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Negative index materials using simple short wire pairs

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Negative refraction is currently achieved by a combination of artificial "electric atoms" (metallic wires with negative electrical permittivity ε) and artificial "magnetic atoms" (split-ring resonators with negative magnetic permeability μ). Both ε and μ must be negative at the same frequency, which is not easy to achieve at higher than THz frequencies. We introduce improved and simplified structures made of periodic arrays of pairs of short metal wires and continuous wires that offer a potentially simpler approach to building negative index materials. Using simulations and microwave experiments, we have investigated the negative index n properties of short wire-pair structures. We have measured experimentally both the transmittance and the reflectance properties and found unambiguously that $n<0$. The same is true for ε and μ. Our results show that short wire-pair arrays can be used very effectively in producing materials with negative refractive indices.

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The first demonstration of a left-handed (LH) material[1,2] by the UCSD group, in 2000, following the work by Pendry *et al.*,[3,4] underscores the relevance of utilizing structured materials to create electromagnetic response not available in naturally occurring materials. This LH material made use of an array of conducting, nonmagnetic elements to achieve a negative effective permeability, $\mu(\omega)$, and an array of conducting continuous wires to achieve a negative effective permittivity, $\varepsilon(\omega)$, the simultaneous combination of which had never before been observed in any previously known material. While a number of theoretical concerns were raised shortly after the reporting of these experiments, subsequent measurements[5–8] on similar metamaterials have firmly established the foundation of negative refraction. LH materials will display unique "reversed" electromagnetic properties, as discussed by Veselago[9] long before such materials existed. All of these reversals stem from the fact that a LH material is characterized by a negative refractive index, a property that does not exist in any known natural material, and represents a new regime of physics.

In the past few years there has been ample proof for the existence of negative index materials (NIMs) in the GHz frequency range.[1–8] All NIM implementations to date have utilized the topology proposed by Pendry, consisting of split-ring resonators (SRRs) (rings with gaps, providing the negative μ) and continuous wires (providing the negative ε). Many groups were able to fabricate[1,2,5–8] NIMs with an index of refraction $n=-1$ with losses of less than 1 dB/cm. Recently, different groups observed indirectly[10–13] negative μ at the THz region. In most of the THz experiments[10–12] only one layer of SRRs was fabricated on a substrate and the transmission, T, was measured only for propagation perpendicular to the plane of the SRRs, exploiting the coupling of the electric field to the magnetic resonance of the SRR via asymmetry.[11] This way it is not possible to drive the magnetic permeability negative. Also, no negative n with a small imaginary part has been observed yet at the THz region. One reason is that it is very difficult to measure with the existing topology of SRRs and continuous wires both the transmission, T, and reflection, R, along the direction parallel to the plane of the SRRs. So there is a need for alternative, improved, and simplified designs that can be easily fabricated and experimentally characterized. Currently, there is much interest in pushing the frequency range for NIM behavior into the infrared and optical regions of the spectrum.

Designing a material structure to have an effective negative refractive index can be achieved by having simultaneously negative permeability and negative permittivity over some range of frequencies. Nearly all negative index materials that have been investigated up until this point have been based on the use of split-ring resonators, which have been described in detail elsewhere.[1,2,5,6] Conceptually, an SRR starts with a loop of wire that provides an inductive response to an incident field. Cutting out a short section of the loop leads to a capacitive gap. The inductance (L) and capacitance (C) together form an LC resonator, with resonance frequency $\omega_R=1/\sqrt{LC}$. For an electromagnetic wave incident with its wave vector parallel to the plane of the SRR and the magnetic field perpendicular to the SRR, the response at the resonance frequency will be as if the SRR had a negative permeability. To build a negative index material, an array of SRRs is combined with a grid of continuous metal wires, which is known to exhibit a negative permittivity,[3] so that the two effects together lead to NIM behavior.

Recent theoretical work[14] has shown that using pairs of finite length wires would not only allow replacing the SRRs as magnetic resonators but could also give simultaneously a negative ε in the same frequency range, and therefore a negative n, without the need for additional continuous wires. The condition to obtain simultaneously negative μ and ε by pairs of finite metallic wires is very restrictive. Recent experiments[15] have not shown evidence of negative n in the

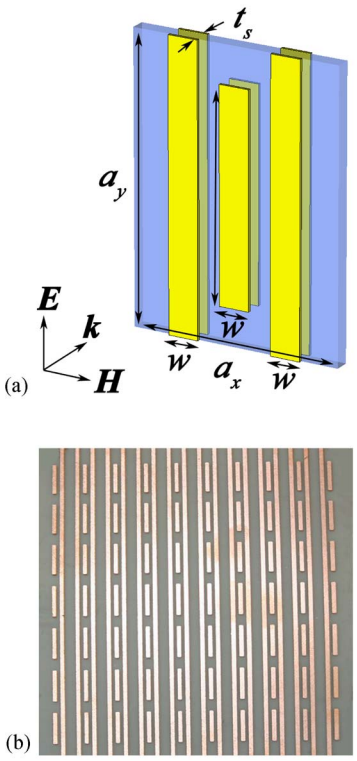

FIG. 1. (Color online) (a) Schematic representation of one unit cell of the wire-pair structure. (b) Photograph of one side of a fabricated microwave-scale wire-pair sample.

short wire-pair cases that were studied. This is in contrast with the claims[16] that one can get negative n at THz frequencies.

In this Communication, we report our investigations of wire-pair structures as alternatives to conventional SRR-based NIMs. The basic structure of a single unit cell of the wire-pair NIM is shown in Fig. 1(a). In the wire-pair arrangement, the conventional SRR is replaced with a pair of short parallel wires and the continuous wires are preserved. The short wire pair consists of a pair of metal patches separated by a dielectric spacer of thickness t_s. In essence, the short wire pair is a "two-gap" SRR that has been flattened to result in the wire-pair arrangement.[15] For an electromagnetic wave incident with wave vector and field polarization as shown in Fig. 1(a), the short wire pair will exhibit both inductive (along the wires) and capacitive (between the upper and lower adjacent ends of the short wires) behavior and will possess magnetic resonance providing a negative permeability. The inductance L of a short wire pair is approximately given, as inductance of parallel plates, by $L=\mu_o(l\cdot t_s)/w$, where l is the length of the short wires, w is the width, and t_s is the separation distance between the short wires. The capacitance C of the short wire pairs can be written as the two plate capacitor formula for the upper and lower halves of the short wire pair $C=\varepsilon_r\varepsilon_o(l\cdot w)/(4t_s)$, where ε_o is permittivity in vacuum and ε_r is the relative dielectric constant of the region between the wires. Then the frequency of the magnetic resonance is

$$f_m=\frac{1}{2\pi\sqrt{LC}}=\frac{1}{\pi l}\frac{1}{\sqrt{\varepsilon_r\varepsilon_o\mu_o}}=\frac{c_o}{\pi l\sqrt{\varepsilon_r}}, \quad (1)$$

where c_o is the speed of light in vacuum. From (1), the magnetic-resonance frequency is inversely proportional to the length of the wires in the pairs, but does not depend on the wire widths or separation between the wires. Resonance frequencies determined by detailed simulations of short wire-pair structures with various combinations of parameters (l,w,t_s) show good agreement with the simple formula above. However, our simulations have shown that it is difficult to obtain a negative n with only pairs of short wires. This is because the electric resonance of the short wires is usually well above the magnetic-resonance frequency, thus preventing ε and μ from becoming simultaneously negative. To realize NIM behavior, the short wire pairs must be combined with a continuous wire grid that provides the extra negative permittivity. In our structure, two additional continuous wires are placed on either side of the short wire pairs. Repeating this basic structure periodically in the x, y, and z directions would result in a NIM structure.

The short wire-pair arrangement has a distinct advantage over conventional SRRs. Since all of the features of the wire-pair NIM lie in parallel planes, conventional microfabrication techniques can be used to build the structures. In particular, the methods for making complex multilevel interconnects in integrated circuits could be applied directly to making wire-pair NIMs.

To examine the potential usefulness of wire-pair structures as NIMs, we characterized the properties of the wire pair of Fig. 1(a) using simulations and microwave measurements, and then used these results to determine the expected properties of NIMs built from the wire-pair building blocks. Simulations of wire-pair structures were done with CST Microwave Studio (Computer Simulation Technology GmbH, Darmstadt, Germany), which uses a finite-difference time-domain method to determine reflection and/or transmission properties of metallodielectric structures. In the simulations, the dielectric properties of the metal patches were handled with a frequency dependent Drude model. The detailed calculations were used to determine reflection and transmission coefficients from a single unit cell. Experimental transmission and reflection data were obtained by building and measuring microwave-frequency versions of the wire-pair structures. These were fabricated using Rogers 5880 printed circuit board stock with a dielectric layer thickness of 254 μm and a listed relative dielectric constant of 2.53. The circuit board was coated on both sides with 10-μm-thick layers of copper. The copper was formed in the wire-pair patterns using conventional photolithography techniques. For the samples reported here (both simulations and experiments), the widths of all metal lines were 1 mm. The length of the short wire pairs was 7 mm, and the unit-cell size was $9.5\times7\times2.274$ mm^3. The total sample size was $7\times10\times1$ unit cells, resulting in approximately square samples. A photograph of one side of a complete sample is shown in Fig. 1(b). With these patterned dimensions on the printed circuit board material, the resonances for NIM behavior were expected to occur near 13.7 GHz.

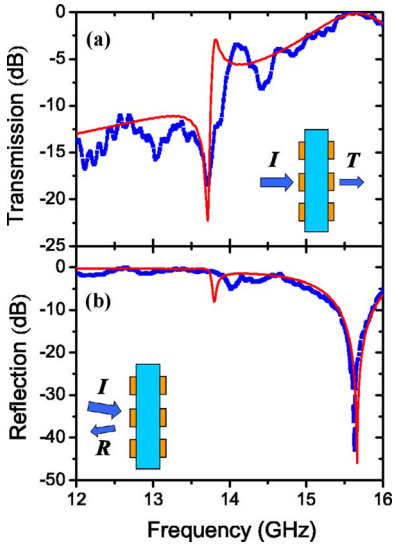

FIG. 2. (Color online) Simulated (red thin line) and measured (blue thick-dotted line) response to electromagnetic radiation incident on the wire-pair structures: (a) transmission, (b) reflection.

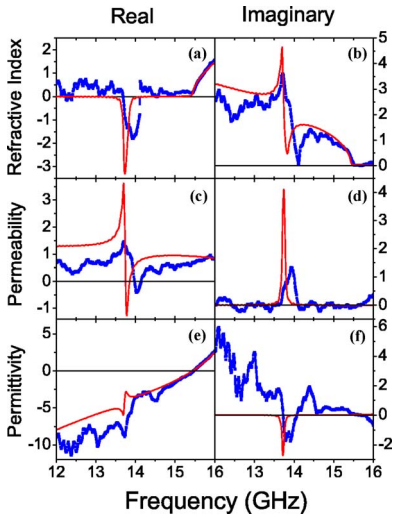

FIG. 3. (Color online) Extracted electromagnetic properties of a periodic array of wire-pair unit cells, using the simulated (red thin line) and measured (blue thick-dotted line) data of Fig. 2. Real (a) and imaginary (b) parts of the refractive index. Real (c) and imaginary (d) parts of the permeability. Real (e) and imaginary (f) part of the permittivity. The negative-index behavior can be seen clearly near 14 GHz in (a).

Transmission and reflection properties of a single-layer structure were measured over the frequency range of 12–16 GHz using a network analyzer (HP 8510) and a pair of standard gain horn antennas serving as a source and receiver, as shown in the insets of Fig. 2. In the transmission measurements, the microwaves were incident normal to the sample surface. This is a tremendous simplification relative to the conventional SRRs and wires where the incident electromagnetic waves have to propagate parallel to the sample surface. With the conventional orientation of the SRRs, it is almost impossible to do these types of measurements at the THz region, since only single-layer samples are usually fabricated.[10,11] Transmission measurements were calibrated to the transmission between the horns with the sample removed. The reflection measurements were done by placing the source and receiving horns on the same side of the sample and bouncing the microwave signal off the sample. The source and receiver horns were each inclined with an angle of about 7.5° with respect to normal on the sample surface. The reflection measurement was calibrated using a sample-sized sheet of copper as a reflecting mirror. In both measurements, the electric field of the incident wave was polarized parallel to the long dimension of the wires. (For perpendicular polarization, the transmission was nearly 100%, independent of frequency in the resonance region, and reflection was essentially zero.)

The calculated and measured transmission spectra are shown in Fig. 2(a). Figure 2(b) shows the calculated and measured reflection spectra. There is good qualitative agreement between simulations and measurements. The measured spectrum does show resonance peaks and valleys due to reflections between the receiving horn and the sample. Also, there is a distinct frequency difference between critical points in the two sets of curves. The frequencies of the measured transmission resonance peak and the corresponding reflection dip near 14.0 GHz are about 2% higher than in the simulations. There are three potential causes for the shift: (1) The external resonances in the measurements may be masking the true peak (dip) in the measured data. (2) The actual dielectric constant of the circuit board material may be slightly lower than the value used in the simulations. (3) The wires on the front and back of the dielectric layer may be misaligned slightly, which would have the same effect as shortening the wires. The dip in the reflection at 15.7 GHz is due to the fact that the sample impedance $z=1$ at that frequency, and so no reflection is possible.

Using the transmission and reflection results from a single layer, we can extract the effective refractive index that would result if a periodic multilayer sample were built using the single-layer structure as a building block. The details of the numerical retrieval procedure have been described elsewhere.[17–19] In performing the retrieval, we have assumed a z-direction size of the unit cell of 2.274 mm. This interlayer spacing is an adjustable parameter in the retrieval process. Smaller spacing would lead to stronger negative index features in the periodic structure, as long as the distance between the short wires is small compared to the length of the unit cell, but may also result in more complicated fabrication procedures in building a multilayer structure. In choosing 2.274 mm as the separation distance for the numerical extraction, we attempted to strike a balance between good negative index properties and having a separation distance that is in line with the other feature sizes of the structure. The extracted permittivity, permeability, and refractive index are shown in the various parts of Fig. 3. The plots show that the real part of the permittivity is negative over most of the measured range.[20] The real part of the permeability is negative over a resonance band near 13.8 GHz for the simulation and at about 14.0 GHz for the measurement. Notice also that

the product of Im(ε) and Im(μ) is negative. This is a well known and real effect, which comes from the periodic effects of the retrieval procedure.[11] It is not relevant to the discussion of our results. The extracted real part of the refractive index is negative[21] over a narrow band at 13.8 GHz for the simulations and 14.0 GHz in the experiments, dipping as low as -2 using measured data, and to less than -3 from the simulation. The ratio of the imaginary part of n to the real part of n is $\frac{1}{4}$, which means that we have left-handed propagation with ε, μ, and n negative. Our preliminary numerical results show that if our structure scales down by a factor of 200, it will give a negative index of refraction at THz frequencies, with both ε and μ negative.

These results show clearly the viability of using short wire pairs to build negative index materials, if combined with additional continuous wires. It is likely that modifications of the basic structure studied here may improve or alter the NIM properties. Also, wire-pair arrangements with significantly different geometries may lead to negative index materials. The relative ease of fabricating wire-pair structures may hasten the development of NIMs working at optical wavelengths.

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[20] We have also done experiments and simulations for samples with only pairs of short wires. For this case both the experiments and the simulations have shown that indeed μ is negative, however ε is not negative in this region and therefore n is also not negative. The extra continuous wires are needed to drive ε to become negative, without changing the magnetic response shown in Fig. 3(c).

[21] In lossy materials it is possible to have the real part n be negative, without having the real parts of ε and μ simultaneously negative. This is the case of the recent work of S. Zhang, W. J. Fan, N. C. Panoiu, K. J. Malloy, R. M. Osgood, and S. R. J. Brueck. [Phys. Rev. Lett. **95**,137404 (2005)]. This can happen if the imaginary parts of ε and μ are sufficiently large, because in a lossy material $n=n'+in''$, and we also have that $n=\varepsilon z$ and $z=\sqrt{\mu/\varepsilon}$. After some algebra we obtain that $n'=\varepsilon' z'-\varepsilon'' z''$ and $z=\sqrt{\mu'\varepsilon'+\mu''\varepsilon''/\varepsilon^2+i(\mu''\varepsilon'-\mu'\varepsilon''/\varepsilon^2)}$, so it is possible to have $n'<0$, provided that $\varepsilon'' z''>\varepsilon' z'$. In this scenario, which occurs at the low-frequency side of the $n'<0$ region in Fig. 3(a), however, the imaginary parts lead to dominant losses such that we have a transmission gap with some negative phase shift rather than LH transmission (with some losses). This type of negative n should not be considered LH behavior. In our experiments, although we have considerable imaginary parts, the behavior is still dominated by the negative real part of n at the high-frequency side where we find the LH behavior. As one can see from the experimental data of Figs. 3(a) and 3(b), we obtain $n'/n''=3.5$ at $n'=-1$, which ratio improves to ~ 15 for $n'=-0.76$. The simulation data gives at least $n'/n''\approx 3.0$ for $n'=-1.7$.

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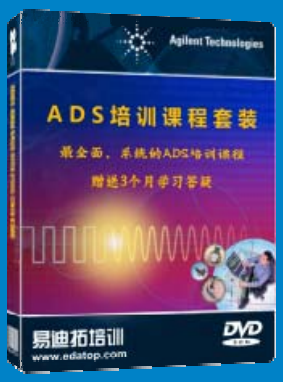

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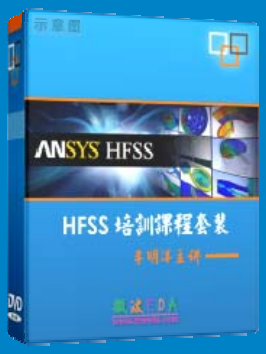

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