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Experimental demonstration of negative index of refraction

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We introduce an improved and simplified structure made of periodic arrays of pairs of H-shaped metallic wires that offer a potentially simpler approach in building negative-index materials. Using simulations and microwave experiments, we have investigated the negative-index n properties of these structures. We have measured experimentally both the transmittance and the reflectance properties and found unambiguously that a negative refractive index with $\mathrm{Re}(n)<0$ and $\mathrm{Im}(n)<\mathrm{Re}(n)$. The same is true for ε and μ. Our results show that H-shaped wire pairs can be used very effectively in producing materials with negative refractive indices. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2208264]

The first demonstration of a left-handed (LH) material[1,2] by the University of California-San Diego (UCSD) group in 2000, following the work by Pendry *et al.*,[3,4] started a field of structured materials to create electromagnetic response not available in naturally occurring materials. This LH material[5–8] made use of an array of conducting, nonmagnetic ring-shaped local resonator elements to achieve a negative effective permeability, $\mu(\omega)$, and an array of conducting continuous wires to achieve a negative effective permittivity, $\varepsilon(\omega)$, a simultaneous combination that has never before been observed in any previously known material. LH materials display unique "reversed" electromagnetic properties, as discussed by Veselago[9] long before such materials existed.

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] Most 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 $n=-1$ and 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. 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.[14–16] However, the currently observed negative index in the THz region[12] is actually due to significant imaginary parts of ε and μ, which lead to a dominant imaginary part of n and consequently result in a rapid attenuation of electromagnetic wave, which make such kinds of metamaterial inapplicable.

In this letter, we report our investigations into wire-pair structures as alternatives to conventional SRR-based NIMs. The basic structure of a single unit cell of the NIM built from H-shaped wires is shown in Fig. 1(a). In the wire-pair arrangement, the conventional SRR is replaced with a pair of short parallel wires, which provide both negative magnetic and electric responses; the continuous wires are not necessary. The short wire pair consists of a pair of metal patches separated by a dielectric spacer of thickness t_s. For an electromagnetic wave incident with a wave vector and field polarization as shown in Fig. 1(a), the short wire pair will pro-

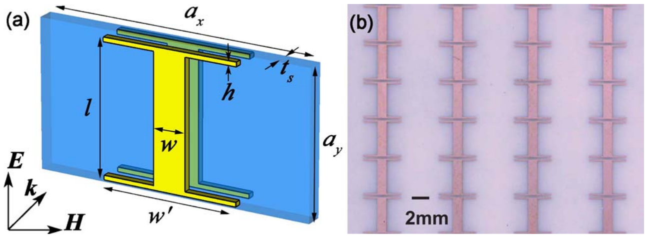

FIG. 1. (Color online) (a) Schematic representation of one unit cell of the wire-pair structure. (b) Photograph of fabricated microwave-scale wire-pair sample.

[a)] Author to whom correspondence should be addressed; electronic mail: soukoulis@ameslab.gov cess not only a magnetic resonance resulting in a negative μ,[15–17] but also an electric resonance with a negative ε simultaneously. The magnetic resonance originates from the antiparallel current in the wire pair with an opposite sign charge accumulating at the corresponding ends; the electric resonance is due to the excitation of parallel current in the wire pair with the same sign charge accumulating at the corresponding ends of both wires. Repeating this basic structure periodically in the x, y, and z directions would result in a NIM structure.

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/transmission amplitudes of metallodielectric structures. In the simulations, the dielectric properties of the metal patches were described by a frequency-dependent Drude model. The detailed calculations were used to determine the reflection and the transmission coefficients from a single unit cell with a periodic boundary condition in the direction perpendicular to the direction of the incident wave. 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 width of the metal wires was 1 mm. The length and the width of the metal bars at each end of the wire pairs were 4 and 0.2 mm, respectively. The length of the short wire pairs was 4 mm, and the unit cell size was $4.2\ \text{mm} \times 8\ \text{mm} \times 2.274\ \text{mm}$. The total sample size was $9 \times 17 \times 1$ 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 15.8 GHz.

Transmission and reflection properties of a single-layer structure were measured over the frequency range of 14–18 GHz using a network analyzer (HP 8510) and a pair of standard gain horn antennas serving as the source and receiver. 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.)

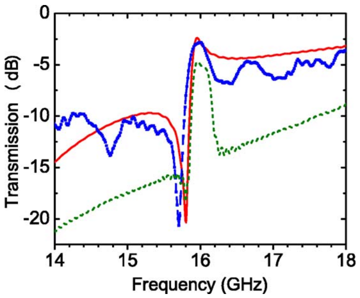

FIG. 2. (Color online) Simulated (red solid curve) and measured (blue dotted curve) transmission spectra for electromagnetic radiation incident on the wire-pair structures. The green dashed curve shows the simulated transmission spectrum for a five-layer sample.

The calculated and measured transmission spectra are shown in Fig. 2. There is good qualitative agreement between simulations and measurements. To demonstrate the appearance of the expected LH transmission band more clearly than it is visible from the single unit cell spectra, we include the simulated transmission through five unit cells as the dashed line in Fig. 2. The measured spectrum does show additional resonance peaks and valleys due to reflections between the receiving horn and the sample. 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 in detail elsewhere.[18–20] In performing the retrieval, we have assumed a z-direction size of the unit cell of 2.274 mm, such that the individual wire-pair layers are separated from each other by a significant air space. The extracted refractive index is shown in Fig. 3 and the extracted permittivity and permeability are shown in Fig. 4. The plots show that the real part of the permittivity is negative over most of the measured range. The real part of the permeability is negative over a resonance band above 15.8 GHz for both the simulation (approximately 15.87–16.00 GHz) and the measurement (approximately 15.82–15.98 GHz). The extracted real part of the refractive index is negative[21] over a narrow band around 15.8 GHz for

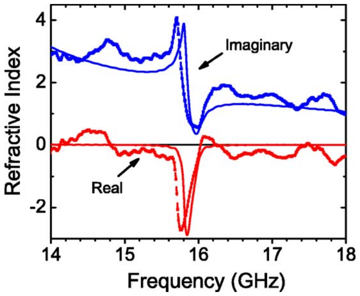

FIG. 3. (Color online) Extracted refractive index n of a periodic array of wire-pair unit cells, using the simulated (solid curves) and measured (dotted curves) transmission and reflection data. The red and blue curves show the real part of n and imaginary part of n, respectively.

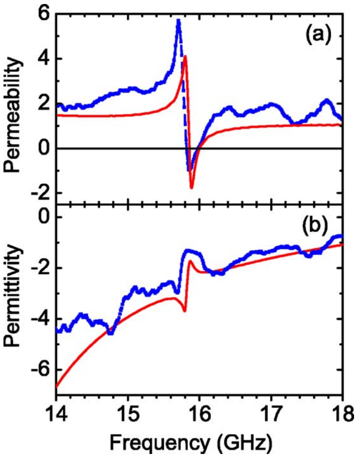

FIG. 4. (Color online) (a) Extracted permittivity ε and (b) permeability μ of a periodic array of wire-pair unit cells, using the simulated (red solid curves) and measured (blue dotted curves) transmission and reflection data.

both the simulations (15.59–16.17 GHz) and the experiments (15.67–16.02 GHz), dipping as low as −2.66 using measured data and −2.86 from the simulation. The ratio of the imaginary part of n to the real part of n reaches 1/3 above the resonance, which means that we have LH propagation with ε, μ, and n negative. The simplicity of the short-wire pair design and the alleviation of the need for continuous wires generating the negative effective permittivity is expected to facilitate scaling of the structure to achieve a LH response well within the THz region. However, the reader should be aware that straightforward geometric scaling of the present design is not possible as the behavior of the metals changes from lossy conductors in GHz to lossy, negative dielectrics in the higher THz region.[22] Our preliminary numerical results show that a negative index LH band with both ε and μ negative, and a n'/n'' ratio better than 6 can be achieved combining the second order magnetic resonance with the first order electric resonance for Drude-model silver short-wire pairs at around 490 THz.

These results clearly show the viability of using short wire pairs to build negative-index materials. 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 structure pairs may hasten the development of NIMs working at optical wavelengths.

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[21] In lossy materials it is possible to have the real part n to 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, 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 Fig. 3, we obtain $n'/n''=2$ for experiment and $n'/n''=3$ for simulation at $n'=-2$.
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