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GHz magnetic response of split ring resonators

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Abstract

Measurements of engineered subwavelength microstructures can be designed to have positive or negative ε and μ at desired frequencies. We present transmission measurements of a metamaterial consisting of split ring resonators (SRR). Results for different polarizations and propagation directions are presented. The transmission shows a dip even for propagations perpendicular to the SRR plane, provided that the incident electric field is parallel to the sides of the split ring resonators (SRRs) which contain the cuts. The experimental results agree well with the theoretical calculations.

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Recently, left-handed materials (LHM) have attracted a great deal of attention, since these materials exhibit a negative refraction index *n*, and therefore can exhibit very interesting properties. It was Veselago who introduced the term "left-handed materials" in his seminal work published in 1968 [1]. The interest in Veselago's work was renewed since Pendry et al. [2] proposed an artificial material consisting of the so-called split ring resonators (SRRs), which exhibit a band of negative μ values in spite of being made of non-magnetic materials and wires which provide the negative ε behavior. Based on Pendry's suggestions and targeting the original idea of Veselago, Smith et al. demonstrated in 2000 the realization of the first left-handed material which consisted of an array of SRRs and thin wires in alternating layers [3].

Since the original microwave experiment of Smith et al., several LHMs were fabricated [4,5] that exhibited a pass band in which it was assumed that ε and μ are both negative. This assumption was based on transmission measurements of the wires alone, the SRRs alone, and the LHMs. The occurrence of a LHM transmission peak within the stop bands of the SRR and wire structures was taken as evidence for the appearance of LH behavior. Further support to this interpretation was provided by the demonstration that

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such LHMs exhibit negative refraction of EM waves [6,7]. Moreover, there is a significant amount of numerical work [8–11] in which the transmission and reflection data are calculated for a finite length of metamaterial. A retrieval procedure can then be applied to obtain the metamaterial parameters ε and μ under the assumption that it can be treated as homogeneous. This procedure was applied in [12] and confirmed that a medium composed of SRRs and wires could indeed be characterized by effective ε and μ whose real parts were both negative over a finite frequency band, as was the real part of the refractive index n. However, it was recently shown [13,14] that the SRRs exhibit a resonant electric response in addition to their resonant magnetic response, and, therefore, make the understanding and the fabrication of true LHMs more challenging.

In the present letter, we report numerical and experimental results for the transmission coefficent of a lattice of SRRs alone for different orientations of the SRR with respect to the external electric field E and the direction of propagation. It is considered an obvious fact that an incident EM wave excites the magnetic resonance of the SRR only through its magnetic field; hence, the magnetic resonance response appears only if the external magnetic field H is perpendicular to the SRR plane, which, in turn, implies a direction of propagation k parallel to the SRR plane. If H is parallel to the SRR, no coupling to the magnetic resonance was expected. We show in this paper that this is not always the case. If the direction of propagation is perpendicular to the SRR plane and the incident E is parallel to the sides of the SRRs which contain the cuts, an electric coupling of the incident EM wave to the magnetic resonance of the SRR occurs. Similar results were obtained by others for other cases of metamaterials [14,15]. Experiments, as well as numerical results based on the Microwave Studio, reveal that for propagation perpendicular to the SRR plane a dip in the transmission spectrum close to the magnetic resonance of the SRR appears whenever the electric field is parallel to the sides of the SRR where the gaps exist.

For the experimental study, a metamaterial consisting of SRRs was fabricated, using a conventional printed circuit board process with 10 μm thick copper patterns on one side of a 0.254 mm thick rexolite dielectric substrate. The rexolite board has a dielectric constant of 2.53 and a dissipation factor of 0.0009 at 1.5 GHz. The design and dimensions of the SRR are almost the same as those described in [5] and quite similar to those in [4]. The geometrical parameters of the SRR are $w = d = t = 0.33$ mm and $l = 3$ mm (see the inset in Fig. 1). The metamaterial was then constructed by stacking together the SRR structures in a periodic arrangement. The unit cell contains one SRR (with outer and inner rings) and has the dimensions 4.33 mm (parallel to the cut side), 3.63 mm (parallel to the continuous side), and 5.0 mm (perpendicular). The transmission measurements were performed in free space on an orthorombic metamaterial block consisting of 11 × 14 × 15 unit cells, using a Hewlett-Packard 8722 ES network analyzer and microwave standard-gain horn antennas.

We performed measurements for both propagation directions, perpendicular and parallel to the plane of SRRs. Fig. 1 presents the measured transmission spectra, T, of the SRRs for the perpendicular propagation direction. The magnetic field, H, is parallel to the plane of the SRRs, and, therefore, no coupling to the magnetic resonance of the SRR is expected. However, as one can see from the dotted line in Fig. 1, there is a dip in the transmission spectra around the 13 GHz region. No dip is observed in the case shown as a solid line in Fig. 1. The only difference between the solid and the dotted lines in Fig. 1 is the direction of the incident electric field E. In the dotted line case of

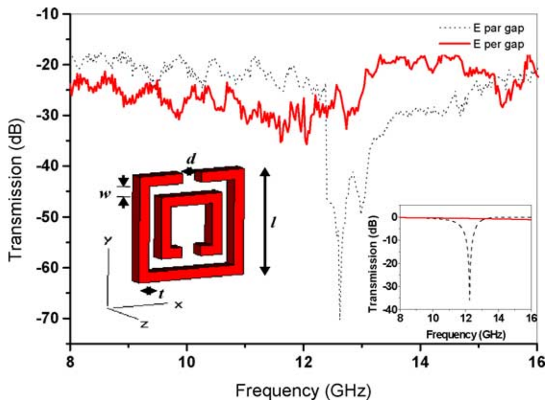

Fig. 1. Measured transmission spectra of a lattice of SRRs for propagation direction perpendicular to the plane of SRRs (along the z-axis) for both directions of the electric field E. The solid line has E along the y-axis, while the dotted line has E along the x-axis. The inset shows the calculated transmission spectra using Microwave Studio software.

Fig. 1, where the dip in *T* is present, *E* is parallel to the gaps of the SRR (along the *x*-axis). In the solid line case of Fig. 1, where there is no structure in *T*, *E* is perpendicular to the gaps of the SRRs (along the *y*-axis). Our results suggest that the magnetic resonance of the SRRs can be also excited by the electric field. In the insert of Fig. 1, we present the numerical results, which are in good agreement with the measurements. They predict what direction of *E* gives a dip in transmission, as well as the frequency position of the dip. The numerical results were obtained by the commercial software Microwave Studio. In our numerical analysis we only use a unit cell and this is the reason for the narrow dip seen in the inset of Fig. 1. If more unit cells were used in the calculation, the dip will become wider, as in the experiment.

In Fig. 2, we present the measurements for the conventional case, where *H* is perpendicular to the SRR and the propagation direction is parallel to the plane of the SRRs. Notice that *T* exhibits a stop band due to the magnetic resonanace of the SRR. Both the solid (*E* parallel to the gaps of the SRRs) and the dotted (*E* perpendicular to the gaps of the SRRs) lines in Fig. 2 exhibit a stop band. In the inset of Fig. 2 we present the numerical results, obtained with the Microwave Studio, which are in good agreement with the measurements. We have, therefore, demonstrated both experimentally and numerically that the magnetic resonance of the SRR can be also excited by the electric field, provided that *E* is parallel to the gaps of the SRRs. If one closes the gaps of the SRRs [13], the dips seen in Figs. 1 and 2 disappear, which means that the dips in *T* are due to the magnetic response of the SRRs.

In Fig. 3, we present the magnitude of the magnetic field, obtained with the Microwave Studio, for the cases presented in Fig. 1. The frequency is 12.64 GHz, exactly at the position of the transmission dip. In

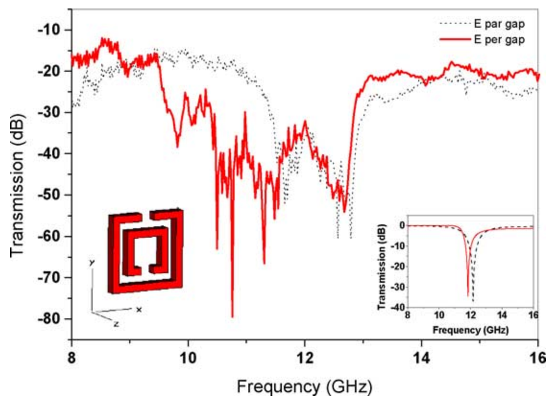

Fig. 2. Measured transmission spectra of a lattice of SRR for propagation direction parallel to the plane of SRRs (along the *x*-axis) for both directions of the the electric field *E*. The solid line has *E* along the *y*-axis, while the dotted line has *E* along the *z*-axis. The inset shows the calculated transmission spectra using Microwave Studio software.

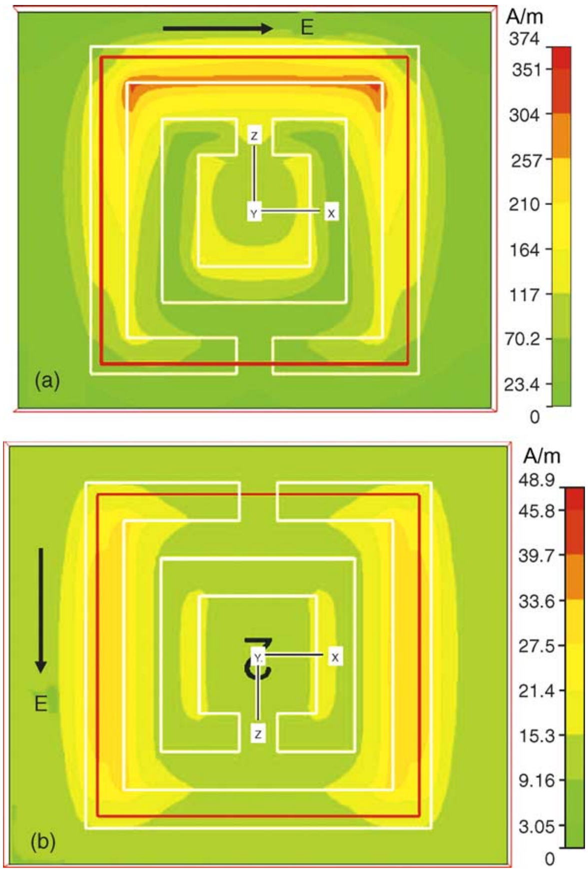

Fig. 3. The polarization currents in two different orientations of a single ring SRR, as obtained by Microwave Studio. For both cases, the propagation direction is perpendicular to the plane of SRRs. (a) The external electric field points along the *x*-axis, parallel to the sides of the SRRs which contain the cuts. In this case a circular current is present, which can excite the magnetic resonance of the SRR. (b) The external field is parallel to the sides of the SRRs without cuts (along the *z*-axis). For this direction no circular current is generated, only a field along the sides of the SRR that does not have gaps, but has a non zero current. Therefore, no coupling to the magnetic resonance of the SRR is possible.

Fig. 3a, E is parallel to the gaps of the SRRs. One clearly sees a circular current that can excite the magnetic resonance of the SRR. In Fig. 3b, E is perpendicular to the gaps of the SRRs. In this case the polarization current only flows up and down the sides of the SRRs. Hence no circular current appears, no coupling to the magnetic resonanace of the SRR is noted, and no dip in the transmission spectra is seen. Marques et al. considered bianisotropy in SRR structures and developed an analytical model to evaluate the magnitude of cross-polarization effects [16].

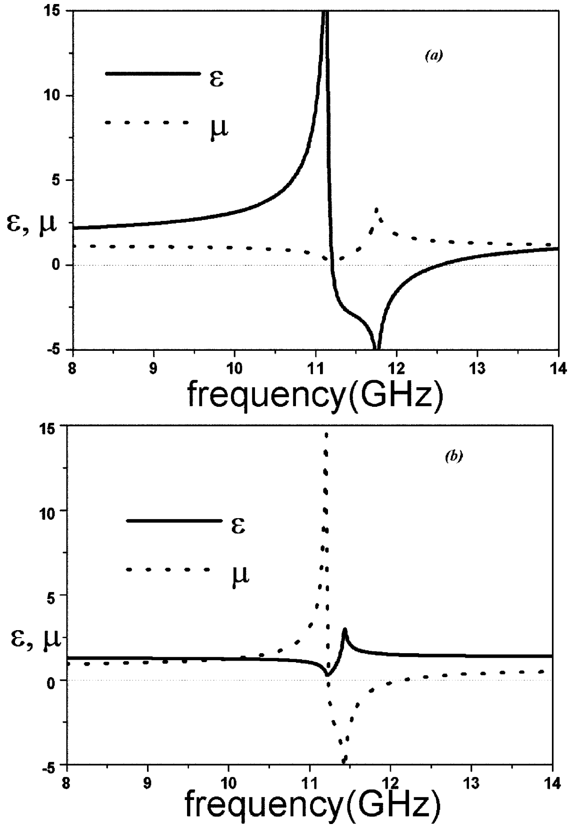

Fig. 4. The retrieval values of ε and μ for two different orientations of a single ring SRR, as obtained by our retrieval method [12]. (a) The propagation direction is perpendicular to the plane of the SRRs and the external electric field points parallel to the gaps of the SRR. In this case no negative μ is obtained, only the ε is negative. Notice that an antiresonance is obtained for the magnetic permiability μ. (b) The propagation direction is parallel to the plane of the SRRs and the external field is parallel to the gaps of the SRRs. For this direction a negative μ is generated, as expected. Notice that an antiresonance is obtained for the electrical permittivity ε.

In Fig. 4, we present the results for effective values of the electrical permittivity ε and the magnetic permiability μ obtained by our retrieval procedure [12]. In Fig. 4a, the propagation direction is perpendicular to the plane of the SRRs, and the electric field points parallel to the gaps of the SRRs. In this case the retrieval procedure does not give a magnetic resonance, and no negative value of μ is obtained. However, there is an electric resonance response, as revealed by the negative value of ε shown in Fig. 4a. As discussed in [12], there is an anti-resonance response in μ, as clearly seen in Fig. 4a. In Fig. 4b, the propagation direction is parallel to the plane of the SRRs, and the electric field points parallel to the gaps of the SRRs. In this case the retrieval procedure does give a magnetic resonance response, as expected, and a negative value of μ is obtained. In this case, too, an anti-resonance response is obtained for ε.

In summary, we have presented experimental and numerical results for the propagation of EM waves for different orientations of the SRR. It is found that the incident electric field couples to the magnetic resonance of the SRR, provided its direction is parallel to the gaps of the SRRs. There is an excellent agreement between numerical results and experiments. This unexpected electric coupling to the magnetic resonance of the SRR is of fundamental importance in understanding the transmission properties of SRRs and LHMs. This new finding might be very important for the design of LHMs in higher dimensions.

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