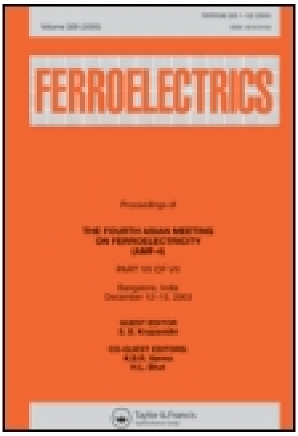

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Zhang Lin-Li [a b], Xu Zhuo [a], Qu Shao-Bo [a], Wei Xiao-Yong [a], Zhang An-Xue [c], Xia Song [a] & Xie Feng [a]

[a] Electronic Materials Research Laboratory, Key Laboratory of the Ministry of Education, Xi'an Jiaotong University, Xi'an, 710049, China

[b] Department of Physics, Xi'an University of Architecture and Technology, Xi'an, 710055, China

[c] School of Electronics and Information Engineering, Xi'an Jiaotong University, Xi'an, 710049, China
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Characteristics of Left-Handed Materials with Magnetic Resonance and Electric Anti-Resonance Based on Ceramics

ZHANG LIN-LI,[1,2,*] XU ZHUO,[1] QU SHAO-BO,[1] WEI XIAO-YONG,[1] ZHANG AN-XUE,[3] XIA SONG,[1] AND XIE FENG[1]

[1]Electronic Materials Research Laboratory, Key Laboratory of the Ministry of Education, Xi'an Jiaotong University, Xi'an 710049, China
[2]Department of Physics, Xi'an University of Architecture and Technology, Xi'an 710055, China
[3]School of Electronics and Information Engineering, Xi'an Jiaotong University, Xi'an 710049, China

Based on ceramics S-shaped left-handed materials with magnetic resonance and electric anti-resonance were prepared by screen printing. The microwave transmittance properties of these samples in a rectangular waveguide were experimentally investigated. It is found that the two frequency bands of negative effective permittivity and negative effective permeability overlap from 8.5 to 9.46 GHz, which is left-handed materials pass-band and the bandwidth is about 1 GHz. Magnetic resonance is due to magnetic coupling between magnetic field component of external fields and the samples, in which the effective permeability could be negative. And electrical anti-resonance originated from electric coupling may contribute to negative effective permittivity. This based on ceramics substrate S-shaped construct possess both remarkable electric and magnetic resonances, which provides a flexible element for constructing planar left-handed materials.

Keywords Left-handed material; negative permittivity; negative permeability; ceramic substrate

1. Introduction

In the late 1960s, Veselago [1] theoretical postulated a new class of materials termed left-handed materials that have simultaneous negative permittivity and negative permeability. It is found that such a medium have dramatically different propagation characteristics stemming from the sign change of the group velocity, including reversal of Cerenkov radiation, Doppler effect and anomalous refraction. The interest in Veselago's work was renewed since Pendry et al. [2, 3] proposed an artificial material consisting of the so-called split-ring resonator which exhibit a band of negative permeability in spite of being made of non-magnetic materials, and wires which provide the negative permittivity. Based on Pendry's

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*Corresponding author. E-mail: shengzhxzhll@gmail.com

suggestion and targeting the original idea of Veselago, Smith et al. [4] demonstrated the realization of the first left-handed material which consisted of an array of SRRs and wires, in alternating layers. Ever since then, explosive research interest in metamaterials has been rekindled, and rapid progress in this area has been achieved [5–14]. So far, SRRs and wires geometries are the most elements for constructing left-handed materials [8–10]. Although these periodic structures exhibit a pass-band and are electrically very small, the measured insertion losses in the allowed band are too high for their practical application.

In this work, the planar electromagnetic resonators, possing both magnetic and electric responses, based on ceramic substrates was developed. The microwave transmittance properties of these samples in a rectangular waveguide were experimentally investigated. The theoretical analysis and experiment results confirm the left-handed properties. Compared with other left-handed metamaterials, this structure exhibits simultaneously negative permittivity and negative permeability and its equivalent circuit is much simpler. Moreover, it has much broader left-handed pass-band in which both the permittivity and the permeability are negative. The structures were fabricated by using screen-printing technology, which is much easier and economical.

2. Sample Preparation and Experimental

Using screen printing which is much easier and economical, we constructed S-shaped patterns on Al_2O_3 ceramic board. The thickness and the relative permittivity of the ceramic board are 1.0 mm and 9.8, respectively. The dimensions of single S-shaped unit cell are shown in Fig. 1. w = 2.8 mm, t = 0.4 mm, h = 2 mm, the periods of horizontal and vertical directions are 3.0 mm and 6.0 mm, respectively. There are four unit cells along x axis (horizontal direction) and one unit cell along y axis (vertical direction) on single ceramic board. The metal material used is silver. Silver electrodes printed on ceramic boards sintered at the temperature of 873.15 K for 20 min. The thickness of silver electrodes is about $50\mu m$ under the Polarizing microscope. Experimental samples were printed silver electrode by ceramic substrates and there is no silver electrodes separated by ceramic substrate by superposition.

An Agilent 8720 ES vector Network analyzer is used to measure all of the scattering parameters at X band. A straight section of rectangular waveguide was used to contain the samples. The EM wave propagated along the x axis, electric field E parallel to the axis, the magnetic field H parallel to the axis, as shown in Fig. 2. The relationship of the experimental

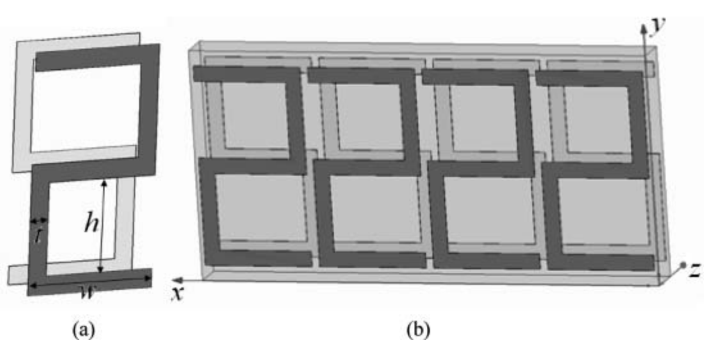

Figure 1. S-shaped structural unit and ceramic samples (a) unit; (b) monolithic ceramic samples.

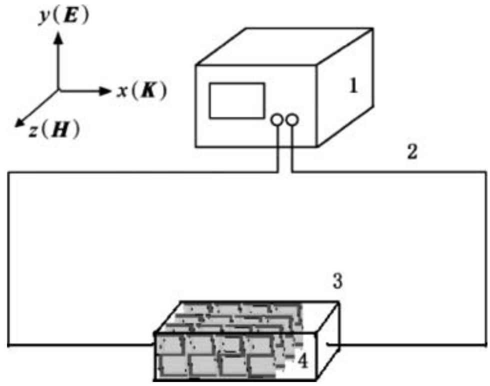

Figure 2. Schematic diagram of test device 1 8720 ES Vector Network Analyzer, 2 for the coaxial cable, 3 for the rectangular waveguide, 4 for sample.

S parameters with the frequency can be seen from Fig. 3. When the frequency is higher than 10.5 GHz band for the test sample, a strong reflection of electromagnetic waves will appears and the electromagnetic waves is almost impossible to transfer, so the frequency bands above 10.5 GHz is not used in our experiment.

The effective permittivity and permeability of the S-shaped ceramic samples are extracted from the transmission and reflection data based on the approach ref. in [15], as shown in Fig. 4. It can be seen that around 8.5 GHz, μ_{eff} has a strong Drude-Lorentz resonance behavior with the real part raging from 1.5 to -5. Interestingly, there is an anti-Drude-Lorentz resonance in the ε_{eff} curve around 9.46 GHz with the minimum values of -2. In the range of 8.5–9.46 GHz, the real part of the effective permittivity and permeability are negative exhibiting a left-handed property with bandwidth of 1 GHz. The effective permeability has a resonance behavior, while effective permittivity has an anti-resonance behavior.

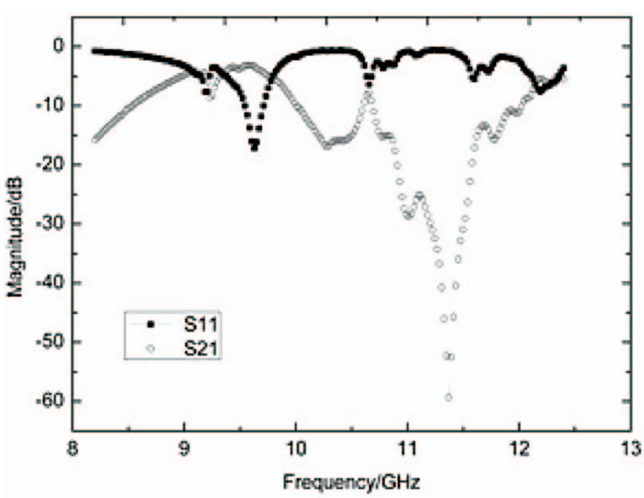

Figure 3. Transmission characteristics of the S-shaped ceramic samples.

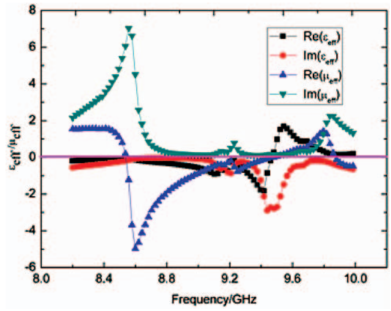

Figure 4. The relationship of the effective permittivity or effective permeability on frequency. (See Color Plate XIV)

The resonance and anti-resonance physical origin of S-shaped ceramic samples are analyzed. The equivalent circuit of S-shaped unit cell is shown in Fig. 5. It can be seen that there exist three equivalent capacitances of the front and back faces of overlapped S-shaped electrode. Due to the existence of capacitor C_1 and C_0, it made the surface induced current in the loop between the two electrodes. Figure 6(a) is the surface current distribution map for HFSS electromagnetic finite element analysis simulation software, and the arrows of the figure indicate the flow of current. When the vertical magnetic field pass through the S-shaped structural unit, the surface induced current, respectively, form a ring around the two sub-loop, which make the current of the capacitance C_0 cancel out each other, so the current flow around the periphery of the macrocyclic. As there is no intermediate silver electrode, which magnetic momentum of two sub-ring generated by resonance is the same phase. So the resonance took place in the 8.5 GHz is the resonance of electromagnetic fields generated by magnetic coupling. As can be seen in the Fig. 6(a), electric field parallel to the direction of the capacitor, electric field can not be coupled to the S-shaped structure units, the electric resonance did not happen in the 8.5 GHz resonant, only magnetic resonance.

When the wave vector k is perpendicular to the S-shaped structure of the sample surface as shown in Fig. 6(b), entirely due to the magnetic field parallel to the sample surface, the magnetic response is small, so it can be neglected. The plane of the electric field on the S-shaped structural unit along the direction of the electric field arise the two branches of resonance, which is similar to Pendry, et al. [2, 3] proposed by metal lines in the electric field action in response. The anti-resonant dielectric behavior (imaginary part is negative) located on 9.46 GHz originated from electrical coupling may contribute to negative effective permittivity. S-shaped structure with an alternative to conventional metal wire to achieve a negative value in a very wide frequency band. That has considerable advantages in the design and realization of a negative dielectric material [16].

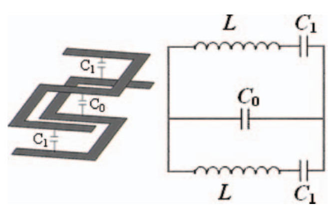

Figure 5. Equivalent circuit of the S-shaped structural unit.

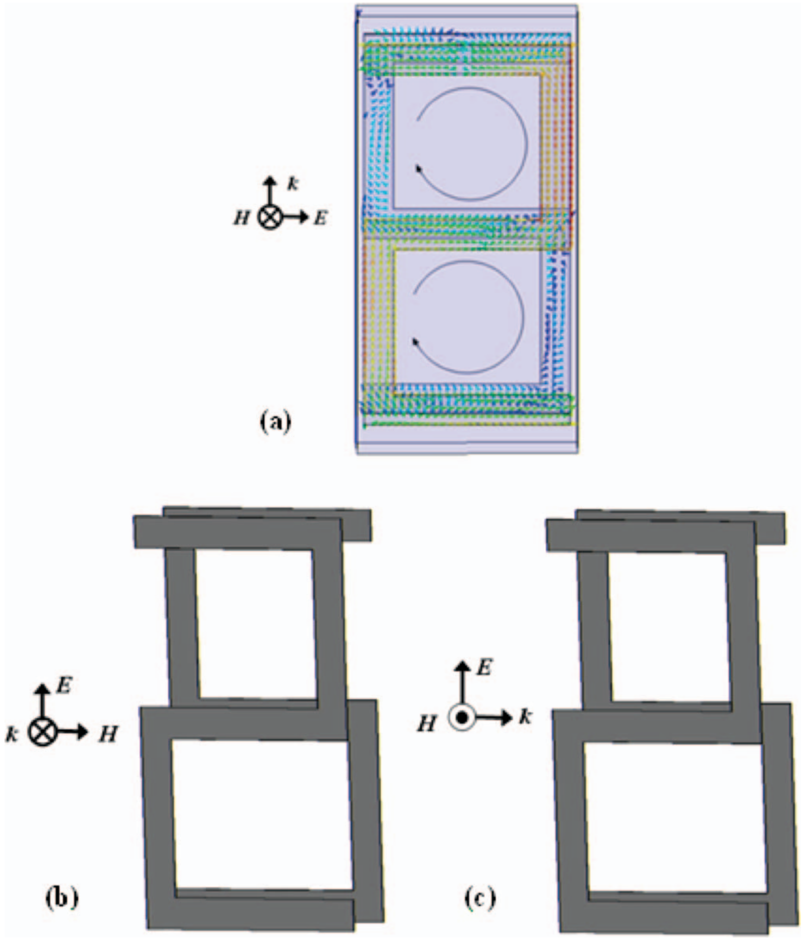

Figure 6. Dependency of S-shaped structural units on external electromagnetic fields. (See Color Plate XV)

When the external electromagnetic field is along the direction of transmission as shown in Fig. 6(c), both the electric field components and magnetic components couple to the S-shaped structural unit resonator. Fig. 6(a) and 6(b) show the combined effect. The relationship of the effective permittivity or effective permeability on frequency is shown in Fig. 4.

In Fig. 4, it also can see the structure of S-shaped ceramic matrix samples take place electromagnetic response at about 9.2 GHz, effective magnetic permeability generated resonance, although the real part of the effective permeability is negative, and the effective dielectric constant generated anti-resonant. This phenomenon is agreement with Reference [17]. Why do the anti-resonant occur? They [17] suggested that the anti-resonant behavior is caused by the requirement that the refractive index must be bounded in the structure samples which posses finite spatial periodicity. As the spatial periodicity is an unavoidable property pf the metamaterials. So the observed seemingly unphysical behavior of effective material parameters is an intrinsic property of ceramic composites samples, which cannot be avoided. Herein we think that the anti-resonant behavior of the effective material parameter is an intrinsic property of S-shaped ceramic samples, a consequence of the finite spatial periodicity.

3. Conclusion

Based on ceramics S-shaped left-handed materials with magnetic resonance and electric anti-resonance were prepared by screen printing. The microwave transmittance properties of these samples in a rectangular waveguide were experimentally investigated. And after parameter extraction, the relationship of the effective permittivity and effective permeability on frequency was obtained. It shows that in the 8.5–9.46 GHz range, the real part of the effective permittivity and permeability of samples is negative which is left-handed pass-band and bandwidth is about 1 GHz. Effective permeability occurred in the 8.5 GHz resonance is determined by external electromagnetic fields arising from magnetic coupling. Dielectric constant in the 9.46 GHz anti-resonant is from electromagnetic fields generated electrical coupling. S-shaped structure of ceramic-based left-handed materials possessing both remarkable magnetic resonances and electric using simple screen preparation and printing and low prices. Such planar left-handed materials are much easier to fabricate and use. The work done in this paper has reference values in designing new types of planar left-handed materials.

Acknowledgments

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