Experimental demonstration of labyrinth-based left-handed metamaterials

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Abstract: In this present work, we propose and demonstrate a resonant structure that solves two major problems related to the split-ring resonator structure. One of the problems related to the split-ring resonator structure is the bianisotropy, and the other problem is the electric coupling to the magnetic resonance of the split-ring resonator structure. These two problems introduce difficulties in obtaining isotropic left-handed metamaterial mediums. The resonant structure that we propose here solves both of these problems. We further show that in addition to the magnetic resonance, when combined with a suitable wire medium, the structure that we propose exhibits left-handed transmission band. We believe that the structure we proposed may have important consequences in the design of isotropic negative index metamaterial mediums.

OCIS codes: (160.0160) Materials; (160.3900) Metals; (160.4670) Optical materials; (160.4760) Optical properties; (350.4010) Microwaves

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1. Introduction

The possibility of the negative refraction of electromagnetic (EM) waves by materials with simultaneous negative permittivity and negative permeability was predicted by Vesalago in 1968 [1]. This proposition was not demonstrated until recently; the main difficulty being in obtaining negative permeability. Negative permittivity is available through metals or the peri-

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odic arrangement of metallic wires [2, 3, 4, 5, 6]. On the other hand, obtaining negative permeability was an issue. Pendry et al. proposed several structures in order to obtain negative permeability [7]. Among these structures split-ring resonators (SRRs) have attracted much attention [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. A single SRR is composed of two concentric rings with slits on each of them. The slits on the rings are situated on the opposite sides of the rings with respect to each other. The planar nature of the SRR structure makes it easy to fabricate and integrate into 2 and 3 dimensional structures. Several research groups have demonstrated negative indices of refraction by using the periodic arrangement of metallic wires with SRRs through several methods such as the retrieval of effective medium parameters [19, 20, 21, 22, 23, 24, 25], refraction type experiments and wedge experiments [26, 27, 28, 29, 30, 31, 32, 33, 34].

While SRR structure provides negative permeability and can be used to obtain negative refraction, it has several disadvantages. First of all, it has been shown that a medium consisting of a periodic arrangement of SRRs is bianisotropic [25, 35, 36, 37]. The bianisotropy is a result of the non-zero electric dipole moment of the SRR structure due to the asymmetric placement of slits on the rings. Second, it has been shown that the magnetic resonance of the SRR structure can be excited via electric fields [38, 39]. The excitation of the magnetic resonance of the SRR structure results from the capacitive coupling of the electric field. The capacitive coupling of the electric field creates non-zero current along the rings. These two disadvantages make it difficult to obtain isotropic, homogeneous two or three dimensional negative refraction media by using SRRs for negative permeability.

In this paper, we present a new structure to solve the problems outlined above. We theoretically and experimentally show that the proposed structure does not exhibit bianisotropy. We show that magnetic resonance of the proposed structure cannot be excited by incident electric fields. In addition, we demonstrate that the periodic arrangement of the proposed resonator and wires exhibit simultaneous negative permittivity and permeability over a frequency range.

2. The Labyrinth Structure

When an EM wave is incident on a metamaterial made of a periodic arrangement of SRRs with a wave vector in the plane of SRRs and with a magnetic field perpendicular to the plane of SRRs, the transmitted electric field contains a component that is perpendicular to the plane of SRRs. This extra component arises from the non-zero electric dipole moment induced by the incident magnetic field [38]. The electric dipole moment is non-zero because the currents that flow across each slit do not cancel out the current flowing on the other slit. As a result, the medium is bianisotropic and the constituent relations assume the following forms [25]:

$$\overline{D} = \overline{\overline{\varepsilon}} \cdot \overline{E} + \overline{\overline{\zeta}} \cdot \overline{H}$$

$$\overline{H} = \overline{\overline{\mu}} \cdot \overline{H} + \overline{\overline{\zeta}} \cdot \overline{E}$$

Several researchers have pointed out the bianisotropy issue related to the SRR structure and they have suggested several ways to overcome it [25, 35, 36, 37]. One such way is to place rings with equal radiuses on the opposite sides of the substrate [36]. In this case the currents flowing across the slits are equally balanced and as a result the bianisotropy is greatly reduced. This approach solves the problem related to the SRR metamaterial medium. But if one desires to combine this modified SRR metamaterial medium with a wire medium in order to obtain negative refraction they face a manufacturing problem. The placement of the wires is not obvious in this case. In addition, this approach cannot solve the problem related to the excitation of the magnetic resonance via incident electric waves.

The magnetic resonance of the SRR structures can be excited by incident waves whose electric field is perpendicular to the slits and whose wave vector is perpendicular to the plane of

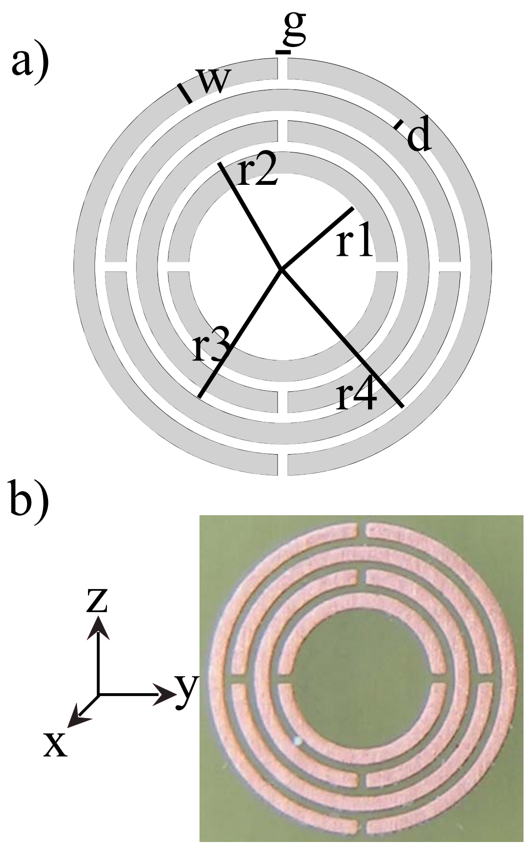

Fig. 1. (Color online) a) Schematics of the labyrinth structure. $r1 = 1.35$ mm, $r2 = 1.8$ mm, $r3 = 2.25$ mm, $r4 = 2.7$ mm, $g = 0.15$ mm, $w = 0.3$ mm, and $d = 0.15$ mm. b) The unit cell of the actual, fabricated structure and the coordinate system that we use throughout the paper.

SRRs. Such an incident electric field couples to the magnetic resonance capacitively and induces currents flowing across the rings. The induced currents on both rings are solenoidal, hence they resemble the currents that are induced by incident magnetic fields at the magnetic resonance. The resonance frequency observed due to the capacitive coupling of electric field is quite close to the magnetic resonance. The transmission spectra of the EM waves with magnetic fields perpendicular to the plane of SRRs and with wave vectors in the plane of SRRs are quite close to the transmission spectrum of electromagnetic waves with electric field perpendicular to the slits and with wave vector perpendicular to the plane of SRRs. Hence, the excitation of the magnetic resonance via incident electric fields introduces another problem if one attempts to obtain isotropic and homogeneous negative refraction media by using SRRs and wires.

The above argument suggests that one needs to modify the SRR structure in order to solve the aforementioned problems. The bianisotropy is related to the asymmetric placement of the slits on both rings. The imbalance in the currents on both rings can be remedied by using a more symmetric resonator structure. This can be achieved by adding two slits on both rings and then rotating both of them 90 degrees with respect to each other. Such a placement of rings results in the cancellation of the currents flowing across each slit by the current flowing

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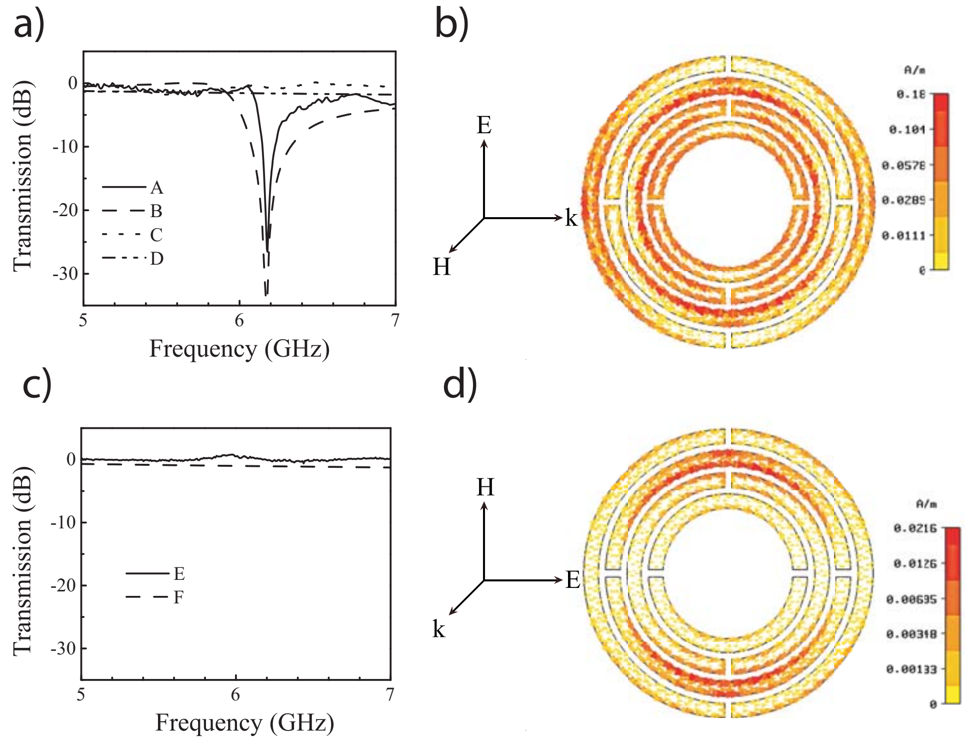

Fig. 2. (Color online) a) Measured transmission through a single labyrinth structure (A), a single closed labyrinth structure (B). Calculated transmission through a single labyrinth structure (C), a single closed labyrinth structure (D). b) Induced surface current density at 6.2 GHz. c) Measured (E) and calculated (F) transmission through a single labyrinth structure. d) Induced surface current density at 6.2 GHz.

on the slit that is located on the same ring. In turn, the resultant electric dipole moment due to the currents flowing across the slits is suppressed. The electric coupling to the magnetic resonance can be avoided by using the same structure. In order to avoid electric coupling to the magnetic resonance one must somehow suppress the currents flowing across the rings due to the capacitive coupling of the electric field through the slits. Such suppression can be obtained by creating opposing current flows on the same ring. This argument suggests that one needs to place two slits on the same ring. Since the currents due to capacitive coupling of the electric field on each slit will be opposite to each other, the net current on the ring will be suppressed. As a result, the net magnetic dipole moment will be reduced.

Figure 1(a) shows schematics of the modified SRR structure that we propose. We call the modified SRR as "labyrinth" structure due to its shape. The labyrinth structure consists of four rings instead of two. The two additional rings are used for two main purposes, of which the first is to enhance the strength of the resonance. Second, the two-ring structure has two magnetic resonances that are close to each other. We used the additional two rings in order to separate the two magnetic resonances further away in frequency from each other. The unit cell of the fabricated structure is shown in Fig. 1(b). The structures are fabricated by using standard printed circuit board manufacturing methods. Figure 1(b) also shows the coordinate system that

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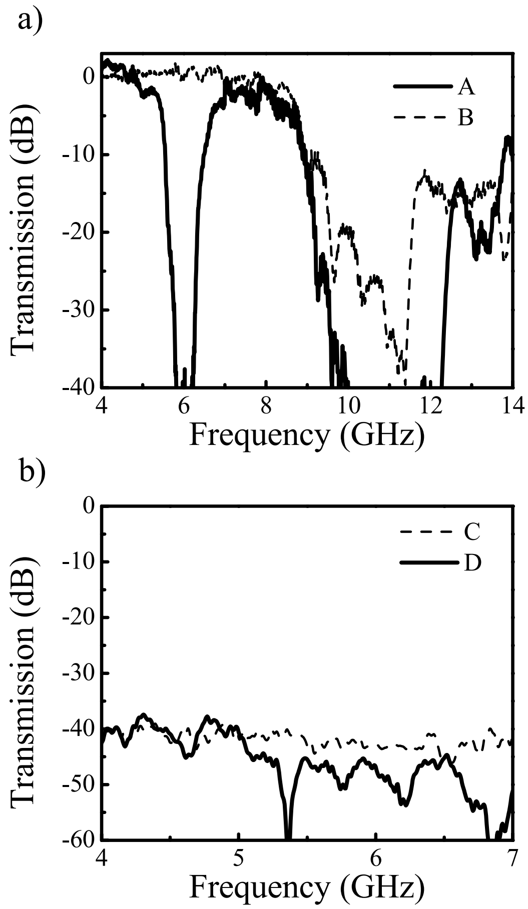

Fig. 3. a) Measured transmission spectrum of the z-component of the electric field through (A) the labyrinth metamaterial medium and (B) through the closed labyrinth metamaterial medium. Only the z-component of the incident electric field was nonzero. b) Measured transmission spectrum of the x-component of the electric field through (C) free space and through (D) the labyrinth metamaterial medium. Only the z-component of the incident electric field was nonzero.

we used throughout the entire paper.

We calculated the induced surface currents, electric field distributions, and transmission properties of incident plane EM waves through the labyrinth structure by using a commercial 3 dimensional full-wave solver. We also measured the transmission properties of the labyrinth structure. The transmission properties of a single labyrinth structure are measured by using a HP 8510C vector network analyzer and two monopole antennas as receiver and transmitter antennas. A single labyrinth structure contains only one unit cell of labyrinth structure. The measured and calculated transmission spectrum of plane EM waves through a single layer of labyrinth structure is shown in Fig. 2(a). The directions of the electric field, magnetic field, and wave vector of the incident EM waves are shown in Fig. 2(b). First of all the transmission spectrum exhibits a resonance around 6.2 GHz with a transmission of -25 dB. Second, the closed labyrinth structure does not exhibit this resonance in the transmission spectrum. The calculated induced surface current is shown in Fig. 2(b). The induced surface currents are solenoidal and in phase along each arm. As a result the induced dipole moment has a magnetic character. The comparison of the transmission spectrum of the labyrinth structure with the transmission spectrum of the closed labyrinth supports this conclusion as the closed labyrinth structure does not exhibit any resonance near 6.2 GHz. Hence, a single labyrinth structure with the given dimensions exhibits magnetic resonance around 6.2 GHz.

In order to check whether the magnetic resonance of the labyrinth structure may be excited by incident electric fields, we measured and calculated transmission spectrum through a single layer of labyrinth structure when the wave vector is in to the plane of labyrinth structure. The directions of the electric field, magnetic field, and wave vector of the incident EM waves are shown in Fig. 2(d). Note that for the case of incidence configuration shown in Fig. 2(d) the magnetic resonance of the SRR structure can be excited by electric fields. The measurement and calculation results for a single labyrinth structure are shown in Fig. 2(c). The transmission spectrum does not show any resonance around 6.2 GHz. In addition, the surface current density that we obtained through our calculations is shown in Fig. 2(d). First of all, the surface current density is reduced by an order of magnitude when compared to Fig. 2(b). Second, the surface current density along each arm of the labyrinth structure is balanced either by an opposite surface current density on the same arm or by an opposite surface current density flowing along the opposite direction on the opposite arm. As a result, the transmission spectrum shown in Fig. 2(c) and the surface current density shown in Fig. 2(d) clearly demonstrate that the magnetic resonance of the labyrinth structure cannot be excited by incident electric fields.

For the case of incidence depicted in Fig. 2(b), the SRR structure exhibits bianisotropy near the first magnetic resonance i.e., one also observes a non-zero electric field component parallel to the incident magnetic field in the transmission spectrum. In order to demonstrate that the labyrinth structure does not exhibit bianisotropy, we measured the transmission spectrum through a labyrinth metamaterial medium. The transmission measurements were performed with a HP-8510C network analyzer by using horn antennas as the receiver and transmitter. The labyrinth metamaterial is composed of periodic arrangement of labyrinths in a 1 dimensional array of 25 layers along the x direction, 20 layers along the z direction, and 5 or 10 layers along the propagation direction (y-axis). The directions are those of Fig. 1(b). The incident electric field is along the z direction and the wave vector is parallel to the y direction. We measured both the x and z components of the transmitted electric fields. Note that the incident magnetic field is parallel to the x-axis. The transmission measurement results for the z component of the electric field are shown in Fig. 3(a). The measured transmission data for the medium composed of closed labyrinth structures with the same number of layers is also shown in Fig. 3(a). The transmission spectrum for the labyrinth metamaterial medium exhibits a band gap between 5.9 GHz and 6.6 GHz for the z component of the electric field. The transmission spectrum for the closed labyrinth structure does not exhibit such a band gap. More importantly, we did not detect any appreciable electric field along the x direction in the transmission spectrum of the labyrinth metamaterial medium (Figure 3(b)). The x component of the electric field is measured by rotating the receiver horn antenna by 90 degrees. We measured the x component of the electric field with and without the labyrinth metamaterial medium in between the transmitting and receiving horn antennas. The transmitted x component of the electric field is around -40 dB within the frequency range of interest in free space. Note that the polarization of the transmitting horn antenna is such that the emitted electric fields are z polarized. The measured transmission coefficients of the x component of the electric fields drop below -40 dB when the labyrinth structure is inserted between the horn antennas. Hence, these results clearly show that the labyrinth metamaterial medium is not bianisotropic.

3. Composite metamaterial medium

In the previous section we showed that unlike the SRR structure, the labyrinth structure does not exhibit bianisotroy. In addition, we showed that the electric coupling to the magnetic resonance of the labyrinth structure is forbidden due to the balanced currents. These properties provide important improvements over the common SRR structure. It is natural to ask if one combines the labyrinth metamaterial medium with a suitable wire medium, would the resulting composite metamaterial medium (CMM) exhibit left-handed transmission within a frequency range.

The wire medium that we considered in our study was a one-dimensional periodic arrangement of metal stripes on the back surface of the printed circuit boards (PCB). The width of the wire stripes was chosen to be 2.5 mm. This choice was made in order to obtain a plasma frequency at a far enough frequency from the magnetic resonance of the labyrinth structure. The length of the wire stripes was 17.6 cm and the thickness of the stripes was 0.05 mm. The periodic arrangement of wire stripes had a lattice constant of 8.8 mm along y-axis and 6.5 mm along x-axis. The propagation direction was along y-axis. There were 10 layers of wire stripes along the y direction and 25 layers along the x direction. Measured transmission spectrum of the wire medium is shown in Fig. 4(a). The transmission spectrum for the wire medium exhibits a forbidden frequency range of up to 10.45 GHz. The plasma edge (10.45 GHz) of the wire medium is 4.2 GHz above the magnetic resonance of the labyrinth structure.

The CMM structure that we used in our study was composed of one-dimensional periodic arrangement of labyrinth structures and wire structures. Wires were printed on the back surface of the PCBs and labyrinth structures were fabricated on the front surface of the PCBs. Wires and labyrinth structures were aligned such that the axis of the wires were parallel to the splits on the labyrinth structure. There were 20 layers of CMM unit cells along z-axis and 25 layers of CMM unit cells along x-axis. The transmission spectrum for 5 and 10 layers of CMM unit cells along the propagation direction is shown in Fig. 4(b). Figure 4 shows that the transmission spectrum of the CMM medium exhibits a transmission band between 5.9 GHz and 6.55 GHz. Note that the magnetic resonance of the single labyrinth structure was observed at 6.2 GHz. In addition, the labyrinth structure exhibited a band gap between 5.9 GHz and 6.6 GHz. Hence, the transmission band of the CMM structure coincides with the band gap of the labyrinth metamaterial medium. We measured the transmission spectrum of the closed CMM medium in order to check whether the transmission band observed between 5.9 GHz and 6.55 GHz is left-handed [20, 40]. The closed CMM medium consists of a periodic arrangement of closed labyrinth structures and wires stripes. The lattice parameters were kept the same as the CMM medium. The transmission spectrum of the closed CMM medium is shown in Fig. 4(c). First of all, the transmission spectrum of the closed CMM medium did not exhibit a transmission band between 5.9 GHz and 6.55 GHz. These results therefore show that the transmission band of the CMM medium is left-handed. In addition, the transmission spectrum of the closed CMM medium showed that the plasma edge of the wire medium shifts dramatically towards lower frequencies when the wire medium was combined either with a labyrinth medium or closed labyrinth medium. The plasma edge shifted from 10.45 GHz down to 7.6 GHz. Similar results demonstrating the shifting of the plasma edge towards lower frequencies were also reported for metamaterial mediums composed of SRR structures and wire structures [40].

4. Conclusion

In summary, we proposed a structure, the labyrinth structure, which exhibits magnetic resonance around 6.2 GHz. The magnetic nature of the resonance was confirmed by comparing the transmission spectrum of the labyrinth structure with that of the closed labyrinth structure. The magnetic nature of the resonance was further confirmed by the strong solenoidal surface currents that flow around the labyrinth structure at the resonance frequency. We experimentally

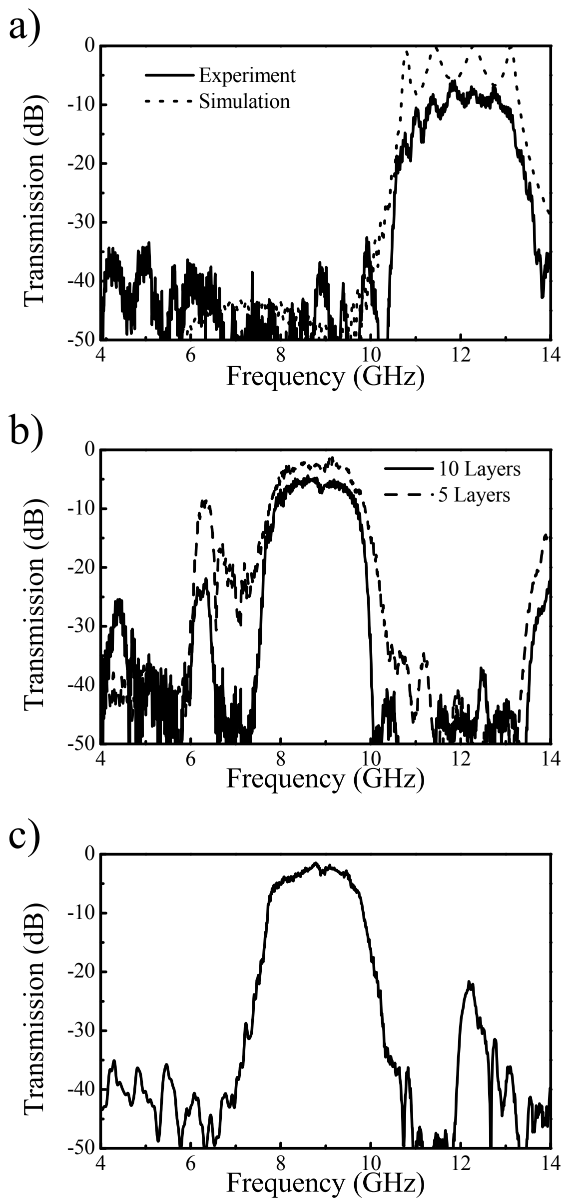

Fig. 4. a) Transmission spectrum of electromagnetic waves through the wire medium. b) Measured transmission spectrum of electromagnetic waves through the CMM medium. c) Measured transmission spectrum of electromagnetic wave through the closed CMM medium.

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demonstrated that the proposed structure does not show bianisotropy and its magnetic resonance cannot be excited by incident electric fields. As a result, the proposed structure provides important improvements over the common SRR structure. We further showed that the composite metamaterial medium of wires and labyrinth structures has a left-handed transmission band between 5.9 GHz and 6.55 GHz. We conclude that the labyrinth structure may have important consequences in the design of three dimensional-isotropic left-handed metamaterial mediums.

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