Experimental observation of left-handed transmission in a bilayer metamaterial under normal-to-plane propagation

Kaan Guven,[1, 2] M. Deniz Caliskan,[2] and Ekmel Ozbay[1, 2, 3]

[1]*Department of Physics, Bilkent University, Bilkent, 06800, Ankara, Turkey*
[2]*Nanotechnology Research Center, Bilkent University, Bilkent, 06800, Ankara, Turkey*
[3]*Department of Electrical and Electronics Engineering, Bilkent University, Bilkent 06800, Ankara, Turkey*
guven@fen.bilkent.edu.tr

Abstract: We demonstrate experimentally the double-negative ($\varepsilon < 0$, $\mu < 0$) transmission band of a one-dimensional metamaterial structure under normal-to-plane propagation in the microwave regime. The structure consists of stacked bilayers of metal cutwire and wire pairs, which are separated by a thin dielectric layer. The existence of the negative index of refraction is inferred from the transmission and phase spectra obtained by using multilayer metamaterial samples. Another metamaterial structure incorporating non-magnetic (electrically shorted) cutwire pairs does not exhibit the corresponding transmission band, which supports the true left-handed behavior of the metamaterial.

OCIS codes: (160.4670) Optical materials; (260.5740) Physical Optics, resonance.

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1. Introduction

We have been long accustomed to the apparent fact that magnetism (in particular, diamagnetism characterized by negative permeability, $\mu < 0$) and negative permittivity ($\varepsilon < 0$ associated with the plasmons) in metals are similar in nature with two siblings that have been separated forever: the former occurring only at frequencies below MHz, whereas the latter resides in the THz regime and beyond. The intriguing properties of electromagnetism in a medium having both $\varepsilon < 0$, $\mu < 0$ was discussed theoretically by Veselago four decades ago [1], but the absence of any naturally occurring material was providing rather little motivation for any further study. The subject remained stored away until recently when Pendry *et al.* took a pioneering approach in "constructing" these materials artificially. They have shown that (i) a periodic metallic wire structure can support plasmons with extremely low cut-off frequencies (e.g. down to MHz) so that negative permittivity response can be obtained without being suppressed by the dispersion at low frequencies [2]; (ii) a metallic structure in the shape of concentric split rings can exhibit a magnetic resonance under an axially applied AC magnetic field, and associated with this, negative permeability at extremely high frequencies (above MHz) [3]. Broadly speaking, these are called "composite metamaterials" (CMMs) consisting of metallic and dielectric features, which provide the desired response to the electromagnetic excitation at the desired frequency band. The size of these features are much smaller than the wavelength, so the medium can be characterized in terms of effective $\varepsilon(\omega)$ and $\mu(\omega)$, in analogy to the characterization of the interaction of atoms in a material with light. With the aid of these materials, the siblings are united, and the third quadrant ($\mu < 0$, $\varepsilon < 0$) of the electromagnetic realm is unlocked for exploration. Indeed, the first experimental realization studies of materials appeared shortly thereafter at microwave frequencies [4, 5], which revealed novel electromagnetic phenomena such as the negative refraction [6].

As the CMM structures evolve through different designs, their composite nature consisting of the split ring resonator (SRR) and wire elements remained essentially the same. A one dimensional CMM can be constructed simply by stacking the wire and SRR layers alternatingly, as shown in Fig. 1(a). The SRR is the dominating element in the design; the propagation direction is dictated by the requirement that the magnetic field vector must be normal to the plane of SRR layer [*z* direction in Fig. 1(a)] so that it induces a current in the split rings, and hence the resonance. This type of CMM can be classified as the CMM with in-plane propagation. In this case, evidently large number of layers has to be stacked to provide full coverage for the incident beam. This restriction turned out to be a major challenge for the construction of LHMs for THz and optical frequencies, since fabricating a multilayer structure with tens of layers on a substrate is extremely difficult at the nano-scale. The fabrication of uniform nano-SRR structures requires very high-resolution photolithography. Thus far, the magnetic response of SRRs is achieved within 10-400 THz range [7-11]. A recent study indicates that the SRR may have a limitation for the highest frequency achievable by scaling [12]. On the other hand, the realization of CMM based on SRR/wire components at THz has progressed slowly mainly due to the restrictions mentioned before. The transmission peaks from a monolayer CMM operating at 2.7 THz is reported for oblique incidence [13]. The highest frequency metamaterial medium with completely in-plane propagation is reported for 100 GHz [14].

Shalaev *et al.* recently proposed a different topology for achieving the magnetic resonance, and therefore, negative magnetic permeability particularly at optical frequencies [15, 16]. The metamaterial structure consists of periodically arranged paired metallic nanorods separated by a thin dielectric layer, which is intended for *normal-to-plane* propagation, as opposed to the CMM with *in-plane* propagation that was discussed above. In this configuration, the electric field acting parallel to the long axis of the rods and the magnetic field acting on the loop between the paired rods (coupled capacitively at their ends across the dielectric spacer) provide the $\varepsilon < 0$, $\mu < 0$ responses, respectively. In their work [16], which employs gold nanorods with an SiO_2 spacer layer, the negative index of refraction at the wavelength of 1.5 µm is reported based on the retrieval from transmittance and reflectance measurements of a *single* layer metamaterial, but the large imaginary parts of the response functions (and thus the rapid attenuation) poses a problem. Another study reported the observation of the magnetic resonance of cutwire pairs and square plate pairs separated by an MgF_2 dielectric spacer for the 1.5 µm wavelength [17]. Soukoulis *et al.* investigated metamaterials based on cutwire/wire pairs [18], and H-shaped metallic wires [19] under plane-normal propagation, which exhibit a negative index of refraction at microwave frequencies obtained by the retrieval procedure from a single layer of metamaterial. Another design consisting of two metal layers perforated by periodic array of holes is proposed and demonstrated at 1.5 µm wavelength [20-22].

In this article, we take a direct approach and demonstrate the left-handed transmission band of composite metamaterial consisting of stacked cutwire/wire bilayers, under normal-to-plane propagation at microwave frequencies. We employed the systematic analysis in our recent study, where the stop bands for cutwire ($\mu < 0$), and wire ($\varepsilon < 0$) components, and the corresponding transmission band of the composite metamaterial are separately measured [23]. While the above-mentioned studies indicate the existence of a negative index of refraction in the normal-to-plane topology, the retrieval procedure necessitates the use of single layer for the unambiguous determination of the effective medium parameters. Thus far, the transmission of a multilayer CMM under normal-to-plane propagation has not been reported in the literature, to our knowledge. By using different number of layers (i.e. different thicknesses) we were able to demonstrate that the phase change occurs negatively and positively in the respective left-handed and right-handed transmission bands of the metamaterial, similar to Ref. [24]. Recently, the negative phase velocity is reported for the 1.5 µm wavelength metamaterial based on interferometric measurements [25]. The direct observation of the left-handed transmission band presented herein, and the above-mentioned retrieval results, are complementary and will spur the further development of metamaterials with plane-normal propagation for microwave and optical applications.

The present paper is organized as follows. In the next section, the design and fabrication of the double layer cutwire/wire metamaterial is described. The experimental measurements and simulations of the transmission spectra of metamaterial are provided in the third section. We subsequently present the phase spectra of the metamaterial showing negative phase change across the left-handed transmission band. The last section summarizes the results and concludes the paper.

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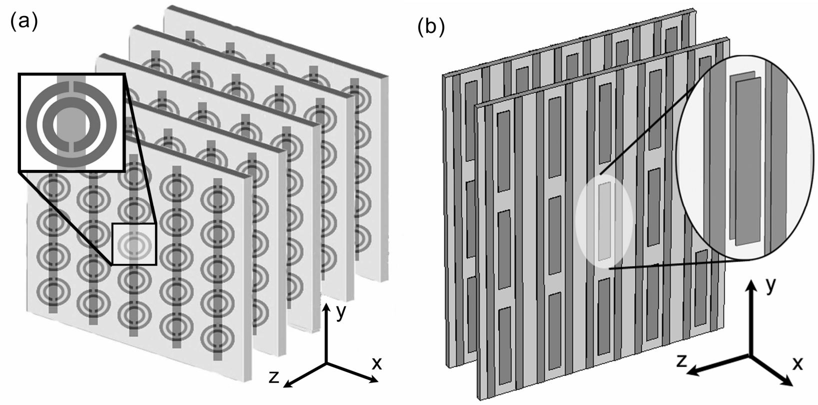

Fig. 1. (a). Schematic view of a 1D CMM consisting of SRR and wire layers for in-plane propagation. There are five layers in the propagation direction, *x*. (b) Schematic view of the bilayer cutwire and wire 1D CMM with normal-to-plane propagation. There are two bilayers in the *x* direction. The insets show the respective unit cells. For both CMM, the electromagnetic field propagates in the *x* direction with *E* and *B* along the *y* and *z* directions, respectively.

2. Planar metamaterial design with plane-normal propagation

In the present study, we employed a metamaterial design depicted in Fig. 1(b), similar to that provided in Ref. [18]. A visual comparison of the CMM topologies in Fig. 1 clearly shows the advantages of normal-to-plane propagation: a *single* bilayer fabricated in proper size is sufficient to cover the incident beam profile. In addition, the number of layers in the propagation direction (i.e. metamaterial thickness) and the stacking periodicity can be easily varied. Figure 2 shows the unit cell of the CMM. The bilayer is fabricated from dielectric printed circuit board (PCB) layers (thickness d = 0.4 mm, listed relative dielectric constant ε_r = 4.2) with a metal coating (thickness t = 30 µm) on both sides. For guidance, we employed a simple model, in which the capacitance and inductance of the cutwire pair are given by $C = \varepsilon_r \varepsilon_0 (l \cdot w)/(4d)$, $L = \mu_0 (l \cdot d)/w$, respectively. Here, l is the length, w is the width of the cutwires, and d is the thickness of the dielectric spacer between the pair elements [18]. ε_r denotes the relative dielectric constant of the spacer. The magnetic resonance frequency is given by $f_m = 1/\left(2\pi\sqrt{LC}\right)$. Using this model, ε_r and d of the available substrate are taken as constraints and the geometric parameters of the cutwire are determined to produce a resonance frequency of approx. 14.0 GHz. The wire units are designed with a high cut-off frequency in order to ensure the $\varepsilon < 0$ within the $\mu < 0$ stop band of cutwire pairs, when they are combined into a CMM. The wires are present on either side of the bilayer for symmetry.

The cutwire and wire pairs are fabricated by etching. Figure 2 illustrates the geometrical parameters of the CMM unit cell. The cutwire dimensions are w_{cutw} = 0.8 mm, y_{cutw} = 5.5 mm, and the wire dimensions are w_{wire} = 0.5 mm, y_{wire} = 7.0 mm. The unit cell has dimensions a_x = 2.0 mm, a_y = 7.0 mm, a_z = 3.5 mm. a_x is the stacking periodicity in the propagation direction.

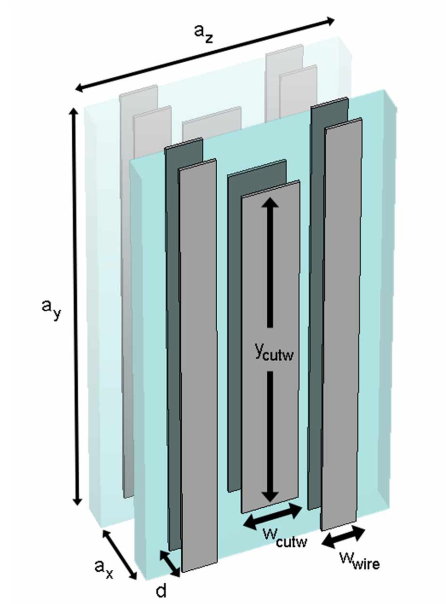

Fig. 2. The unit cell of the bilayer CMM consisting of one cutwire pair and two wire pairs with dielectric spacer (green transparent). Numerical values of the parameters are given in the text. Another bilayer is shown in the background to show the stacking periodicity a_x.

We have fabricated five different structures: cutwire, wire, CMM, shorted cutwire, and shorted CMM. The last two are control samples in which the cutwire pairs are electrically shorted at their ends through the dielectric spacer. The shorted cutwire structure is used to identify the magnetic nature of the cutwire resonance. The shorted CMM is used to identify the left-handed transmission band of the CMM. The details of this analysis are provided in the next section.

3. The transmission and phase spectra of the bilayer metamaterial

The transmission spectra of the metamaterial components are measured in free space, using an HP8510C Network Analyzer and a set of antennas. Figure 3 shows the transmission spectra of the cutwire metamaterial for a different number of layers. A clear stop band is observed near 14.0 GHz, which becomes stronger with an increasing number of layers. For comparison, one cutwire unit is taken from a layer and its transmission spectrum is measured by using two monopole antennas (black solid line in the inset). We observe that the unit element and the full layer match in their resonance frequency. The inset compares the transmission spectra of one cutwire unit, one cutwire unit rotated 90° around its long axis, and one electrically shorted cutwire unit. The shorted cutwire pair does not show any resonance, since no capacitance is present between the pair elements. For the rotated cutwire, the magnetic field vector is not between the pair elements, and cannot induce the resonance. We can conclude from these results that the resonance of the cutwire pair is induced by the magnetic field under normal-to-plane propagation, and hence provides a $\mu < 0$ medium at ~ 14 GHz. The magnetic resonance behavior of the cutwire pair appears to be weaker when compared qualitatively to that of a SRR unit [26]. However, a quantitative assessment of this comparison and its impact on the left handed transmission band of the corresponding CMM structure requires the investigation of the permeability near the resonance. Figure 3 further indicates that the cutwires also exhibit electric coupling. A stop band arising from this can be seen particularly in the spectrum of the four layer thick cutwire structure (black curve), starting at ~17 GHz. We will discuss the effect of the electric coupling later in the analysis of the transmission spectrum of the CMM.

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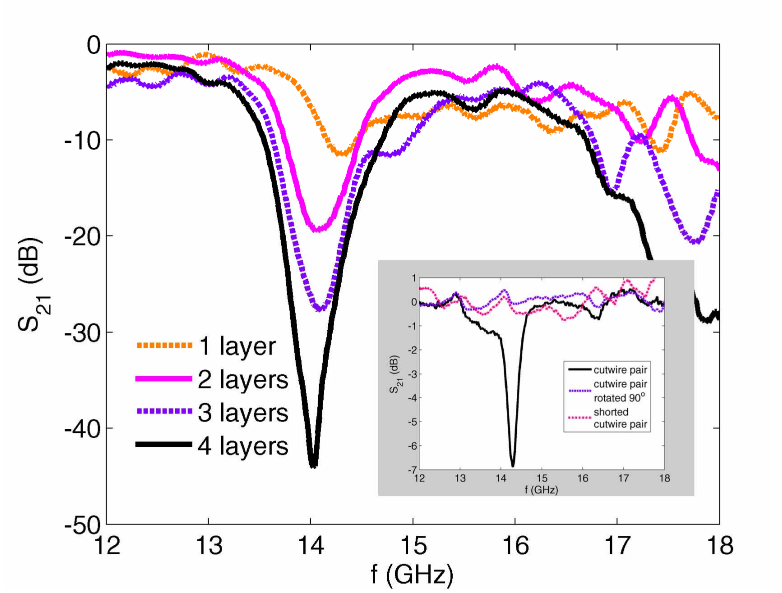

Fig. 3. The transmission spectrum of the cutwire metamaterial with a different number of layers in the propagation direction. The inset shows the transmission spectrum of a single cutwire pair, under normal-to-plane, in-plane (i.e. rotated 90° along wire axis) and the transmission spectrum of an electrically shorted single cutwire pair.

The main results of the present paper are summarized in Fig. 4. Here, we plot the transmission spectra of the cutwire, wire, CMM, and shorted-CMM structures obtained by measurements (a) and simulations (b). Each structure consists of three stacked layers in the propagation direction. The wire structure is completely opaque, since its plasma cut-off frequency is above the measured frequency range (bottom dotted line, added 20 dB for visibility). The cutwire structure exhibits a $\mu < 0$ stop band at approx. 14.25 GHz. The CMM structure exhibits a clear transmission band within the stop band of the cutwire. In contrast, the shorted-CMM (i.e., CMM containing shorted cutwire pairs) does not have such transmission band here. Based on these results, we conclude that in this transmission band at approx. 14.25 GHz, the CMM acts as a double negative medium.

The simulations are performed by the CST Microwave Studio®. This software employs a transient solver where the spatial discrete mesh is generated by the finite integration method in combination with the perfect boundary approximation. In the simulations, the structure is assumed to extend to infinity in the lateral directions, and the metallic features are modeled as perfect electrical conductor. All of the features observed in the experimental transmission spectrum are obtained in the simulation with a good agreement in the spectral position. We found that the conductivity of the dielectric layer can affect the transmission level significantly. In the simulations we used a higher conductivity value than the listed value (σ = 0.0068 S/m) for the dielectric layers, which resulted in a loss in the overall transmission similar to that in the experiment.

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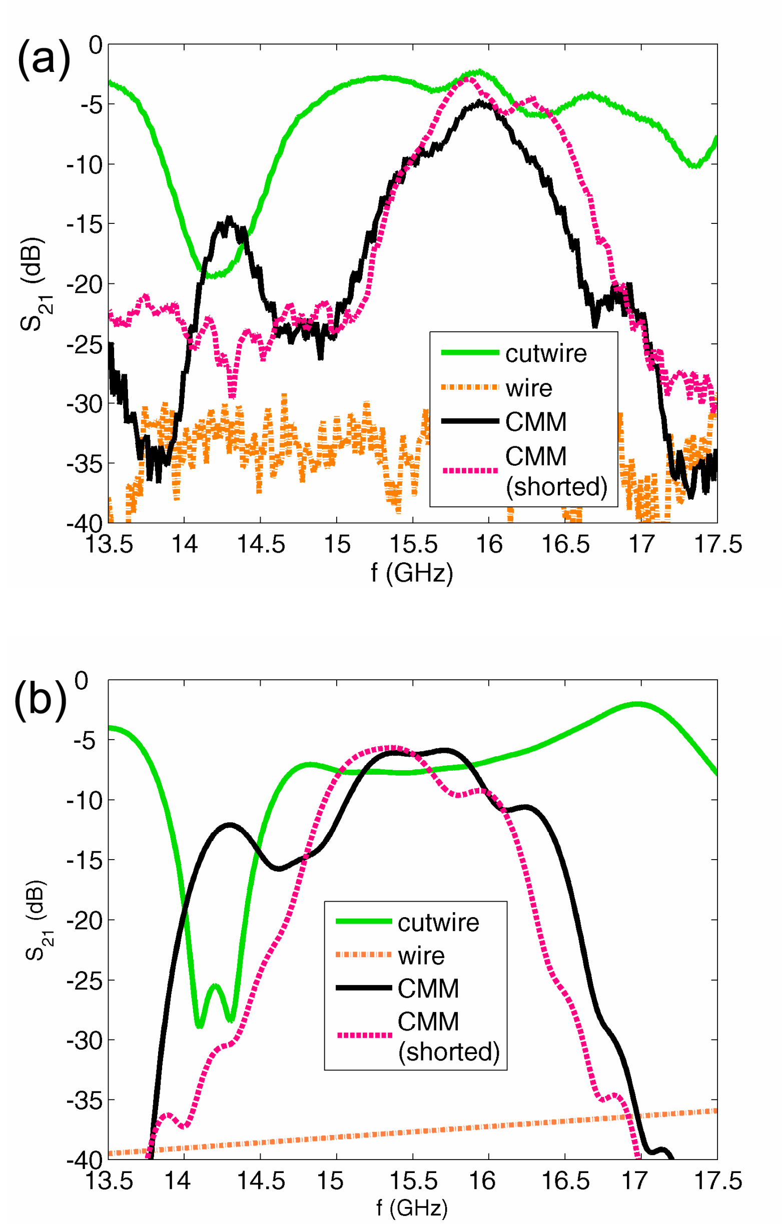

Fig. 4. The (a) measured and (b) simulated transmission spectra of cutwire, wire, CMM, and shorted-CMM structures. Each structure consists of three bilayers stacked in the propagation direction with the period a_x. A clear transmission peak is observed within the magnetic resonance ($\mu < 0$) of cutwires. The CMM containing shorted cutwires does not exhibit such a transmission peak.

While the left-handed transmission band is of primary interest, the common transmission band for the CMM and shorted-CMM structures between 15-17 GHz provides important information about the total dielectric response of the CMM. First, this is a right-handed transmission band: $\mu = 1$, $\varepsilon > 0$. Evidently, the electric field couples to cutwires as well, since it is parallel to the long axis of the cutwires. As a result, the periodic cutwire array on either

#72898 - $15.00 USD Received 10 July 2006; revised 11 September 2006; accepted 11 September 2006

surface of the bilayer support plasmons with a lower and upper cut-off frequencies (in the case of continuous wires, a lower cut-off frequency is not present). We recall that for the SRR-wire type CMM, the inherent electric response of the SRRs causes a significant downshift of the plasmon cut-off frequency, which is determined solely from a wire structure [15]. Therefore, the $\varepsilon < 0$ behavior of the present CMM cannot be attributed to the wire component alone. The upper frequency edge of this band near 17 GHz is roughly in agreement with the band edge of the multilayer cutwire structure depicted in Fig. 3. Let us further note that the electric response of the CMM and shorted CMM is anticipated to be slightly different, because in the shorted case, the additional metal parts in the dielectric may exhibit capacitive coupling between the facing ends of successive shorted cutwire pairs along the y direction.

It was demonstrated in the SRR-wire type CMM (in-plane propagation) that when an electromagnetic wave that has a frequency within the left-handed transmission band propagates in the CMM, the acquired phase shift is negative, that is, the phase decreases [24]. We measured the phase delay of the CMM across the left-handed and right-handed transmission bands. Figure 5 shows the ordering of the phase delay as a function of the number of layers in the CMM, and in relation to the left-handed and right handed transmission bands. Evidently, in the left-handed transmission bands, the phase *decreases* with increasing sample thickness, whereas in the right-handed band, we observe the usual positive medium behavior.

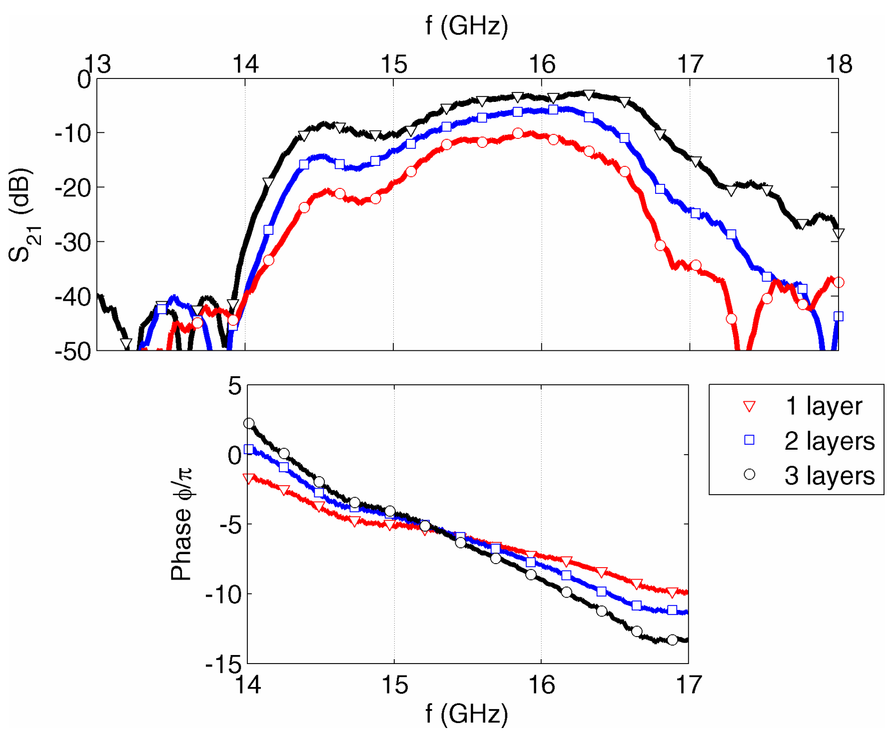

Fig. 5. The transmission (top) and phase (bottom) spectra of the CMM for a different number of layers in the propagation direction. The peak at around 14.5 GHz corresponds to the left-handed transmission band. The broad transmission band at approx. 16 GHz is right-handed. Note that the phase delay is negative in the left-handed band, and then becomes positive in the right-handed band.

For a fair analysis, we have to address the loss problem. The phase measurements of the multilayer structures reveal that the loss becomes an issue with an increasing number of

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layers. First of all, the present structure parameters are not optimized for minimal loss, yet. We anticipate that the loss originates from the highly dense design of the wire layer. A quantitative analysis of the permittivity permeability functions that were retrieved from the transmission and reflection spectra can reveal this more rigorously, and particularly their imaginary parts. Employing a sparse wire array can improve the transmission level, provided that the plasma cutoff frequency remains sufficiently high.

4. Conclusion

In conclusion, we investigated the transmission and phase spectrum of a composite metamaterial (CMM) that was designed for normal-to-plane propagation. The CMM consists of cutwire and wire pairs in the form of a bilayer along with a thin dielectric spacer. The measured transmission spectra show that the cutwires alone have a magnetic resonance at the specified operation frequency. The CMM exhibits a clear transmission peak within this resonance. By using complementary shorted-cutwire and shorted-CMM structures, we identified the left-handed nature of the transmission peak unambiguously. The measured phase delay decreases with increasing CMM thickness, indicating in turn the existence of a negative index of refraction. The loss in the medium is high, but this can be improved by incorporating a sparse wire layer.

The CMM in this present work is designed and fabricated for the microwave regime. The planar geometry and normal-to-plane propagation topology conforms to the existing nanofabrication techniques extremely well. In view of the near-infrared metamaterial studies reported recently in the literature, we anticipate that the research of such CMM structures can be geared towards device applications at near infrared and optical wavelengths, particularly to the CMM based imaging devices with subwavelength resolution capabilities.

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