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Scattering of electromagnetic waves in metamaterial superlattices

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The authors study experimentally both transmission and reflection of microwave radiation from metamaterial superlattices created by layers of periodically arranged wires and split-ring resonators. The authors measure the dependence of the metamaterial resonance on the spatial period of the superlattice and demonstrate resonance broadening and splitting for the binary metamaterial structures. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2741148]

Metamaterials are artificial composite structures designed to exhibit a macroscopic response to electromagnetic waves not found in natural materials. One type of such microstructured materials with exotic properties in the microwave range is created by arrays of electrically small split-ring resonators (SRRs) and long wires; such structures are known to possess negative effective dielectric permittivity and negative magnetic permeability.[1] It has been shown that metamaterials possess quite unusual properties such as negative refraction[2] and allow imaging by a flat lens with subwavelength resolution.[3] Many more interesting linear and nonlinear effects were predicted theoretically.

Most experimentally studied metamaterials are made from *regular periodic arrays* of SRRs and wires. However, the first theoretical studies of *disordered metamaterials*[4,5] demonstrated that disorder in the resonant frequencies of the individual constituent resonators can decrease and even suppress completely the resonant response and negative magnetic permeability of the microstructured composite. Experimental studies of the metamaterial containing identical resonators, but slightly randomized in their arrangement, were reported in Ref. 6, where it was shown that a small deviation from the regular structure can also suppress the negative response of the metamaterial. Another type of nonuniform metamaterial was suggested in Ref. 7 where, instead of SRRs, the authors used resonators of a more complicated form which possess multiple resonances. A metamaterial of this type has been used to form a dual-band microwave resonator.[8]

In this letter, we summarize our experimental studies of the free-space scattering properties of a microwave metamaterial created by layers of printed circuit boards with SRRs and wires arranged to form a superlattice. First, we study both transmission and reflection of electromagnetic waves from a regular structure with different spacings between the layers. Then, we arrange the boards in different superlattice configurations, and analyze the dual resonance behavior of the metamaterial. In contrast with earlier studies, the resonance splitting is achieved in a material with *identical* resonators but with a superlattice arrangement of the SRR board layers.

Our experimental metamaterial sample consists of 30 1.6 mm thick FR4 printed circuit boards. Each circuit board has a lattice of SRRs etched on one side and a lattice of wires etched on the other [see Fig. 1 (top)]. The lattice of parallel wires has a period of 8.8 mm, and each wire is parallel to the x axis. The SRRs on each board form a square lattice with a period of 8.8 mm, and the geometry of individual SRRs was chosen to be the same as that reported earlier in Ref. 9, i.e., the internal radius of each SRR is 1.6 mm, the width of both rings is 0.9 mm, and the gaps between the rings and the ring slots are all 0.2 mm. The number of resonators on each board is 5×29. In order to control the spacing between the boards, which for brevity we will call "spacing" in the rest of this letter, we made 4 mm holes in the corners, and the boards were put together on M4-threaded nylon rods. The dielectric rods were chosen instead of metallic rods in order to minimize unwanted reflections. To control the spacing, we used sets of nylon washers, each washer being 0.8 mm thick. When the material was assembled, we used nylon nuts to

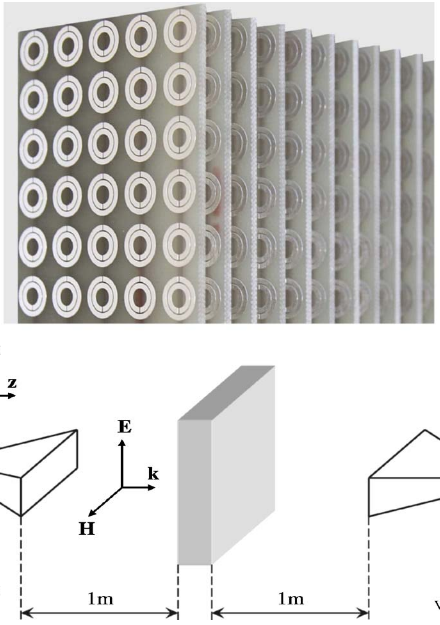

FIG. 1. (Color online) Top: Metamaterial sample used in the experiment. Bottom: Experimental setup for free-space measurements.

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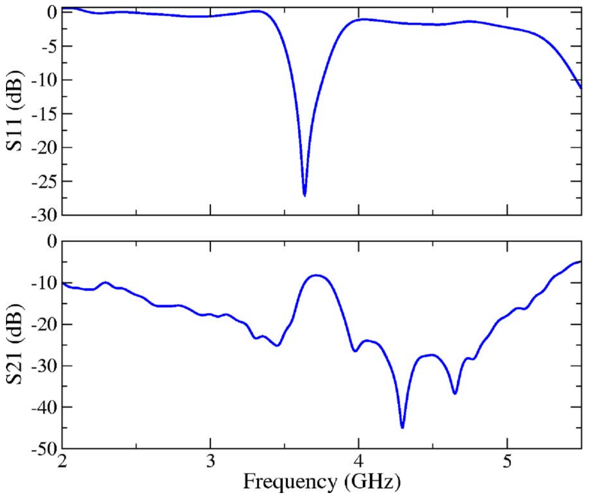

FIG. 2. (Color online) Reflection S_{11} (top) and transmission S_{21} (bottom) coefficients for a regularly arranged metamaterial layer with the spacing of 7.2 mm.

keep the boards together. Such a setup provides a rigid metamaterial structure with a high positional accuracy of the boards, and it proved to be convenient for quick rearrangement of the metamaterial structure, particularly for creating different superlattices.

The experiments were performed in an anechoic chamber in order to diminish reflections from surrounding objects. The metamaterial was mounted in a dielectric (Delrin) frame on a tripod, so that the boards were parallel to the direction of electromagnetic wave propagation. The frame was designed in such a way that one can insert two copper plates to measure the reflection from the metal surfaces positioned at the same planes as the surfaces of the metamaterial sample. Such reflection measurements are needed for normalization of the measured results. The designed frame setup provided an accurate positioning of the sample and allowed sequential experimental measurements. In order to suppress diffraction of the waves around the sample, we attached a microwave absorber around the frame. Broadband microwave horn antennas (ETS-Lindgren 3115) were placed 1 m on either side of the sample [see Fig. 1 (bottom)], so that the material was exposed to a vertically polarized incident wave. The horn antennas were connected to a ZVB-20 Rohde and Schwartz vector network analyzer. We used time-domain gating in order to exclude the effect of reflections from the antennas and connectors, so that only reflections from the frame-metamaterial setup were measured. To account for the contribution of the frame in our measurements and the attenuation due to radiation in unwanted directions, we normalized the reflection (S_{11}) of the metamaterial measured in the dielectric frame to the reflection with the metal plate in the frame. The transmission (S_{21}) was normalized to the transmission through the empty frame. Typical reflection and transmission curves for a regular periodic metamaterial structure are shown in Fig. 2. Improved transmission and decreased reflection occur in the same frequency range as reported in the earlier work,[9] and we attribute this to the presence of a left-handed transmission band.

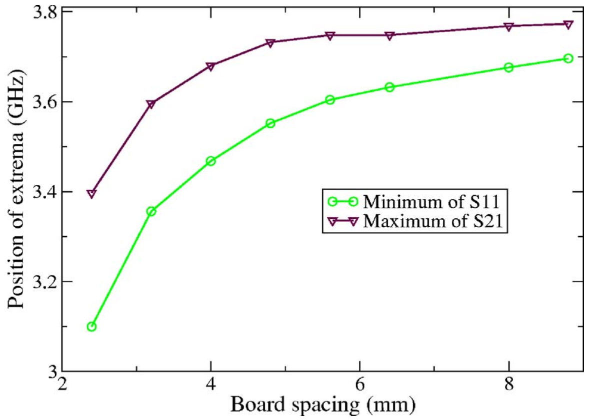

FIG. 3. (Color online) Position of the minimum of the reflection coefficient and maximum of the transmission coefficient as a function of board spacing.

Firstly, we studied the effect of different spacings between the boards on the resonance frequency of the composite. Previous theoretical work has shown that the resonant frequency of the composite metamaterial can be significantly lower than the eigenfrequency of a single resonator[10] due to the mutual inductance between resonators. By varying the spacing we change the mutual inductance between resonators, and we expect a shift of the resonant frequency of the whole composite. Indeed, by placing the boards closer together, the mutual inductance is increased, and therefore we expect a decrease in the resonant frequency of the metamaterial sample. We measured the frequencies of the minimum of the reflection coefficient and the maximum of the transmission coefficient as functions of the spacing and show them in Fig. 3. We observe a shift of the reflection resonance of more than 15% of the resonant frequency as we change the spacing from 2.4 to 8.8 mm. The maximum of the transmission coefficient is shifted toward higher frequencies with respect to the minimum of the reflection coefficient. This may be caused by losses being stronger at the resonance and decaying for higher frequencies, thus significantly modifying the transmission coefficient.

Next, we studied the superlattice structures in which spacing alternates between 2.4 and 8.8 mm. In the reflection from such a structure, we observe a significant broadening of the response with the signature of a second reflection peak [see Fig. 4 (top)]. The resonance depth is also decreased, as compared to Fig. 2. The transmission shows several maxima [see Fig. 4 (bottom)].

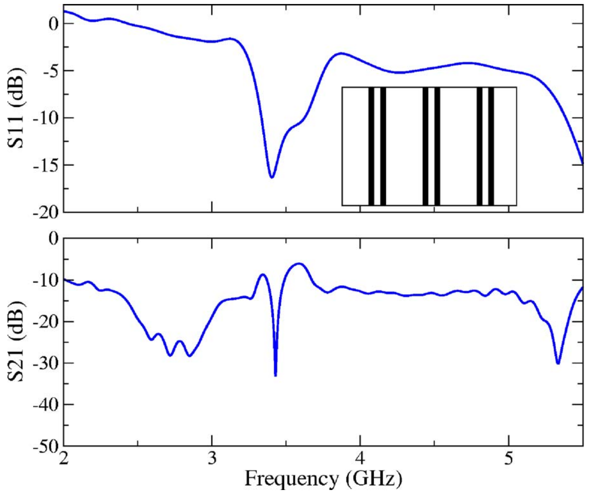

FIG. 4. (Color online) Reflection S_{11} (top) and transmission S_{21} (bottom) for the structure with the spacing alternating between 2.4 and 8.8 mm. The inset in the top figure shows schematically board arrangement in the superlattice.

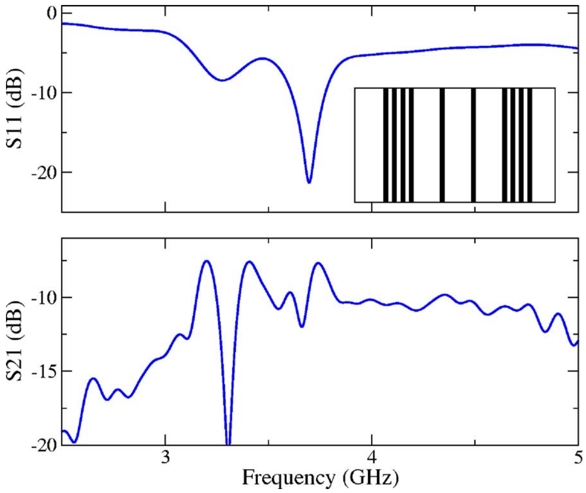

FIG. 5. (Color online) Reflection S_{11} (top) and transmission S_{21} (bottom) for the structure with alternating four boards with the spacing of 2.4 mm and four boards with the spacing of 8.8 mm. The inset in the top figure shows schematically board arrangement in the superlattice.

We note here that we have observed strong sensitivity of the metamaterial response to positioning accuracy and disorder. The reflection and transmission extrema are strongly suppressed by a relatively weak disorder in the position of the boards, which is in agreement with previous theoretical and experimental results.[4,5,9] The effect of rarefied defects predicted in Ref. 5 was also studied for a sample with one different spacing in the middle of the structure. The reflection minimum was significantly modified, indicating a weaker resonant magnetic response compared to a regular structure.

Finally, we studied a superlattice made of alternating blocks containing four boards separated by 2.4 mm and four boards separated by 8.8 mm. These two spacings were chosen so that the difference of resonant frequencies is significant enough to see separate resonances. Using superlattice with almost identical spacings will result in a wider band without two independent resonances. The results of these measurements are summarized in Fig. 5, which shows the appearance of two reflection minima and several transmission maxima.

The experimental results reported here do not allow direct retrieval of the effective parameters of the metamaterial. Free-space measurements are usually used to determine the material properties at higher frequencies, where the requirement for the samples to be much larger than the wavelength is more easily fulfilled. Our sample had a transverse size of around two wavelengths at the resonant frequency. This renders invalid the one-dimensional model approximation for the scattering parameters, which is used to relate them to the effective electromagnetic properties of the structure. Some of the possible techniques to retrieve effective properties of a composite metamaterial for low frequencies were demonstrated in Ref. 11, where either measurement of wave scattering on metamaterial samples of different thicknesses or measurement of the angle of refraction of the wave on a wedge shaped sample was suggested.

We note that analytical treatment of superlattices can be done as a straightforward generalization of the structure with regular array of SRRs, which was done in Ref. 10. The double-resonance structure of the metamaterial response will appear due to modified mutual impedance matrix of the composite.

In conclusion, we have studied the scattering of microwave radiation from a sample of composite metamaterial with varying periodicity in one dimension. We have shown that the reflection and transmission resonances can be shifted by more than 15% of the resonant frequency, allowing for mechanical tuning of the electromagnetic properties of metamaterials. We have demonstrated that using superlattice structure for arranging the metamaterial constituents, one may obtain several reflection and transmission resonances.

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