# Microwave solid-state left-handed material with a broad bandwidth and an ultralow loss

L. Ran,[1,2] J. Huangfu,[1,2] H. Chen,[1,2] Y. Li,[1,2] X. Zhang,[1,2] K. Chen,[1,2] and J. A. Kong[1,3]
[1]*Electromagnetics Academy at Zhejiang University, Zhejiang University, Hangzhou 310027, People's Republic of China*
[2]*Department of Information and Electronic Engineering, Zhejiang University, Hangzhou 310027, People's Republic of China*
[3]*Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
(Received 16 April 2004; published 20 August 2004)

We present in this paper a solid-state sample of microwave metamaterial produced by a standard hot-press technique for the manufacture of printed circuit boards. We performed three experiments to demonstrate that this sample is a left-handed material with negative refractive index. The three experiments are power transmission, prism refraction, and beam shifting. We used differently shaped samples for the experiments and observed clear left-handed behaviors in a 1-GHz-wide passband with an insertion loss of less than 0.5 dB per unit cell, which is no greater than the insertion loss of many microwave devices. The sample has very stable characteristics and all results are consistent with one another.

DOI: 10.1103/PhysRevB.70.073102 PACS number(s): 78.20.Ci, 41.85.Ja, 42.25.Bs, 42.25.Fx

## I. INTRODUCTION

The left-handed material (LHM), introduced by Veselago in 1968,[1] was experimentally verified in 2001[2] by using metamaterial fabricated with periodical patterns composed of a unit split-ring resonator and conducting wire. These periodical patterns were proposed by Pendry.[3,4] Controversy immediately followed concerning the validity of the beam refraction experiment[5] and the fundamental issue of whether the negative refraction phenomena associated with LHM can physically exist.[6] Rebuttals of such theoretical issues were addressed[7,8] and more beam refraction experiments were repeated.[9,10] All such experiments used unit patterns proposed by Pendry, and printed on circuit boards that are interlocked or arranged in a honeycomb form. The metamaterial sample is fragile, with high loss, and with a narrow bandwidth. In this paper we produce a solid-state metamaterial sample using a unit pattern with a $\Omega$-like shape. The sample is used to verify the phenomena of negative refraction by first repeating the beam refraction experimentation, and then using the setup for a transmission measurement and a beam shifting experiment. All three experiments verify the negative refraction phenomena. The sample is shown to have a very low insertion loss and broad frequency band, as well as stable mechanical and electromagnetic characteristics, which satisfy the requirements for real practical applications.

## II. METHOD FOR PRODUCING A SOLID-STATE SAMPLE

We have shown that a proper arrangement of $\Omega$-like rings can yield a clean and wide band of negative index of refraction, where losses are smaller than those reported using other ring geometries.[11] In this paper, we use two series-stacked $\Omega$-like metallic patterns to serve as the basic resonator unit to be printed on a PC board. Applying a standard hot-press technique for the manufacture of printed circuit boards, we further produced a solid-state metamaterial sample of the left-handed medium by compressing pieces of alternately stacked PC boards with and without the $\Omega$ patterns. Figure 1 shows the photograph of the sample and its fabrication process. The inner and outer radii of the $\Omega$ pattern are 1.5 and 1.9 mm, respectively. The length of the arm of the $\Omega$ is 2.3 mm and the gap between the two arms is 0.4 mm. The width of the printed track is also 0.4 mm. The $\Omega$ patterns are printed on the two sides of a 1-mm-thick standard PC board substrate with reversed orientations in order to cancel chiral effects.[12] Each unit cell occupies a 5-mm space. The boards without $\Omega$ patterns have the same permittivity value (2.65) as those printed with $\Omega$ patterns, and have thicknesses of 2 mm. The pieces of the PC boards with and without $\Omega$ patterns are stacked and compressed under a temperature above 380 °C and an initial pressure above 4 tons. We performed three experiments to demonstrate that this sample is a LHM with negative refractive index. The three experiments are power transmission, prism refraction, and beam shifting. We used differently shaped samples for the experiments and observed clear left-handed behaviors in a 1-GHz-wide passband with an insertion loss of less than 0.5 dB per unit cell.

## III. TRANSMISSION MEASUREMENT

Figure 2 shows the experimental power transmission property of a metamaterial slab, consisting of ten unit cells and 100 layers of printed and empty PC boards. In Fig. 2(a), the curve corresponding to the transmission property of a metamaterial slab is represented by a solid line and has a passband with a center frequency at 8.85 GHz and a bandwidth near 1 GHz, which is in good agreement with the simulation result shown in Fig. 2(b). The detected peak value is −14.8 dBm at 8.85 GHz. To estimate the insertion loss of the metamaterial slab, we measured the transmission power in the same experimental setup after the metamaterial slab is removed. The result is represented by a dashed line in Fig. 2(a), in which the corresponding value at 8.85 GHz is −9.8 dBm, which can be approximated as the power incident upon the interface of the slab and air. Thus, with a return loss at the incident interface, the maximum insertion loss of the slab composed of ten unit cells will be less than 5 dB, corresponding to a 0.5-dB loss for each unit cell.

## IV. PRISM REFRACTION EXPERIMENT

Figure 3(a) shows the experimental results of the prism refraction experiment, in which the horizontal axis represents

 

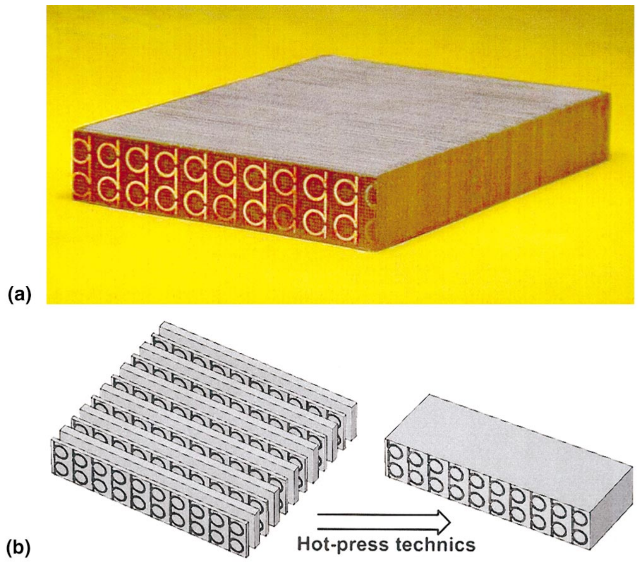


FIG. 1. (Color) (a) Photograph of the solid-state sample. (b) Diagram of the fabricating method.

frequency, the vertical axis represents the refraction angle, and the contour lines represent the detected power in dBm. In the experiment, the setup is the same as that described in Ref. 2, and has also been tested with a Teflon sample. We see that the frequency band below 8 GHz is a stop band; only

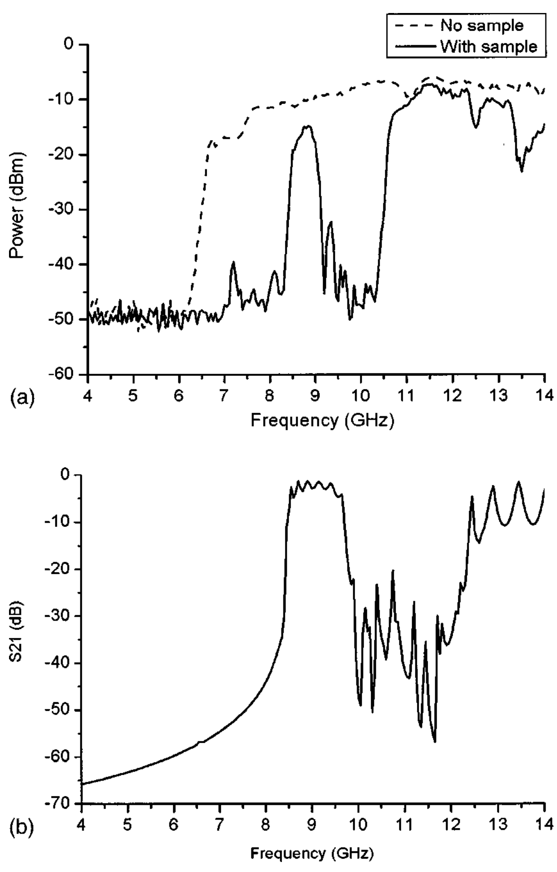


FIG. 2. Power transmission results: (a) Experimental and (b) simulation results.

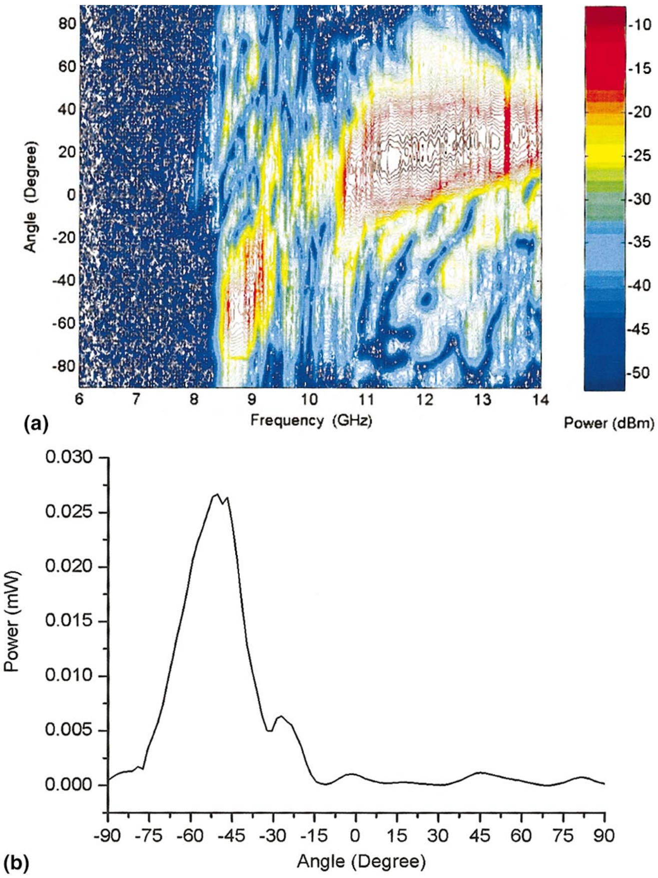


FIG. 3. (Color) Experimental results of negative refraction: (a) Three-dimensional illustration and (b) result for 8.85 GHz.

noise power can be detected. The frequency band from 8.3 to 9.3 GHz shows clear left-handed behavior, in which the beam is bent toward negative angles. Figure 3(b) shows a cut plane of Fig. 3(a) at 8.85 GHz. The refractive angle is about −50°, corresponding to a refractive index of −2.44. Above 10.5 GHz, the output power is bent to positive angles, corresponding to the behavior of a right-handed medium.

## V. BEAM SHIFTING EXPERIMENT

An electromagnetic beam, when incident at an angle upon a slab of medium, will shift its position at the exit plane of the slab from its straight path. For a slab of LHM, its position of the beam will shift much more than that of normal right-handed material.[13,14] Figure 4 shows the beam shifting results. The experiment is performed in a planar waveguide with microwave absorbers on the two sides. The metamaterial sample, as well as a Teflon sample, is cut into a shape of a parallelogram. The thickness of the slab is 5 cm and the incidence angle is about 18.4°. A beam shift exceeding the location of −15 mm will ensure that the slab consists of LHM. For a detailed experimental setup and analysis, please refer to Ref. 15. In Fig. 4(b), determined by the peak value of each curve, the beam centers in the cases of air, Teflon, and the metamaterial sample are located at 1, −3, and −23 mm, respectively, demonstrating that the metamaterial sample is indeed a left-handed medium.

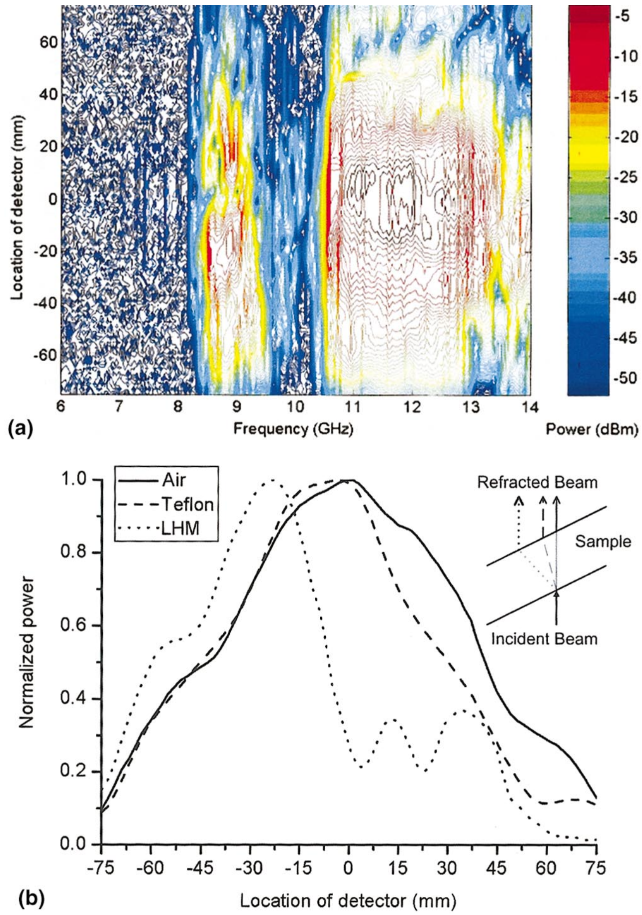


FIG. 4. (Color) Beam shift experiment results: (a) Three-dimensional illustration and (b) result for 8.65 GHz.

## VI. CONCLUSION

Through the above three experiments, we conclude that the metamaterial sample as described indeed exhibits clear left-handed behavior in a wide frequency band and with very low loss. It is in solid-state form and has stable characteristics. We can cut it into various shapes, plate metallic films on its surfaces, and fix or install it into a device package. The insertion loss of one unit cell is smaller than 0.5 dB, which has been an acceptable figure in some real applications. For comparison, the insertion loss of a surface acoustic wave filter used in the RF front end in a GPS receiver is usually 0.4–1.5 dB, a generalized microwave filter usually has an insertion loss of 1–2 dB, and the insertion losses of some wideband microwave switches may vary from 1 to 4 dB. We think the apparently improved loss property is due to the disappearance of a large amount of mismatched interfaces formed by air and substrates in the traditional realizations. A lot of inner reflections or scatterings are eliminated, therefore the loss and bandwidth are greatly improved. More efforts are being made to further improve the LH properties, and we have observed a 2-GHz-wide LH band after decreasing the thickness of the empty boards to 1 mm in a latest measurement.

## ACKNOWLEDGMENT

This work is supported by the Chinese Natural Science Foundation under Contract Nos. 60201001, 60271010, and 60371010.

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