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

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Using transmission and reflection measurements in a five layers μm-scale split-ring resonators (SRRs) system, fabricated by a photolithography procedure, we 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 SRRs plane, which excites the resonant circular currents constituting the magnetic resonance.

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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 novel physics but also due to the new 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].

The experimental demonstration to date has definitively proven the existence of LHMs only in the GHz regime (1-100 GHz) while the achievement of negative magnetic permeability and LH behavior in the infrared and optical wavelengths is a target of intensive research. In the framework of this research there are claims for achievement of left-handed behavior in 1-2.7 THz [11] and at 2 μm [12], without though definitive proof of this behavior, and also there is experimental demonstration 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 SRRs 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 in respect to **E** (see configuration (b) of Fig. 1). Since EEMR is possible also for propagation normal to the SRR plane, it enables the experimental demonstration of a magnetic resonance through normal incidence transmission and/or reflection measurements, as in Refs. [14-16]. 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=μH), but as a resonance in ε (coming from the non-zero 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.

To demonstrate directly that an SRR metamaterial behaves as a negative μ material one has to introduce an external magnetic field perpendicular to the SRRs 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, $\mathbf{k}_{//}$. For oblique incidence one can achieve an **H** component perpendicular to the SRRs 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 5 layers μm-scale SRR metamaterial. These measurements confirm the occurrence of an 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 SRRs-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 7×7 μm^2 in the SRRs plane and 5 μm in the perpendicular direction; the SRRs 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 25×25 mm^2.

The transmission/reflection measurements have been taken using a Bruker IFS 66v/S FT-IR 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 φ=90°, where φ is the angle between the propagation vector **k** and the SRRs plane) in the 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 (φ=77°, 70°, 60°, 50°) incidence, for the configuration (a) of Fig. 1 (**E** parallel to the no-gap sides of the SRRs). At the minimum obliqueness case (φ=77°), the reflection (R) spectrum at ~6 THz shows a weak peak 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 in respect to **E** [17]. Thus, the changes in the reflection 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 SRRs 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 spectrum for the same SRR metamaterial and the same measurement procedure is depicted in Fig. 2(b). The dashed curve refers to normal incidence (φ=90°). The oscillations observed in the *T*-spectrum are due to the polyimide multilayer structure. However, at oblique incidence (φ = 80°, 60°) $\mathbf{H}_\perp$ excites the magnetic resonance. This is manifested also in the *T*-spectrum with the evolution of a dip for φ=80°, which broadens and deepens at φ=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 Fig. 3(a) the reflection spectra of the SRR metamaterial are presented for the configuration (b) of Fig. 1 (**E** parallel to the gap-bearing side of the SRRs). In the case of minimum obliqueness (φ=77°) the reflection (*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 incidence (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 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 the 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-layers single-ring SRRs system that there is indeed an 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 definitively the existence of magnetic response with negative magnetic permeability in the ~6 THz regime.

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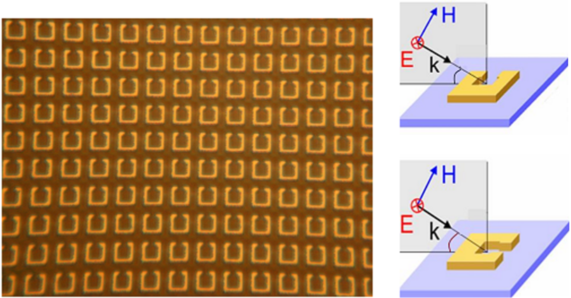
Figure captions

Fig. 1: *Left:* A photo of the structure studied. *Right:* The SRR and external EM field configurations studied; (a) Electric field (**E**) parallel to the SRRs sides with no gap and (b) **E** parallel to the SRRs sides with the gap.

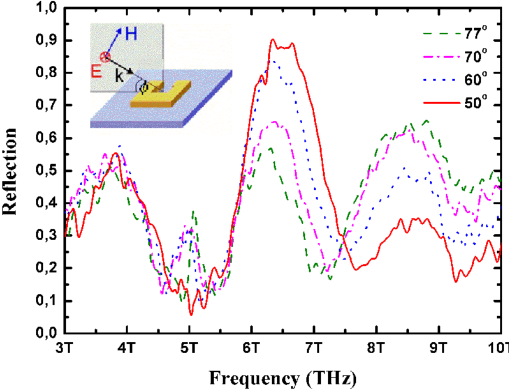
Fig. 2: (a): Measured reflection spectra at oblique incidence for our five layers SRRs system, for the configuration (a) of Fig. 1 (shown also in the inset). One can observe the evolution of a reflection peak as the angle ϕ changes (ϕ is the angle between **k** and the SRRs plane). (b): Measured transmission spectra as ϕ changes, for the configuration (a) of Fig. 1.

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

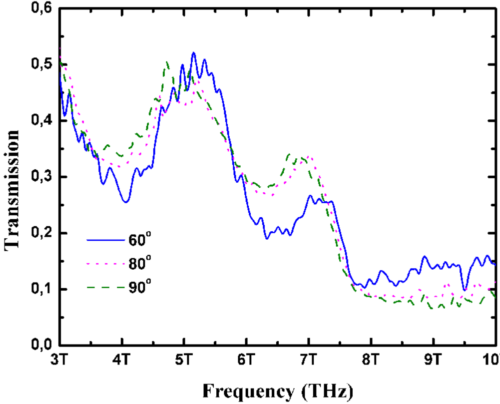


(a)

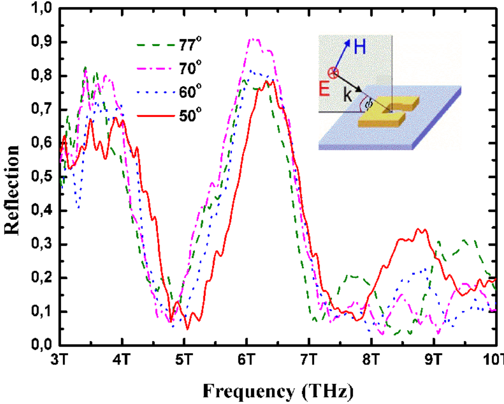
(b)



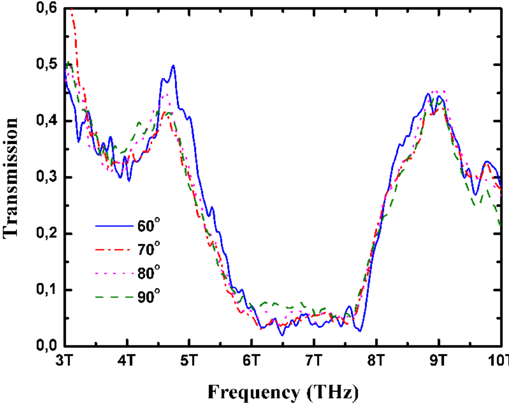
H
E
k
φ
77°
70°
60°
50°
Reflection
Frequency (THz)
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
3T
4T
5T
6T
7T
8T
9T
10T



0,6
0,5
0,4
0,3
0,2
0,1
0,0
Transmission
3T
4T
5T
6T
7T
8T
9T
10T
Frequency (THz)
60°
80°
90°



77°
70°
60°
50°
H
E
k
ϕ
Reflection
Frequency (THz)
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
3T
4T
5T
6T
7T
8T
9T
10T



0,6
0,5
0,4
0,3
0,2
0,1
0,0
Transmission
60°
70°
80°
90°
3T
4T
5T
6T
7T
8T
9T
10T
Frequency (THz)