Experimental Investigation of R(ω), T(ω) and L(ω) for Multi-Layer SRRs and Wires Metamaterials

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Abstract

Reflection($R(\omega)$), transmission($T(\omega)$) and loss($L(\omega)$) characteristics of multi-layer metamaterials are investigated experimentally in free space with the incident EM waves perpendicular to the substrate plane. The sample is made of split-ring resonators(SRRs) and wires which are the typical model of metamaterials. The $R(\omega)$ and $T(\omega)$ of multi-layer metamaterials have been calculated from the measured *S*-parameters. In this paper, we got the impedance-matched result according to the curves of $R(\omega)$, meanwhile the $T(\omega)$ decreased with increasing number of layers. At last, we attained the result that the $L(\omega)$ gets to nearly 98% around 8 GHz, with $R(\omega)=T(\omega)=0$. The design presented in this paper achieves experimented loss near unity.

Key words : Metamaterial, Loss, Characteristics, Multi-layer, Composite Structure.

Ⅰ. Introduction

Recently, metamaterials with a negative index of refraction have attracted great attention due to their fascinating electromagnetic(EM) properties. It was Veselago who introduced the term "left-handed substances" in his seminal work published in 1968[1]. Until 1996, Pendry *et al.* successively proposed a theoretical model that could realize negative permittivity by periodic arrangement of metallic wires[2] and negative permeability by periodic array of split-ring resonators(SRRs)[3]. In 2000, Smith *et al.* designed artificial materials at microwave frequen cies[4], and the negative refraction was also experimentally verified in the wedge prism of metamaterials[5]. Metamaterials have many peculiar electromagnetic properties, such as reversed Doppler shift[6], Cherenkov radiation[7], and Snell effect[8],[9], etc.

At present, the research of metamaterials focuses on the incident EM wave parallel to the metamaterials samples plane. Most experiment used lithography which etches the cycle with single-layer structure of metal pattern on media substrate. Because it is difficult to realize the structure design of metamaterials by the methods of paralleling to the substrate plane. There is an urgent need to allow the incident EM waves to be perpendicular to the substrate plane[10].

In this work, we mainly reported the experiment of reflection, transmission and losses of metamaterials with the incident electromagnetic wave perpendicular to the sample substrate plane. The sample was the typical model of the SRRs and wires. We have experimented for multi-layer metamaterials in free space. The characteristics of the $R(\omega)$, $T(\omega)$ and $L(\omega)$ of metamaterials with various layers were investigated in detail.

Ⅱ. Experiments

2-1 Sample Preparation

Fig. 1 shows the structure of the designed samples. The samples consisted of an array of the SRRs and continuous wires. Fig. 1(a) illustrates the structure of SRRs, where *r* presents the radius of the SRRs, *t* is the width of each ring, *w* is the spacing between the two rings in a single SRRs's structure, and *g* is the gap of each ring. In Fig. 1(b), wires structure is illustrated, *d* is the width of the wire and *a* is the cell side of the square lattice. The size parameters are listed as the following: $a=1.0\times10^{-2}$ m, $t=1.0\times10^{-3}$ m, $w=3.0\times10^{-4}$ m, $r=2.0\times10^{-3}$ m, $d=0.5\times10^{-3}$ m, $l=1.4\times10^{-3}$ m, $g=3.0\times10^{-4}$ m. The above structures were fabricated using a standard printed circuit board process with 20-μm-thick copper patterns on 0.2-mm-thick FR4 dielectric substrates. In order to assemble it much more easier, we have designed the sample with the size of 300×300 mm^2. The number of SRRs on the board was 30×30. The number of wires on the board is

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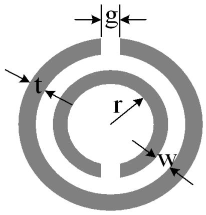
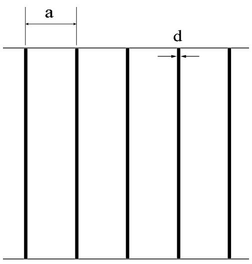
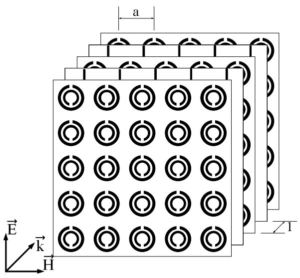


(a) SRRs



(b) Wires



(c) Prepared sample

Fig. 1. The structure of the designed samples.

30. These boards were then sandwiched(using an adhesive with 0.06 mm thickness) with another 0.5 mm thick FR4 blank substrate to obtain the correct spacing, the sample of one layer contained the SRRs, 0.5 mm thick FR4 and the wires. Then we could get the sample of multi-layers metamaterials, as shown in Fig. 1(c).

2-2 Experimental Characterization

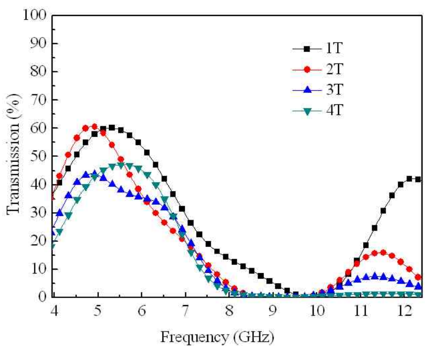
The scattering parameters were measured by a vector network analyzer HP8722 ES with a TEM mode. The measured frequency range from 3.95 GHz to 12.4 GHz. In free space, the size of microwave horn is 24×16 cm and the interval space of two horn antennas is 20 cm. The samples were vertically placed in the middle of two horns. Poynting vector *k* perpendicular to the SRRs substrate plane. As a result, we attained *S*-parameters of S_{11} and S_{21}, where $T(\omega)=|S_{21}|^2$ and $R(\omega)=|S_{11}|^2$ are the transmission and reflectance, respectively. The value of $L(\omega)$ can be inferred by the formula of $L(\omega)=1-T(\omega)-R(\omega)$[11].

Fig. 2(a)~(c) present the curves of $T(\omega)$, $R(\omega)$, $L(\omega)$ of various layers, respectively. As shown in Fig. 2(a). All the samples show a maximum $T(\omega)$ peak within 3.95~8 GHz. For one-layer, the peak amplitude is about 60 % at 5.5 GHz. Clearly, we can observe that the intensity of peak decline with the increase of layer. The peak amplitude of four-layer sample almost drops to 40 % in the range of 3.95~8 GHz and the $T(\omega)$ is inclined to zero in the range of 8~12.4 GHz . There is no much change in the $T(\omega)$ curves in the measured frequency range when the numbers of layer are larger than four layers. The decline of $T(\omega)$ is mainly due to the loss of the medium of metamaterials.

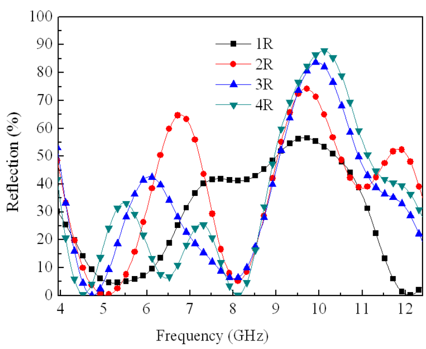
Ⅲ. Results and Discussion

The curves of reflection are presented in Fig. 2(b). With the increase of layer, the number of $R(\omega)$ peak ($R(\omega)\approx 0$) increases and the peaks shift to low frequency range. Clearly, the $R(\omega)$ peaks amplitude are relatively low at 5 GHz and 8 GHz. These results are related to impedance characteristic, which can be described by the formula $\Gamma=\frac{Z_{IN}-1}{Z_{IN}+1}$, where Γ is reflection coefficient(corresponding to $R(\omega)$ in the present work), Z_{IN} is the normalized input impedance. Γ equals to zero when $Z_{IN}=1$, which leads to the relatively low reflection.

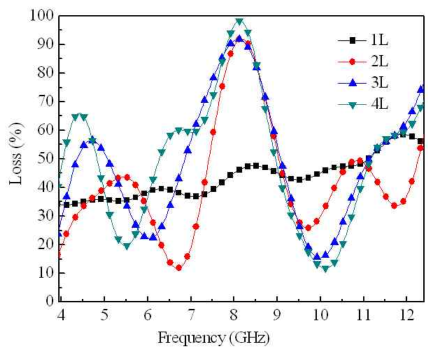
As the above description, an impedance-matched structure may yield zero $R(\omega)=0$. The real part ($Z_{IN'}$) and the imaginary part ($Z_{IN''}$) of impedance of metamaterials can be calculated by $Z_{IN}=\pm\sqrt{\frac{(1+|S_{11}|)^2-|S_{21}|^2}{(1-|S_{11}|)^2-|S_{21}|^2}}$, which are determined by the condition $Z_{IN'}>0$[12]. The impedance of one-layer metamaterials approaches the impedance of air at 5 GHz and 12 GHz, $Z_{IN}\approx 1$, so $R(\omega)\approx 0$. (As well as



(a) T(ω)



(b) R(ω)



(c) L(ω)

Fig. 2. The curves of metamaterial with various layers.

Table 1. The real (z') and imaginary (z'') parts of impedance at characteristic frequencies for various layers.

Frequence (GHz)	1 layer		2 layers		3 layers		4 layers	
	ZIN'	ZIN''	ZIN'	ZIN''	ZIN'	ZIN''	ZIN'	ZIN''
4.5							0.81489	0.04955
4.7					1.09104	0.02054		
5	0.99505	−0.84406	1.06905	−0.09273				
8			0.60398	0.18073	0.67223	−0.2	0.85476	−0.06759
12	1.05752	−0.10901						

two-layer at 5 GHz and 8 GHz, $Z_{IN}\approx 1$, $R(\omega)\approx 0$, three-layer at 4.7 GHz and 8 GHz, four-layer at 4.5 GHz and 8 GHz, $Z_{IN}\approx 1$, $R(\omega)\approx 0$) Same results could be observed for the other layer metamaterials samples, as shown in Table 1.

For one layer metamaterials, Fig. 2(C) the maximum of $L(\omega)$ is about 50 %. The peaks of loss increase in multiple layers, and the $L(\omega)$ reaches to more than 90 % for two layers at 8 GHz. The peak of $L(\omega)$ is 98 % for four layers at 8 GHz. The increase of $L(\omega)$ is originating from the conductivity of the metallic layer, the dielectric loss of substrate, and the adhesives used to hold the structure together[13].

According to the result of experiment, we get the characteristics of the metamaterials' reflection, transmission and loss in perpendicular incidence. The transmission of metamaterials maintains a high level within 3.95～8 GHz, and those are relatively low in the frequency range of 8～12.4 GHz. On the other hand, the multi-layer metamaterials can realize a low reflection due to their impedance approaching one. In a conclusion, a loss of metamaterials is relatively high as long as it’s reflection is low. When the layer number of metamaterials exceeds four layers, the loss is asymptotic to unity around 8 GHz. So we only present the results of four-layer metamaterials.

From the above analysis, the amplitude of transmission reduces while the corresponding loss enhances with the increase of layers. For the four layers metamaterials, the transmission almost falls to zero within 8 GHz to 12.4 GHz, and there exists a nearly 100 % loss around 8 GHz. It is obvious that electromagnetic wave can effectively incident to metamaterials when $R(\omega)=T(\omega)=0$. The results demonstrate that electromagnetic wave can be perfectly absorbed around 8 GHz via the present design. These could provide a method of enhancing an absorption properties of microwave absorbing materials using metamaterials[14]. Simultaneously, it is possible to extend the bandwidth of metamaterials by adjusting the scales, shapes and arrangement of unit cell[15].

Ⅳ. Conclusion

The characteristic of reflection, transmission and loss of the metamaterials with the incident EM waves perpendicular to the substrate plane has been investigated. The curves of transmission, reflection and loss have been calculated by measuring the complex S parameters with 3.95～12.4 GHz. The results show the phenomenon that the transmission decline with increasing number of layers. We have attained $T(\omega)=0$ from 8 GHz to 12.4 GHz and achieve impedance-matched and realize $R(\omega)=0$. The amplitude of loss peak increases with number of layer increasing, the loss almost gets to 100 % in four-layers at 8 GHz. These results indicate that it is possible for metamaterials applied to microwave absorbing materials.

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