Reflection behaviors of negative permeability metamaterials in X-band*

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Received June 6, 2005; revised September 20, 2005

Abstract We experimentally investigate the reflection behaviors of negative permeability metamaterials (NPMs) consisting of a periodic array of copper hexagonal split ring resonators (SRRs). Results show that, for the two-dimensional (2-D) NPMs samples, a reflectivity peak with the height of 10 dB appears near the resonance frequency, and the reflectivity is remarkably weak on both sides of the transmission gap; the reflection behaviors of 3-D samples similar to that of the 2-D ones are strongly affected by the lattice constants; the reflection phase increases with the frequency, and an inflexion exists at the resonance frequency of 2-D samples.

Keywords: negative permeability metamaterials, reflection behaviors.

It has long been known that the electrical permittivity ε and the magnetic permeability μ fundamentally determine the behaviors of electromagnetic waves in matter. Generally, they are both positive. Although a few kinds of materials have negative permittivity ε or permeability μ, few natural materials have been found with negative permittivity ε and permeability μ. In 1968, Veselago introduced the concept of left-handed metamaterials (LHMs)—a medium with both negative permittivity ε and negative permeability μ[1]. Pendry et al. proposed the models of periodic array of thin metallic wires and split ring resonators (SRRs), and obtained the effctive negative permittivtty ε_{eff} below the plasma frequency and the effective negative permeability μ_{eff} in the resonance frequency range, respectively[2,3]. Till now, left-handed metamaterials (LHMs) have become a new focus of research because of their unique properties.

Negative permeability metamaterials (NPMs) consisting of a periodic array of SRRs are a part of LHMs. As a new kind of information material, NPMs are expected to be applied in many fields of communication, whose quality is limited by the electromagnetic properties of the materials in the component. It is known that transmission and reflection properties are the two main properties used in the existing communication component. In view of the potential applications of NPMs, we consider that special attention should be paid to the reflection behaviors of NPMs, which would have a more wide application space. However, recent studies on metamaterials are mainly focused on theoretical studies, attempts of different scales samples, and researches of unique transmission properties, etc.[4—14], and studies on the reflection behaviors of NPMs are very few. In this paper, we fabricate the NPMs samples and experimentally investigate their reflection behaviors in a rectangular waveguide.

1 Experiments

1.1 Samples

Using a shadow mask/etching technique, we fabricated a hexagonal SRRs array on one side of the circuit board. The NPMs samples are obtained by further arraying. As shown in Fig. 1(a), the size of the SRRs can be represented by d_1/d_2(mm), where d_1 and d_2 are the diameter of the inscribed circle of the inner and outer hexagon rings, respectively. The gap g and width c of SRRs are 0.3 mm. In the experiments, we design two kinds of NPMs samples: the 2-D NPMs samples with lattice constants a and b of both 7.0 mm, and the 3-D NPMs samples with lattice constants of a = 7.0 mm, e = 3.3 mm, and b = 5.0 mm, 7.0 mm and 9.0 mm, respectively. The vector $\boldsymbol{K}$ represents the propagation direction of microwave.

* Supported by the National Science Fund for Distinguished Young Scholars (Grant No. 50025207), National Natural Science Foundation of China (Grant No. 50272054) and the Major State Basic Research Development Program of China (Grant No. 2004CB719805)

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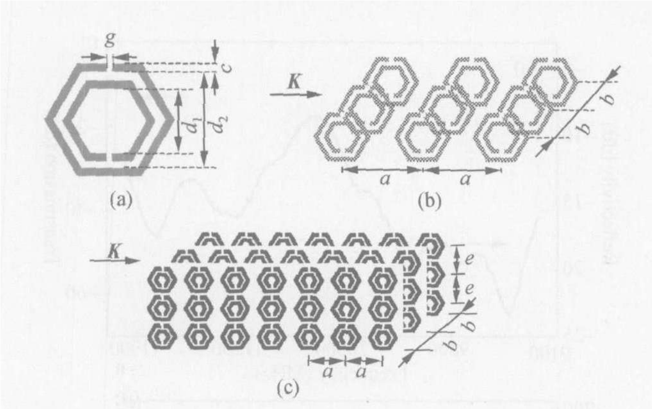

Fig. 1. Schematic diagram of the NPMs samples. (a) Split ring resonators (SRRs); (b) 2-D samples; (c) 3-D samples.

1.2 Measurements

Using a vector network analyzer AV3618, we measured the X-band (8—12 GHz) scattering parameters of 2-D and 3-D NPMs samples, which are placed in a rectangular waveguide (section 22.86 mm × 10.16 mm). As shown in Fig. 2, the incident microwave propagates from left to right and it is divided into two parts after coupling with the NPMs sample, including the reflection part and the transmission one. The reflection microwave is in the opposite direction to that of the incident microwave. And then, the reflectivity and reflection phase are obtained by the analyzer. On the other hand, the transmission microwave through the samples is absorbed by a little reflection load. Therefore, we consider that the energy detected by the analyzer comes from the microwave reflected by the NPMs samples.

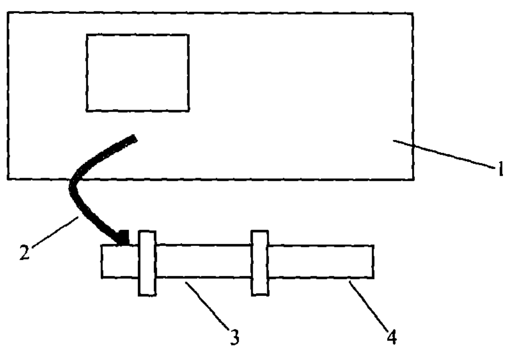

Fig. 2. Schematic diagram of the measurements. 1, Vector network analyzer; 2, coaxial line; 3, waveguide (sample room); 4, little reflection load.

2 Results and discussions

2.1 Results of 2-D NPMs samples

The reflectivity spectrum and the reflection phase versus frequency are shown in Fig. 3. The dot line in Fig. 3 (a) represents the transmission spectrum of the samples. It can be seen that there is a band gap at the resonance frequency (10.3 GHz) in the transmission spectrum of the 2-D NPMs samples. A reflectivity peak appears in the resonance frequency range of 2-D NPMs samples, and the reflectivity is remarkably weak within ranges of both sides of the band gap. Fig. 3 (b) shows that the reflection phase increases with the frequency and it has an inflexion at the resonance frequency.

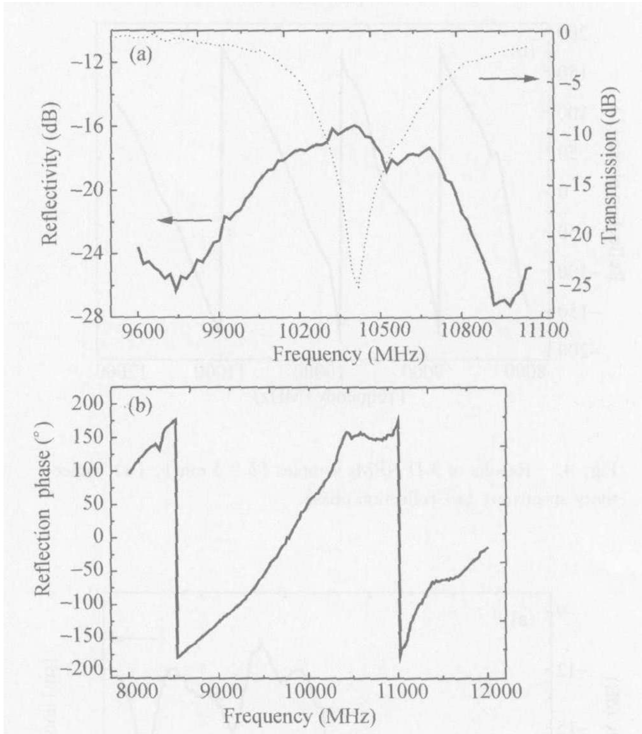

Fig. 3. Results of 2-D samples. (a) Reflectivity spectrum; (b) reflection phase.

2.2 Results of 3-D NPMs samples

The reflection spectra and reflection phase versus frequency of the 3-D NPMs samples with different lattice constant b are measured and shown in Fig. 4, Fig. 5 and Fig. 6, respectively. The dot lines represent the transmission spectrum of the samples. It can be seen that there is a band gap in the resonance frequency range, respectively.

For these three types of 3-D samples, a reflection peak with the magnitude of −7 dB, −10 dB and −9 dB appears at the relative resonance frequency of samples, respectively. The reflectivity is remarkably weak on both sides of the band gap of the samples, and the reflection phase increases with the frequency for the three types of samples.

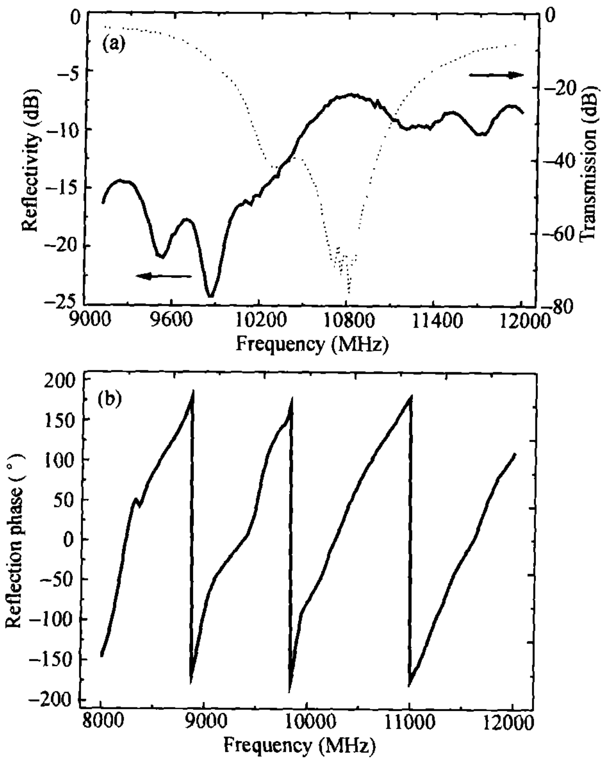

Fig. 4. Results of 3-D NPMs samples (b = 5 mm). (a) Reflectivity spectrum; (b) reflection phase.

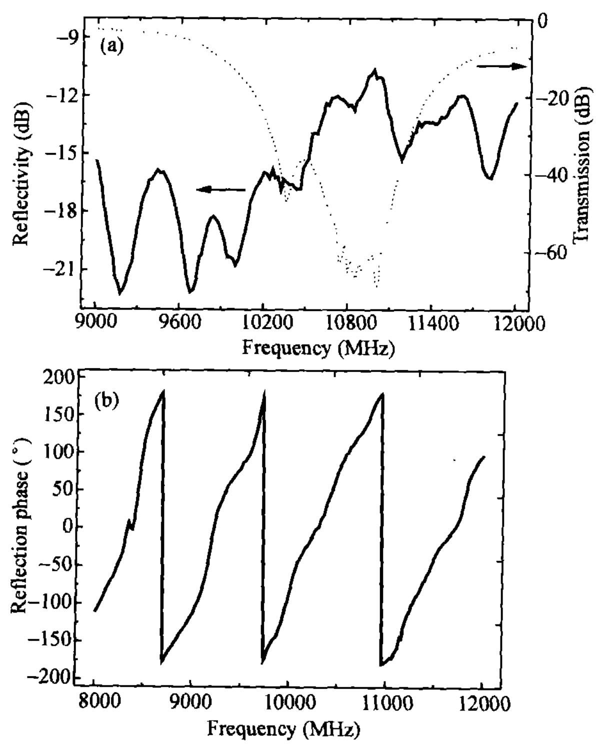

Fig. 5. Results of 3-D NPMs samples (b = 7 mm). (a) Reflectivity spectrum; (b) reflection phase.

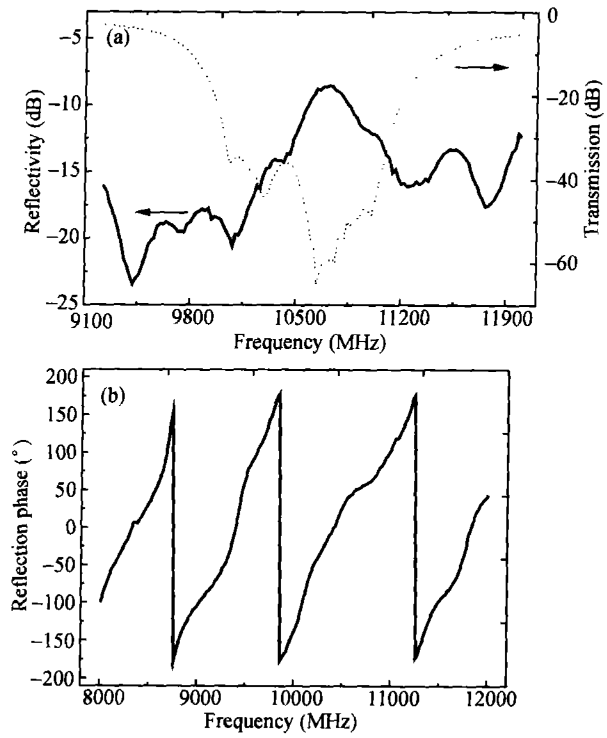

Fig. 6. Results of 3-D NPMs samples (b = 9 mm). (a) Reflectivity spectrum; (b) reflection phase.

2.3 Discussion

The above experimental results show that 2-D NPMs samples have a transmission band gap in the resonance frequency. A reflection peak with the height of 10 dB appears in the same frequency range, and the reflection is remarkably weak on both sides of the band gap. The reflection behaviors of 3-D NPMs samples are similar to that of the 2-D ones. Although the behaviors are remarkably affected by the lattice constants of the structures, the frequencies of reflection peaks are consistent with the resonance frequencies of 3-D NPMs samples. In addition, the reflection phase increases with the frequency and there is an inflexion in the reflection phase of the 2-D NPMs samples.

It is well known that NMPs consist of a periodic array of SRRs resonate and have a negative permeability at the resonance frequency because of their unique structures. The responses of the NPMs have a phase transition at the resonance frequency of the metamaterials, which results in a band gap within the same frequency range and a strong absorption of the electromagnetic energy by the samples on both sides of the band gap. From the energy conservation principle, $I_{\text{incident}} = I_{\text{reflection}} + I_{\text{transmission}} + I_{\text{absorbed}}$

($I_{incident}$, $I_{reflection}$, $I_{transmission}$ and $I_{absorbed}$ represent the energies of different parts of the microwave before and after coupling, respectively.), it can be seen that our experimental results of the power of microwave are consistent with the theoretical one. The transition of the transmission phase at the resonance frequencies can clearly mark the resonant character of NPMs. In our experiments, there is an inflexion in the reflection phase at the resonance frequency of the 2-D NPMs samples, which indicates that to some extent, the reflection phase can also mark the resonant character of the NPMs. The resonant effects of 3-D NPMs are stronger than that of the 2-D ones, and both transmission and reflection behaviors of 3-D samples can be affected by the interaction of cells with different lattice constants.

3 Conclusions

In this paper, we have experimentally investigated the reflection behaviors of 2-D and 3-D NPMs samples with a periodic array of copper hexagonal SRRs. It is found that 2-D NPMs samples resonate at 10.3 GHz and a reflectivity peak appears in the same frequency range. On both sides of the resonance frequency range, the reflectivity of the 2-D NPMs samples is remarkably weak. 3-D samples with different lattice constants have different reflection peaks, but the peak frequencies are consistent with the relative resonance frequencies. The reflection phase of NPMs increases with the frequency and an inflexion appears in the curve of the reflection phase of 2-D samples.

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