Experimental Observations of a Left-Handed Material That Obeys Snell's Law

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We measure two-dimensional profiles of collimated microwave beams transmitted through composite wire and split-ring resonator prisms. Prior experiments suggest these structures have a negative index of refraction, though these claims have been questioned. Our 2D measurements demonstrate that transmission obeys Snell's law with a negative index, confirming the refractive nature of this signal and refuting alternatives posed in the criticisms. In addition, we present preliminary evidence that a flat rectangular slab of this material can focus power from a point source.

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The index of refraction of traditional materials is positive, requiring curved surfaces or inhomogeneous structures to construct lenses which focus light [1]. Recently, however, there have been reports of new, artificial materials which can have a negative index [2], in theory allowing a homogeneous flat slab of the material to behave as a "perfect" lens [3], for which numerous applications in science and medicine can be expected [4–6]. These materials, known as left-handed media (LHM) [7], were realized using regularly structured composite materials producing a negative index in the microwave regime [8]. However, theorists have since questioned whether materials with a negative index are possible [9], and have predicted undesirable side effects such as dispersion and loss when implemented [10]. Furthermore, the flat lensing ability of these materials has remained beyond the reach of experiment, and the ability to transcend the diffraction limit has also been questioned theoretically [11]. Here we produce new experimental evidence showing that transmission through these materials obeys Snell's law with a negative index. We also provide preliminary evidence of focusing behavior.

The recent LHM realization involved measurement of the angle of refraction of a microwave beam by an angled LHM prism [2], with corroborating numerical support [12]. This ground-breaking experiment introduced a key method for constructing the LHM using a millimeter-scale composite resonator structure of metallic wires and rings operating in the microwave regime. It was proposed that if the wire and ring resonators could be crafted independently to have negative permittivity and permeability in the desired frequency regime, then a combination of the two in a three-dimensional structure would give negative index behavior [2,8]. While this work was revolutionary, it remained open to question on two points. First, the transmitted power was measured only at the perimeter of the waveguide, measuring only a cross section of the beam at a fixed distance from the prism. Moreover, the experiment measured only a single angled prism; this is sufficient to confirm a negative index only if transmission through the material is assumed refractive. However, at least two prisms are needed to verify that Snell's law applies and thus transmission is refractive. These points admit the possibility of other explanations of the reported data; in particular, the results can be attributed to near-field effects due to either rapid dispersion along the direction of propagation [9] or smaller amounts of attenuation on the shorter side of the prism [10]. These effects would not produce an angled beam, but rather a deflected peak in output power at the waveguide perimeter whose position does not obey Snell's law. In the experiment reported in Ref. [2], this signal would be similar to that of a negative index material.

We address these concerns by constructing a new experimental apparatus. Our setup allows complete measurement of the two-dimensional profile of the electric field at all points inside a completely closed waveguide; this also eliminates edge effects. Using this apparatus, we perform two experiments. In the first, we verify the refractive nature of transmission through LHM materials by measuring complete angled beams from multiple prisms. In the second experiment, we measure transmission from a point source through a flat slab of material and show that a focused concentration of power appears at the output. In both, we show that while naively combining negative permittivity and permeability materials is insufficient to create a LHM, the system can be adjusted to achieve negative index behavior. The apparatus and two experiments are described in detail below.

Our measurement apparatus consists of a two-dimensional waveguide formed by parallel aluminum plates with a fixed input antenna and an effectively scannable output antenna. The bottom plate of this apparatus is a 42 cm $\times$ 27 cm piece of aluminum with microwave absorber on all sides. At 1 cm from the midpoint of the long side, an 8 mm input antenna consisting of the bare center conductor of a semirigid coaxial cable rises perpendicular to the plate. The top plate of the waveguide is twice the size of the bottom plate in each dimension, with an identical antenna pointing down into the waveguide.

This antenna measures the electric field inside the cell. The bottom plate is attached to a translation stage with 50 cm $\times$ 50 cm travel. Because the top plate is much larger than the bottom plate, the 2D waveguide confined by the absorber attached to the bottom plate remains unchanged even as the bottom plate is translated. Thus, translating the bottom plate has no effect other than to change the relative position of the output antenna to the bottom plate. In this way, we can effectively scan the output antenna over the entire cell, measuring a complete two-dimensional electric field profile in a waveguide whose perimeter is completely sealed with absorbing material. Additionally, because the material behavior is sensitive to the height of the top plate above the material, the plate is mounted on four stepper motors capable of controlling the height to within 0.1 mm. In these experiments, power is sourced at -2 dBm by an HP 8673e synthesized generator, and measured with an Agilent E4407B spectrum analyzer.

Our material reproduces the wire and ring structures of Ref. [8] with 50 μm thick tin-plated copper on a 0.5 mm thick GML-1000 circuit board substrate with a 6 mm lattice constant (Fig. 1). The material is designed to work in a two-dimensional waveguide at X-band microwave frequencies, where the material can be treated as homogeneous because the ≈ 3 cm wavelength is much larger than the lattice constant. Transmission measurements on lattices containing only one type of element verify the performance of the wires and resonators independently. Assuming the permittivity ϵ and permeability μ are negative in the frequency range where the material reflects a majority of the power [14], there is a broad region of negative ϵ above 9.5 GHz for the wires and a narrow band of negative μ between 11 and 12 GHz for the resonators. In the region where both $\epsilon < 0$ and $\mu < 0$, we expect a transmitting band with negative index of refraction [8]. A possible passband exists at 10.5 GHz with the top plate of the waveguide touching the top of the material. However, this region shows no signs of negative index of refraction. After raising the top plate of the waveguide 2 mm above the top of the material, a stronger passband emerges at 10.5 GHz, which does show a signature for a negative index of refraction. This is the configuration used in all the experiments described below.

We determine the index of refraction of our material at 10.5 GHz by measuring the angle of refraction of a beam normally incident on a prism whose opposite face is cut at an angle (Fig. 2). Microwaves emitted from the input antenna in our waveguide are collimated with a horn made from absorbing form, and the electric field profile of the microwaves emerging from the prism is measured. Measurements are taken on four prisms. As a control, refraction from a Teflon prism with $\varphi = 18°$ is measured. We then measure our composite material with the top waveguide plate lowered. Finally, to confirm that transmission through LHM is refractive, we measure

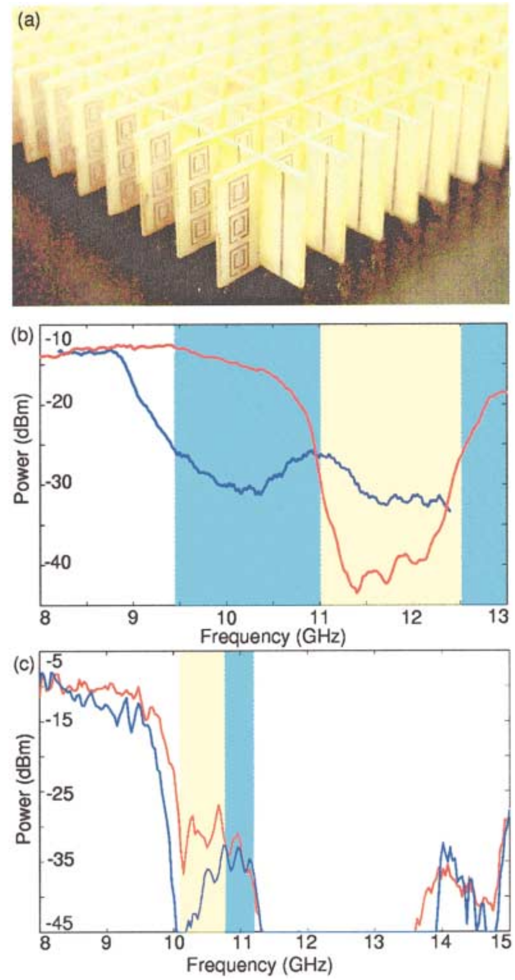

FIG. 1 (color). A composite material with a negative index. (a) A photograph of the composite material, showing arrays of split-ring resonators and vertical wires. The individual strips are cut from sheets of printed circuit board using a computer controlled laser cutter. This cutting process often leaves a thin carbon film on the surface of the board; we have found that care is needed in removing this film in order to see LHM behavior. (b) Transmission spectra for a material with only wires (blue) and a material with only resonators (red). The low transmission regions correspond to negative ϵ (shaded blue) or negative μ (shaded tan). Transmission is measured through a flat slab of material as a spatial average of the emerging beam. The high transmission at low frequency for the wires is not in agreement with the model proposed by Ref. [13]; however, it is clear that we have $\epsilon < 0$ in a broad frequency range. Microwaves are sourced at -10 dBm in these experiments. (c) Transmission through composite material with plate touching top of material (blue) and raised 2 mm (red). Transmission is high for low and high frequencies, where both ϵ and μ are positive. The LHM passband (shaded tan) emerges from the feature at 10.5 GHz (shaded blue and tan) as the height of the top waveguide plate is raised via stepper motors. We believe this is due to a change in capacitance from the vertical wires to ground. From 1.5 to 3 mm above the top of the material, we observe LHM behavior. Even in this passband, losses are still on the order of 20–25 dB. Above 3 mm, we begin to see leakage above the material, which appears as broadband noise that overwhelms the LHM signal.

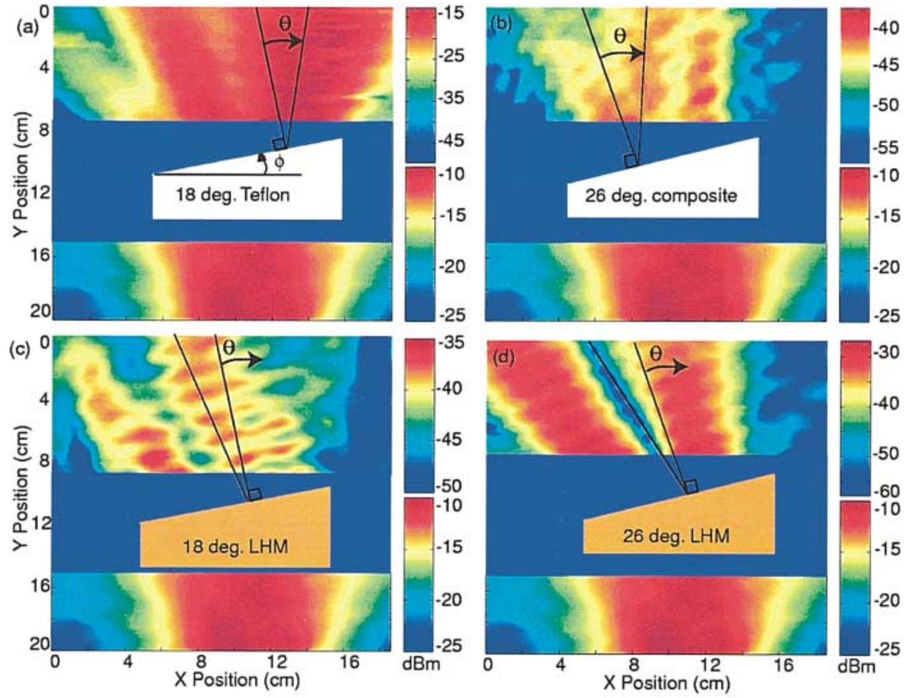

FIG. 2 (color). Results of a microwave scattering experiment to measure the angle of refraction from a prism with a single angled surface. The input antenna is at the bottom of the scans, and the propagation is towards the top of the figure. Absorbing foam is used in the lower half of the figures to both collimate microwaves and prevent leakage out of the sides of the prism. The measured indices were (a) $n = 1.5$ for Teflon with a $\varphi = 18°$ face. (b) $n = 1.3 \pm 0.15$ for our composite material with a $\varphi = 26°$ face and the top plate lowered. (c) $n = -0.36 \pm 0.13$ for our composite material with a $\varphi = 18°$ face and the top plate raised. (d) $n = -0.35 \pm 0.08$ for our composite material with a $\varphi = 26°$ face and the top plate raised.

transmission through two different LHM prisms, with angles $\varphi = 18°$ and $\varphi = 26°$, and with the top plate raised. Snell's law, that $n_0 \sin\varphi = n \sin\theta$ (where $n_0 \approx 1.00$ for air), is verified only if a consistent value of the index n describes the output angle θ from multiple prisms.

Data from these four prisms are shown in Figs. 2(a)–2(d). In all four scans, the refracted signal has a broad structure due to the imperfect collimation of the input source. In the LHM scans, two lobes appear due to the corrugation of the refractive surface [2]. All data are single scans. A least-squares fit to a power weighted average of the data points is used to determine the propagation direction of the transmitted beam. In the case of the Teflon prism [Fig. 2(a)], this analysis yields $\theta = 28° \pm 2°$, corresponding to $n = 1.52 \pm 0.07$, compared to the actual index for Teflon, $n = 1.5$. We observe only 5 dB of attenuation after propagating through the Teflon prism. With the $\varphi = 26°$ composite material prism [Fig. 2(b)], and the top waveguide plate lowered, we observe strongly attenuated transmission at $\theta = 35° \pm 5°$, corresponding to $n = 1.3 \pm 0.15$, indicating that the material is not an LHM. When the $\varphi = 18°$ LHM prism is placed in the cell, with the top waveguide plate raised, we measure an attenuation of 25 dB, but the refracted signal is clearly on the negative index side of the normal [Fig. 2(c)]. Using Snell's law, the signal at $\theta = -6.4 \pm 2.4°$ corresponds to an index of $n = -0.36 \pm 0.13$. We can verify that this result is indeed refraction and not some other effect by measuring the transmission from the $\varphi = 26°$ prism of LHM, also with the top plate raised [Fig. 2(d)]; for this prism, the transmitted beam propagates at $\theta = -9 \pm 2°$, corresponding to $n = -0.35 \pm 0.08$, with lower attenuation because the prism is thinner. Because both angled prisms show propagation according to Snell's law with a consistent index, this clearly demonstrates that the observed signal corresponds to refraction from a negative index medium.

Given this successful observation of negative index refraction, we now examine the hypothesis that a flat rectangular slab of the LHM material can act as a lens, and image a point source to another point [3]. If the material were infinite and lossless, with $n = -1$, theory predicts that a perfect image of the point source would appear both inside and on the far side of the material, surpassing the diffraction limit of conventional optical materials [3,4]. However, finite size effects, loss, and the index mismatch will cause the transmission to appear more collimated [15]. We place a 6 cm thick piece of material at a distance of 2 cm from the input antenna, and scan the transmitted region, beginning 1.5 cm from the edge of the material [Fig. 3(a)]. Applying Snell's law in this case, we expect to see an elongated image of the point source with highest concentrations of power beginning 4 cm from the edge of the material.

The electric field profile of the transmitted radiation is presented in Fig. 3(b). We see a concentration of power that is removed from the edge of the material. This focused image supports the claim that a flat slab of homogeneous LHM can act as a lens. It is an elongated image of a point source, as expected due to the small index and lossiness of the material. The power is removed from the edge of the material by 2.5 cm, closer than we would have expected given the measured index, but not surprising given the breadth of the transmission in

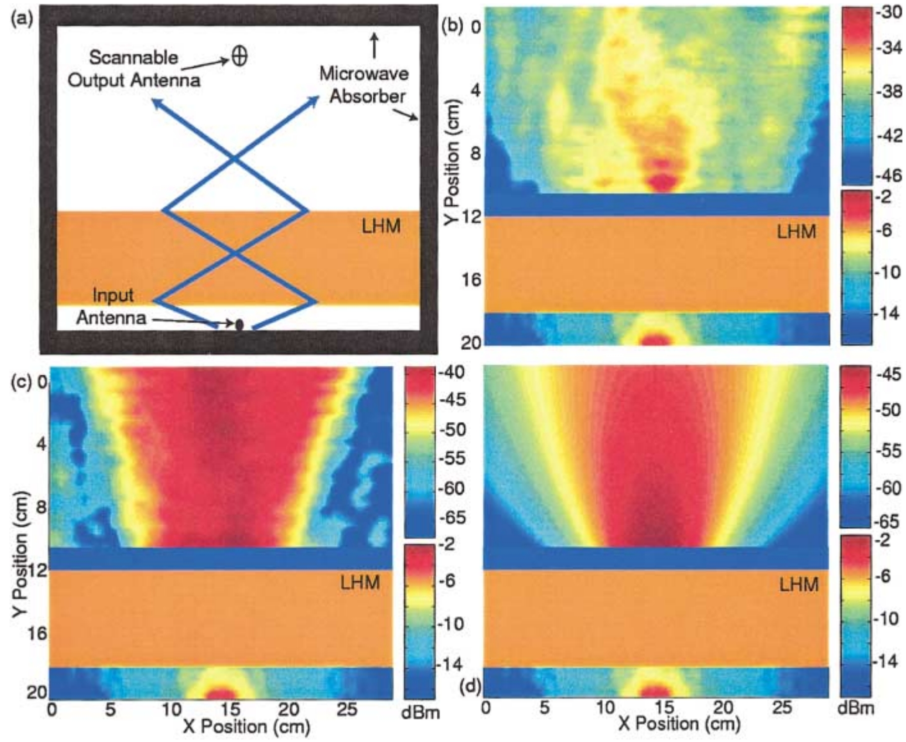

FIG. 3 (color). Experimental observations of LHM focusing. (a) A flat rectangular slab of LHM is placed in front of an antenna that serves as a point source. The radiation from the input antenna with no LHM present is shown in the bottom halves of (b), (c), and (d), to show the power incident on the material. (b) With the plate raised 2 mm, we see an elongated focus, removed from the surface of the material. The dark blue region at the edge of the material was not scanned. (c) Transmission through the material with the plate lowered. The focusing effect disappears, confirming that it is due to the negative index of the material. (d) Theoretical electric field profile expected from a lossy material with index $n = 1.3$, but 6 dB/cm attenuation. Path length differences through the material result in a collimated image similar to transmission through our material with the plate lowered. This lossy medium is one of the most common failure modes of our LHM.

the prism experiment. Furthermore, with the top plate lowered — a configuration that does not show negative index behavior—the focus disappears. This behavior [Fig. 3(c)] is consistent with the theoretically calculated transmission profile of a material with a positive index ($n = 1.3$, as measured in the prism experiment) and a high degree of attenuation, 6 dB/cm [Fig. 3(d)]. Taken as a whole, these data indicate focusing behavior associated with a negative index of refraction.

While these results are encouraging, they are still only the first steps towards making LHM a practical reality. The design of these materials is more complicated than first thought. It is not sufficient to design independent media with negative ϵ and μ, as the composite material shows extreme sensitivity to its electromagnetic environment even when the individual elements do not. The high loss will need to be reduced, and the discrete nature of the material adversely affects transmission. Also, a free-space material is necessary for most potential applications. However, despite the subtleties involved in material design, we have shown that transmission through these composite materials is a refractive effect, described by a negative index in accordance with Snell's Law.

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