ABSTRACT	TÓM TẮT
We investigated experimentally the	Chúng tôi tiến hành nghiên cứu thực

electromagnetic behavior of two different structures: split-ring resonator and cut-wire pair for providing a negative magnetic permeability. The free space transmission properties of the combined structure of cut-wire pairs and continuous wires were studied. The combined structures exhibit a pass band within the stop band of cut-wire pairs and continuous wires, which is a clear demonstration for the left-handed behavior. These structures were designed, fabricated, and measured in the microwave frequency regime.	nghiệm các tính chất điện từ của hai cấu trúc khác nhau: vòng cộng hưởng có rãnh và cặp thanh kim loại để tạo độ từ thẩm âm. Đặc tính truyền qua trong không khí của cấu trúc kết hợp cặp thanh kim loại và các dây liên tục được nghiên cứu. Các cấu trúc kết hợp thể hiện pass band (dải thông) trong stop band (dải chặn) của các cặp thanh kim loại và các dây liên tục, đây là minh chứng rõ ràng cho đặc tính tam diện thuận. Những cấu trúc này được thiết kế, chế tạo và được đo ở chế độ tần số vi sóng. Stopband: những tần số không thể qua thiết bị. Passband: khoảng tần số có thể qua thiết bị.
Keywords: Left-handed material, split-ring resonator, cut-wire pair.	Từ khóa: vật liệu tam diện thuận, vòng cộng hưởng có rãnh, cặp thanh kim loại.
INTRODUCTION Negative-index materials have attracted great attention in recent years due to their unique physical properties and novel applications [1-5]. The materials with simultaneously negative permittivity ε and negative permeability μ have been first proposed and theoretically studied in 1968 by Veselago [6], who has shown that such materials exhibit a number of unusual physical properties like negative refraction, reversal of Doppler shift and Czerenkov radiation. Owing to the simultaneous negative values of ε and μ, the electric field E, the magnetic field H and the wave vector k form a left-handed coordinate system, and the name “left-handed materials (LHMs)” is one of the terminologies has been	[redacted]

used for the description of these materials. It also follows that the LHM is characterized by a negative refractive index, hence these materials is also called negative-index materials. After the Veselago's paper, more than 30 years have elapsed until the first LHM was conceived and demonstrated experimentally by Smith et al. [7], which 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. In general, LHMs do not exist in nature and can be fabricated only artificially. LHM consists of two main elements, one is the "magnetic component," providing a negative magnetic permeability $\mu < 0$, and the other is "electric component," yielding a negative electric permittivity

ε Combining two components we get a material with negative ε and μ and, therefore, this material exhibits a negative refractive index n. It is well known that a negative permittivity medium can be easily obtained by a periodic array of wires [8]. The continuous wire structure behaves like a high-pass filter which means that the effective permittivity takes negative values below the plasma frequency. On the other hand, a negative effective magnetic permeability medium is difficult to obtain at high frequencies. In 1999, Pendry et al. have proposed that an array of split-ring resonators (SRRs) might exhibit a negative

[redacted]

[redacted]

effective permeability at a frequency close to the resonance frequency of these structures [9]. Based on this proposal, several different structures have been claimed by researchers, such as S-shaped [10], H-shaped [11], cut-wire pair [12], and π-shaped [13] structures. The main purpose of these modified structures is to find out the optimized structure that can be easily fabricated and experimentally characterized, especially, LHM working at optical frequencies. In this paper, we investigated experimentally the electromagnetic response of two different structures: SRRs and cut-wire pairs to provide a negative magnetic permeability. In addition, we report the left-handed behavior of a combined structure of cut-wire pairs and continuous wires. These structures were designed, fabricated, and measured in the microwave frequency regime.

EXPERIMENT

The printed copper board (PCB) with a copper thickness of 36 μm and a dielectric constant of 4.8 was used to fabricate a SRR, cut-wire pair and LHM structures. 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 periodicity along the z direction was obtained by stacking a number of pattern boards with a lattice constant az = 1 mm. To obtain the LH behaviour, the SRRs or cut-wire pairs were

[redacted]

[redacted]

[redacted]

[redacted]

combined with continuous wires. The geometrical parameters of LHM are defined in Fig. 1(a). The length of cut-wire pair is l = 5.5 mm and the widths of cut-wire pair and continuous wire are 1 and 0.7 mm, respectively. The thickness of the dielectric layer ts is 0.4 mm. These structures were designed,built, and measured in the microwave frequncy

For SRRs 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 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. Therefore, 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 [15]. The cut-wire pair consists of a pair of finite-length wires separated by a dielectric layer as shown in Fig. 4. In essence, the cut-wire pair is a SRR with two gaps that has been flattened to results in the wire-pair arrangement. For an electromagnetic wave incident with wave vector and field polarization as shown in Fig. 4, the cut-wire pair will exhibit both inductive and capacitive behavior and will possess magnetic resonance

[redacted]

[redacted]

[redacted]

providing a negative permeability.

Therefore, the electromagnetic response of cut-wire pair can be also explained by the LC simple model.

This structure exhibits not only a magnetic resonance but also an electric resonance as in the SRR.

Figure 5 shows the measured transmission spectra of the cut-wire pair structure with different numbers of layers. In this measurement, the electromagnetic wave was incident normal to the sample surface (see Fig. 4). 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 observed results are similar to those in Ref. 16. Hence, it is confirmed that the first band gap in 13.4 – 14.8 GHz is due to the magnetic resonance, providing a negative magnetic permeability, and the second band gap starting at ~ 17 GHz is due to the electric resonance, providing a negative electric permittivity. This result reveals that the cut-wire pair structure exhibits both a magnetic and an electric resonance as an SRR.

It is well known that the SRR structure exhibits both magnetic and electric resonance. Closing the gap of the SRR, it eliminates the capacitor of the SRR, and therefore the magnetic resonance will be destroyed. By this way we can easily identify the magnetic and electric resonance frequencies of the SRR. Figure 3 presents the measured

[redacted]

[redacted]

transmission spectra of a lattice of closed ring resonators and SRRs. As can be seen in Fig. 3, there are two band gaps in the transmission spectra of the SRR medium (solid line): the first band gap between 8 and 9.3 GHz and the second band gap 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 quite destroyed (dotted line). This result confirms that the first band gap in 8 - 9.3 GHz in the transmission spectrum of periodic SRR medium is due to the magnetic resonance and the second band gap between 15.6 and 18 GHz is due to the electric resonance.

To obtain the LH behavious, cut-wire pairs are combined with continuous wire, as shown in Fig. 1(a).

Figure 6 presents the measured transmission spectra of the cut-wire pair, continuous wire and the combined structures.

For this measurement, all structures here consist of three layers and the electromagnetic wave were incident normal to the sample surface as shown in Fig. 1. 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. 6, the continuous wire structure exhibits a plasma cutoff frequency, which is higher than the measured frequency range. The cut-wire pair structure displays a stop b

[redacted]

[redacted]

[redacted]

[redacted]