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Transmission Properties of Electromagnetic Metamaterials: From Split-Ring Resonator to Fishnet Structure

Nguyen Thanh TUNG[1], YoungPak LEE[1], and Vu Dinh LAM[1,2]*

[1]*Quantum Photonic Science Research Center and Department of Physics, Hanyang University, Seoul 133-791, Korea*
[2]*Institute of Materials Science, Vietnamese Academy of Science and Technology, Hanoi, Vietnam*

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We experimentally presented the electromagnetic behavior of transformative magnetic metamaterials: from the early invented split-ring resonator to its improvement, the cut-wire pair, for providing a negative magnetic permeability. By adding the continuous wire to cut-wire pair structure, the left-handed (LH) transmission made by doubly negative permittivity and permeability was demonstrated in combined structure. Interestingly, until the width of cut-wire pair increases to be physically merged with the adjacent continuous wire, in other words, to form the so-called fishnet structure, the LH behavior is still observed. This result indicates that in a broad sense, the essence of the electromagnetic response in the fishnet structure is similar to that in a combined structure. Our experimental results show a good agreement with previous theoretical study.

Keywords: metamaterials, split-ring resonator, cut-wire pair, combined structure, fishnet structure

1. Introduction

A representative item in the field of photonics aiming at ultrafast devices is photonic crystal (PC) which is a new-concept material or structure to control the propagation of light in various ways. Even spin PC (SPC) and metamaterials such as left-handed materials (LHMs) have recently appeared, where magnetic components are included in the basic periodic arrangement of nonmagnetic ones to be controlled magnetically as well. The interest in photon–spin interaction has grown, but the basis is not solid yet. LHMs were first theoretically studied in 1968 by Veselago,[1)] who showed that such materials exhibit a number of unusual physical properties. More than 30 years then elapsed until the first LH material was conceived and demonstrated experimentally by Smith *et al.*,[2)] this was a combination of split-ring resonators and continuous wires. Following this seminal paper, a large number of both theoretical and experimental reports confirmed the existence and the main properties of LHMs.[3–7)] The LHMs, which belong to the category of SPC in a broad sense, are composed of two parts: a magnetic component providing a negative magnetic permeability $\mu < 0$, and an electric component yielding a negative electric permittivity $\varepsilon < 0$. If the permeability and permittivity are simultaneously negative in a certain frequency range, this medium is termed as negative-index materials or LHMs. Negative permittivity naturally occurs in plasma at frequencies below the plasma frequency ω_p and for the conduction band electrons in metal at an optical frequency. A periodic array of wires can also exhibit plasma-like behavior when the orientation of applied electric field **E** is along the wire direction.[8)] However, the search for magnetic systems with a negative effective magnetic permeability up to the optical range remains an actual task. In regular LHMs, to apply the uniform effective medium theory in determining the effective ε and μ values, the size of the unit cell must be much smaller than the wavelength; hence, nano-fabrication technologies are required in the optical range. Therefore, the development of geometry and fabrication techniques is still an area of significant effort. The design and the construction of magnetic and electric components play a central role in the electromagnetic response of LHMs. In this paper, we investigated experimentally the electromagnetic response of several different structures for providing a negative magnetic permeability, starting from the early invented split-ring resonator (SRR) structure[9)] with one gap to the SRR with two gaps, and then the cut-wire pair structure. Together with the continuous wire, the LH behavior of a combined structure was also studied. Especially, when the width of cut-wire pair was increased until it merged with the adjacent continuous wires to form the fishnet structure, the LH behavior was still observed. This structure is considered as a highly promising design for fabricating LHM at optical frequency.

2. Experimental Setup

A printed copper board (PCB) with a copper thickness of 36 μm was used to fabricate the SRRs, cut-wire pairs and LHMs. The thickness and dielectric constant of substrate were 0.4 mm and 4.8, respectively. To fabricate the patterns, we used the conventional PCB process. The periodicity along the x and the y direction was achieved by printing the 2-dimensional array of the patterns on the planar PCB. The boards were stacked with a fixed distance of 1.0 mm. To obtain the LH behavior, the SRRs or the cut-wire pairs were combined with continuous wires. These structures were designed, built, and measured in the microwave frequency range. We performed the transmission measurements in free space, using a Hewlett-Packard E8362B network analyzer connected to microwave standard-gain horn antennas.

3. Results and Discussion

3.1 *Electromagnetic behavior of SRRs*

The geometrical parameters of the SRR (l, w, and d) are

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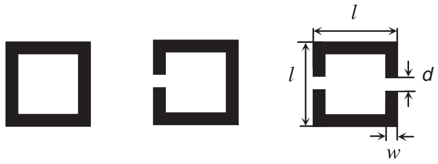
*E-mail address: lamvd@ims.vast.ac.vn



(a) (b) (c)

Fig. 1. Geometry of single-ring SRR: (a) closed ring resonator, (b) asymmetric SRR with one gap, (c) symmetric SRR with two gaps. Length $l = 3$ mm, and width w and cut width $d = 0.3$ mm.

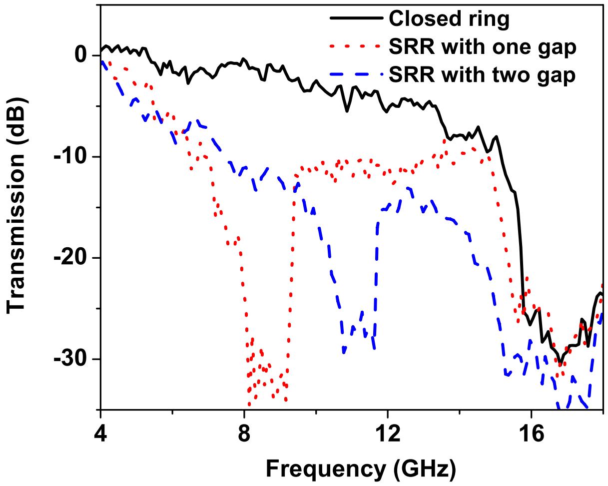


Fig. 2. (Color online) Measured transmission spectra of closed ring resonator and SRR with one gap and two gaps.

defined in Fig. 1. It is known that the SRR structure exhibits both magnetic and electric resonances. The coupling between two or more SRRs is quite complex and strongly depends on their geometrical arrangement.[10] Closing the gap of the SRR eliminates the SRR capacitor, and therefore the magnetic resonance will be destroyed. In this way we can easily identify the magnetic and electric resonance frequencies of the SRR. Figure 2 presents the measured transmission spectra of a lattice of closed ring resonators and SRRs with one and two gaps. The solid line exhibits the transmission spectra of the closed ring resonator medium while the dotted and dashed lines give the transmission spectra of the SRR medium with one and two gaps, respectively. As can be seen, there are two band gaps in the transmission spectra of the SRR medium with one gap (dotted line): the first band gap is between 8 and 9.3 GHz and the second is between 15.6–18 GHz, whereas for the case of closed ring resonator medium there exists only one band gap between 15.6 and 18 GHz and the first band gap is entirely destroyed (solid line). This result confirms that the first band gap in 8–9.3 GHz is due to the magnetic resonance and the band gap between 15.6 and 18 GHz is due to the electric resonance. For the SRR medium with two gaps, both the magnetic and electric resonances were still observable (dashed line). However, it is easy to see that the band gap which exhibits the magnetic resonance of the symmetric SRR with two gaps (10–12.3 GHz) is higher than that of asymmetric SRR with one gap (8–9.3 GHz). This result is quite reasonable since the total capacitance of the symmetric SRR is decreased; therefore, the magnetic resonance frequency increases. Besides obtaining a higher magnetic resonance frequency, the symmetric SRR can prevent the electric coupling of the external electric field to the magnetic resonance of the SRR.[11,12]

3.2 *Electromagnetic behavior of cut-wire pairs*

For SRR structures, to obtain the magnetic resonance the magnetic field vector H must be perpendicular to the SRR plane. This means that the incident electromagnetic microwave k has to propagate parallel to the sample plane. Hence, a larger number of layers are required to fully cover the incident beam, which is a major drawback for the fabrication of LHMs working at THz and optical frequencies, considering the current nano fabrication technology. An alternative to the SRR design is necessary to overcome the aforementioned difficulties. Shalaev *et al.* have shown that the cut-wire pair can replace the SRR for the magnetic resonance.[13] The cut-wire pair consists of a pair of finite-length wires separated by a dielectric layer as shown in Fig. 3(a). In essence, the cut-wire pair is a SRR with two gaps that has been flattened to result in the wire-pair arrangement. For an electromagnetic wave incident with wave vector and field polarization as shown in Fig. 3, the cut-wire pair will exhibit both inductive and capacitive behavior and will possess magnetic resonance providing a negative permeability. Therefore, the electromagnetic response of a cut-wire pair can also be explained by a LC simple model. Figure 3(c) shows the measured transmission spectra of the cut-wire pair structures with different numbers of layers, where the width of cut-wire is 1.0 mm. Clearly there is a band gap between 13.4 and 14.8 GHz in the transmission spectra. This band gap becomes more evident when the number of layers increases, as expected. Another band gap begins to be formed at ~17 GHz. The reasonable explanation for this is that the first band gap in 13.4–14.8 GHz is due to the magnetic resonance from circular current between cut-wires, providing a negative magnetic permeability.[14] And the second band gap starting at ~17 GHz is due to the electric resonance, providing a negative electric permittivity. These points are confirmed by our experiments shown in Fig. 3(d). The effective medium method[15] is presented to demonstrate the origin of electromagnetic behavior in case of the cut-wire pair structure. We shorted at the ends of cut-wires through the dielectric spacer. This method eliminates the effective capacitance, which in turn subsequently vanishes in the magnetic resonance without causing any considerable effect on electric resonance. The comparison of transmission spectra between this structure and its shorted version shows that in the case of shorted cut-wire pair structure, the first band gap is destroyed according to the magnetic resonance as mentioned above. The unchanged second band gap in both of the cases is due to electric resonance of cut-wire pair structure. This result confirms that the cut-wire pair structure exhibits both a magnetic and an electric resonance as an

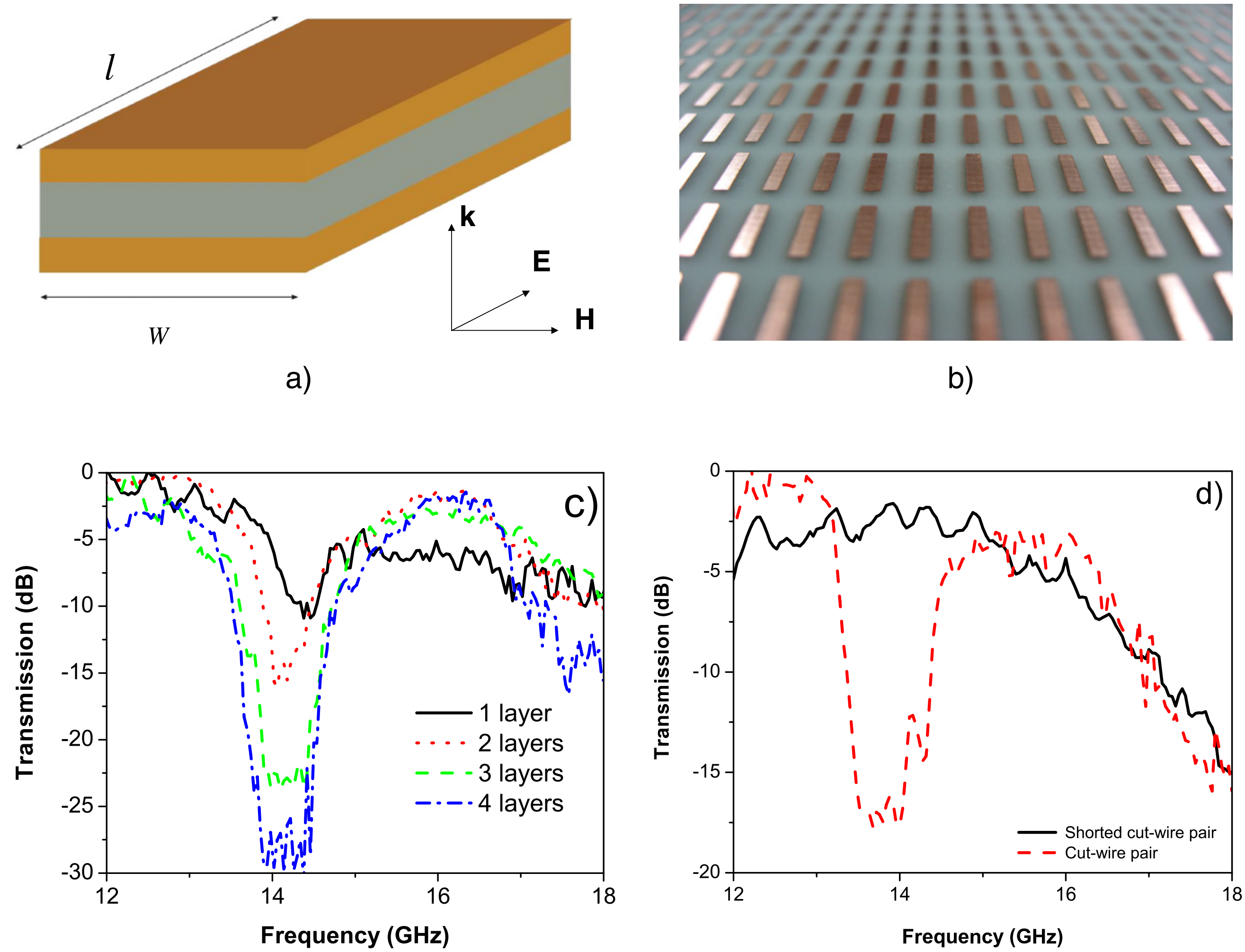


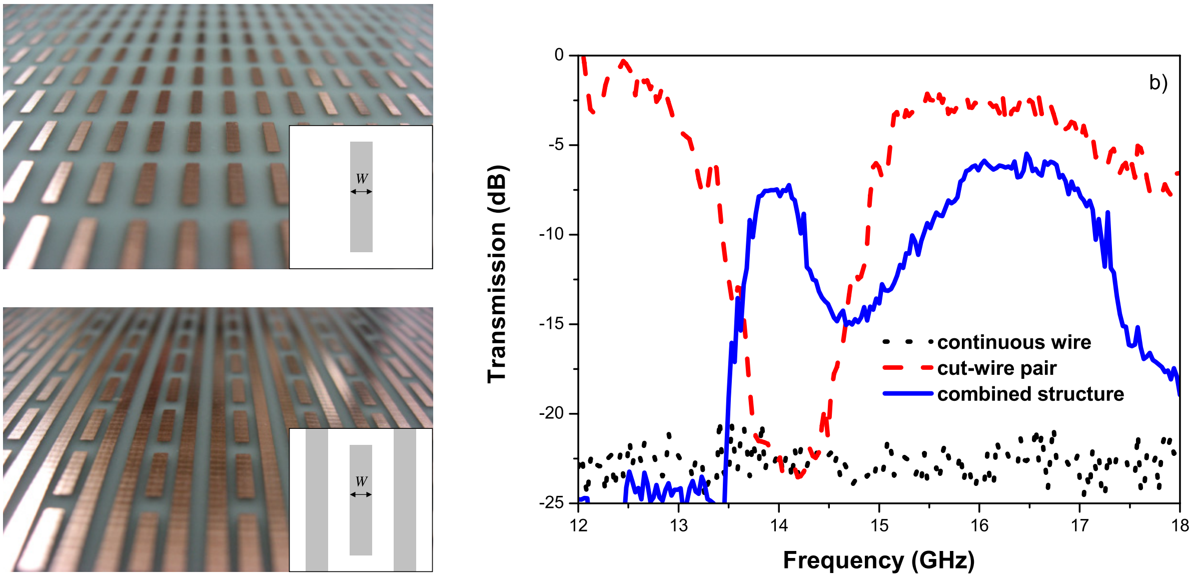
Fig. 3. (Color online) (a) Geometry of cut-wire pair: the length of cut-wire is $l = 5.5$ mm and width $w = 1.0$ mm, (b) Photo of one side of the fabricated cut-wire pair structure. (c) Measured transmission spectra of the various cut-wire pair media with four layers. (d) Comparison of transmission spectra between cut-wire pair structure and its shorted version.

SRR. However, it is important to note that these resonances strongly depend on the lattice constants[16)] as well as an dielectric-spacer thickness.[17)] Combining the cut-wire pairs with continuous wires, one can get a combined structure that exhibits the LH behavior, which will be discussed hereinafter.

3.3 LH behavior of the combined and fishnet structure

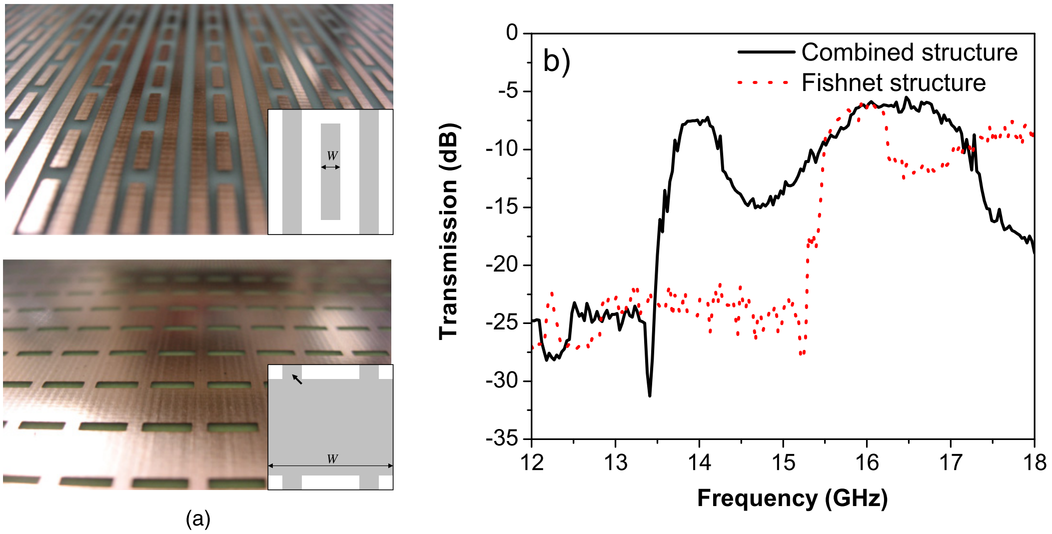
To obtain the LH behavior, cut-wire pairs are combined with continuous wires. Figure 4 presents the measured transmission spectra of the cut-wire pair, continuous wire and combined structures, where the width of cut-wire pair and continuous wire is 1.0 mm. The dotted line gives the transmission spectra of the continuous wire structure while the dashed and solid lines show the transmission spectra of the cut-wire pair and the combined structures, respectively. As shown in Fig. 4, the continuous wire structure is completely opaque throughout the measured frequency range, which means that the continuous wire structure exhibits a plasma cutoff frequency, that is higher than the measured frequency range. The cut-wire pair structure displays a stop band between 13.4 and 14.8 GHz, corresponding to the magnetic resonance frequency range where $\mu < 0$, while the combined structure exhibits a pass band, this band gap exactly coincides with the stop band of the cut-wire pair structure, indicating that both permittivity and permeability in this pass band of the combined structure are negative. Based on these results and the previous study,[18)] it was confirmed that the pass band between 13.4 and 14.8 GHz in the transmission spectra of the combined structure exhibits clear evidence of the appearance of the LH behavior.

In a case where the width of cut-wire pair increases to physically connect with the adjacent continuous wire, the combined structure will become the so-called fishnet structure. Figure 5 presents a comparison between the measured transmission spectra of the combined and fishnet structures. The solid line gives the transmission spectra of the combined structure while the dotted line shows the transmission spectra of the fishnet structure. As can be seen, there also exist two pass bands in the transmission spectra of the fishnet structure as the combined structure; the two bands



(a)

Fig. 4. (Color online) (a) Photo of one side and the corresponding unit cell viewed from k direction (insets) of the fabricated cut-wire pair (top) and combined structure (bottom). The thickness of continuous wires is equal to that of the cut-wire pair, 36 µm. Size of the unit cell and the geometrical parameters of the cut-wire pair are unchanged in the combined structure. (b) Measured transmission spectra of the cut-wire pair, the continuous wire and the combined structures.



(a)

Fig. 5. (Color online) (a) Photo of one side and the corresponding unit cell viewing from k direction (insets) of the fabricated combined (top) and fishnet structure (bottom). From combined to fishnet structure, the width of cut-wire pair (w) increases to be as wide as the size of unit cell in H direction. (b) Comparison between measured transmission spectra of the combined and the fishnet structures.

are separated by a shallow dip. According to Kafesaki *et al.*,[19] the first pass band between 15.5 and 16.2 GHz exhibits the left-handed behavior while the second one starting at 17.3 GHz is the right-handed transmission. Furthermore, the LH peak of the fishnet structure is shifted to high frequency compared to that of the combined structure. In fact, magnetic-resonance frequency in the fishnet structure is higher than that in the combined structure. This is due to an additional inductance at the neck of fishnet design while the broadened cut-wire pair does not considerably affect the magnetic resonance. The increased magnetic-resonance frequency leads to the shift of LH pass band in the fishnet structure. Our experimental result is in good agreement with the previous theoretical study and is explained by the LC simple model.[19] Figure 5 confirms that the fishnet structure can be considered as a continuous transformation of the combined structure where the cut-wire merges with the continuous wire.

4. Conclusions

In this paper, we systematically studied electromagnetic behavior of several transformative metamaterial structures: from the split-ring resonator and cut-wire pair structure for providing a negative magnetic permeability to the combined and fishnet structure exhibiting the LH behavior. The electromagnetic responses of SRRs and cut-wire pair structure were experimentally investigated using a known experimental method based on the effective medium theory. The LH transmission slightly shifts to higher frequency for the transformation from combined to fishnet structure.

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