus, the changes in the R spectra with decreasing φ are exclusively due to the interaction of the SRRs with the increasing $\mathbf{H}_{\perp}$. $\mathbf{H}_{\perp}$ results in the excitation of circular currents in the SRRs and thus to the excitation of the magnetic SRR resonance. Thus, the peak in the R spectra at ~5.5–7.5 THz, for oblique incidence, can only be a result of negative μ in that frequency regime.

The transmission (T) spectrum for the same SRR metamaterial and the same measurement procedure is depicted in Fig. 2(b). The dashed curve refers to normal incidence ($\varphi=90°$). The oscillations observed in the T spectrum are due to the polyimide multilayer structure. However, at oblique incidence ($\varphi=80°$, 60°) $\mathbf{H}_{\perp}$ excites the magnetic resonance. This is manifested also in the T spectrum with the evolution of a dip at 5.5–7 THz for $\varphi=80°$, which broadens and deepens at $\varphi=60°$. However, this T dip is not as pronounced as the respective R peak of Fig. 2(a), most probably due to multiple scattering effects at the interfaces between the adjacent Ag/polyimide layers as well as due to absorption. In the inset of Fig. 2(b) we show the calculated T spectrum for $\varphi=0°$ (**k** is parallel and **H** is perpendicular to the SRR plane). The transmission was calculated using the finite integration technique (employed through the MICROWAVE STUDIO commercial software) and treating the metal as a dispersive medium following the Drude dispersion model [$\varepsilon=1-\omega_{\mathrm{pm}}^2/(\omega^2+i\omega\gamma)$, with $\omega_{\mathrm{pm}}=13.66\times 10^{15}\ \mathrm{s}^{-1}$ and $\gamma=2.73\times 10^{13}\ \mathrm{s}^{-1}$]. For the polyimide background we used dielectric constant $\varepsilon_b=2.5$ and loss parameter tan $\delta=0.03$. As it can be observed, T has a dip at ~5.5–7 THz for $\varphi=0°$, where the excitation of the resonance at ω_m is purely magnetic. The T dip at ~5.5–7 THz is associated with a resonance in μ, which becomes negative in this frequency regime (as it is concluded from the calculation of ε and μ from the inversion of the theoretical T and R data[14]).

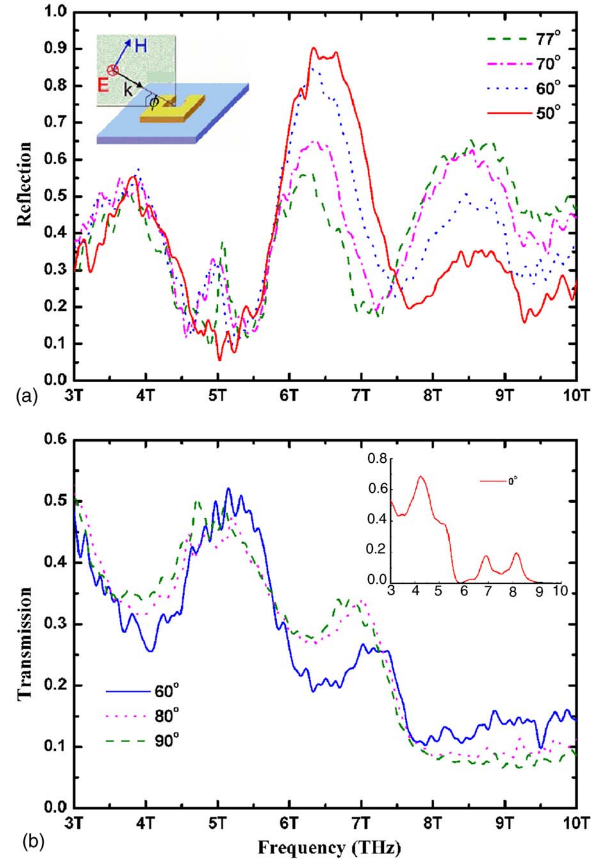

FIG. 2. (Color online) (a) Measured reflection spectra at oblique incidence for our five layer SRR system for configuration (a) of Fig. 1 (shown also in the inset). One can observe the evolution of a reflection peak as the angle ϕ changes (ϕ is the angle between **k** and the SRR plane). (b) Measured transmission spectra as ϕ changes for configuration (a) of Fig. 1. In the inset of (b) the calculated transmission spectrum for $\varphi=0°$ is also presented.

In Fig. 3(a) the reflection spectra of the SRR metamaterial are presented for configuration (b) of Fig. 1 (**E** parallel to the gap-bearing side of the SRRs). In the case of minimum obliqueness ($\varphi=77°$) the R spectrum shows a well-defined peak [dashed curve in Fig. 3(a)], which is attributed to the EEMR effect, present in all cases. For stronger oblique inci-

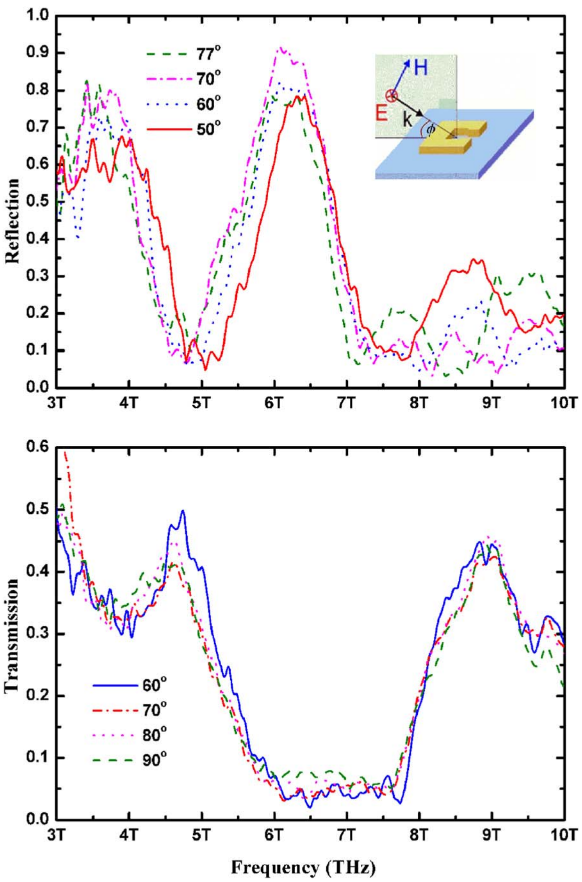

FIG. 3. (Color online) (a) Measured reflection at oblique incidence for configuration (b) of Fig. 1 (shown also in the inset). The angle mentioned in the legends is the angle ϕ between **k** and the SRR plane. (b) Measured transmission spectra for configuration (b) of Fig. 1 as ϕ changes.

dence (φ=70°, 60°, 50°) the peak in R remains almost unchanged in shape and amplitude, despite the emergence of $\mathbf{H}_\perp$. One would expect the R peak to broaden and strengthen for increasing oblique incidence due to the addition of the $\mathbf{H}_\perp$ excitation of the magnetic resonance [$\mathbf{H}_\perp$ produces a resonance structure in $\mu(\omega)$, in addition to the resonance structure in $\varepsilon(\omega)$ produced by **E** (for configuration (b)]. However, theoretical calculations of the effective ε and μ parameters extracted from the corresponding theoretical reflection-transmission results (considering the SRR metamaterial as a homogeneous effective medium) show that the resonance in ε is much stronger and wider than that in μ and thus dominates the reflection and transmission spectra. This large strength ratio of the two resonances explains the fact that the R peak observed in our measurements due to the EEMR effect remains almost unaffected by increasing oblique incidence. Our conclusions are further supported by the corresponding oblique incidence transmission measurements [see Fig. 3(b)], which show no altering of the well-studied T dip, attributed to the EEMR effect, as one goes from normal to oblique incidence. The dip does not change with decreasing φ, which implies that the resonance in ε masks the occurring resonance in μ. In other words, in configuration (b) the electric field is the dominant driving force of the resonance.

In summary, it has been demonstrated through oblique incidence transmission and reflection measurements on a five layer single-ring SRR system that there is indeed a SRR resonance associated with negative magnetic permeability at around 6 THz. This resonance is manifested by the emergence of a reflection peak and a corresponding transmission dip as the obliqueness of incidence increases in the symmetric configuration (a) (**E** parallel to the no-gap sides of the SRR); for this configuration and for oblique incidence, a component of **H** perpendicular to the SRR plane emerges, which is the only cause of the excitation of the magnetic resonance; hence, the latter appears as a resonance in $\mu(\omega)$. For the configuration with **E** parallel to the gap-bearing side of the SRRs, the same resonance is excited mostly by the electric field, resulting to an electric response of the system, i.e., a resonance in the permittivity $\varepsilon(\omega)$, while the magnetic field component for oblique incidence plays a minor role in exciting the SRR resonance. Thus, our results provide further evidence for the existence and the importance of the EEMR effect and prove definitely the existence of magnetic response with negative magnetic permeability in the ~6 THz regime.

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