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Microwave left-handed composite material made of slim ferrite rods and metallic wires*

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This paper reports on experimental study of the microwave properties of a composite material consisting of ferrite and copper wires. It finds that the slim ferrite rods can modify the magnetic field distribution through their anisotropy, so that the ferrite's negative influence on the copper wires' plasma will be reduced. Left-handed properties are observed even in the specimen with close stuck ferrite rods and copper wires.

Keywords: left-handed materials, ferrite, anisotropy, electromagnetic coupling
PACC: 7650, 5240D, 5235H, 4110H

1. Introduction

Left-handed materials (LHMs) possess negative permeability and negative permittivity simultaneously, and have received considerable attention due to their peculiar physical properties.[1−4] However, there is almost no natural substance with simultaneously negative permittivity and negative permeability, therefore much attention has been devoted to constructing LHMs using artificial structures, such as thin metallic wires[5] and split ring resonators (SRRs).[6,7] The first LHM consisting of SRRs and metallic rods was reported in 2000.[8] Also, many researchers have devoted attention to realizing LHMs by using continuous media partially or wholly, such as in producing negative permeability using ferromagnetic material. If ferromagnetic materials are used, the frequency band of negative index can be tuned by the bias magnetic field, which benefits applications in microwave devices.[9,10] For several years, the possibilities of realizing LHM with ferromagnetic materials have been widely discussed theoretically and many suggestions have been proposed, such as metallic magnetic film,[11] composite with ferromagnetic particles,[12] and composite with metallic wires in ferrite host.[13] Among them, the last proposal has attracted much attention where metallic wires produce negative permittivity using plasma resonance[4] and ferrite produces negative permeability using domain wall resonance, spin resonance or ferromagnetic resonance.[14,15] Although many theoretical works have been reported, to our knowledge, only a few experimental results have been reported on LHM with ferromagnetic materials.[9,10,16]

It was reported in theory that the electromagnetic coupling would prevent metallic wires from producing negative permittivity when metallic wires were embedded directly in a homogeneous Mue-negative (MNG) medium.[17,18] That is the main obstacle to realize LHM using ferromagnetic materials and metallic wires. In this paper, the microwave properties of a composite material consisting of ferrite and copper wires are studied experimentally. It is found that substituting bulk ferrite by slim ferrite rods in the composite is an efficient route to alleviate electromagnetic coupling and thus to promote left-handed properties.

2. Experimental details

In this experiment, Y-type hexaferrite of $Ba_2Co_{1.8}Cu_{0.2}Fe_{12}O_{22}$ is selected as the ferromagnetic material. The ferrite samples are prepared by conventional ceramic method. The ferrite slab has a dimension of $22\times4\times10\,\mathrm{mm}^3$ and the ferrite rod has a dimen-

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sion of $3.3 \times 4 \times 10\,\mathrm{mm}^3$. Copper wires with diameter of 0.8 mm are used in metallic wires' array and the lattice parameter of the array is 5 mm. The samples are packed into the cross section of a rectangular waveguide WR90 with a cross section of $22.8 \times 10.18\,\mathrm{mm}^2$, as depicted in Fig.1(a). The waveguide is connected to a vector network analyser HP-8720ES which is used to measure the scattering parameters. An electromagnet is used to provide an external magnetic field (H_0) along the z axis.

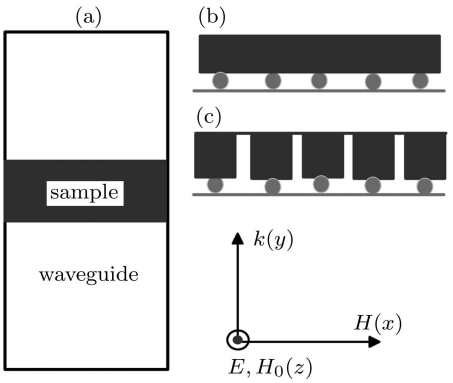


Fig.1. Schematic diagram of ferrite combined with copper wire arrays: (a) loaded in a rectangular wave guide; (b) ferrite slab; (c) ferrite rods.

3. Results and discussion

For a ferromagnetic material, negative permeability can be obtained by ferromagnetic resonance (FMR) in the vicinity of resonant frequency. According to Maxwell's equations, microwave cannot propagate in a single negative medium, whether negative permeability or negative permittivity, therefore an electromagnetic band gap will appear in the corresponding frequency range. The permeability will turn negative in the frequency range of the appearing electromagnetic band gap. Figure 2 shows the transmission spectra of a ferrite slab ($22 \times 4 \times 10\,\mathrm{mm}^3$) under different external magnetic fields. When the intensity of bias magnetic field is higher than 3000 Oe (1 Oe = 1 Gb/cm), a downward dip emerges and shifts towards higher frequency with the strengthening of bias magnetic field.

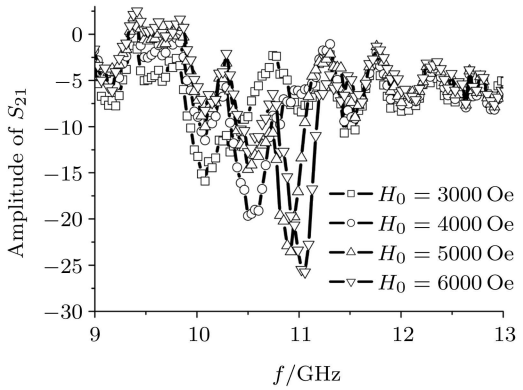


Fig.2. The amplitude of S_{21} for the bulk ferrite slab under different magnetic fields (1 Oe = 1 Gb/cm).

Figure 3 shows the transmission spectra for the sample consisting of bulk ferrite and metallic wires. Because the negative permittivity is produced by the metallic plasma resonance, there will be a wide forbidden band in the transmission spectrum of copper wires. When a bulk ferrite is combined closely with the array of copper wires ($d = 0$), as shown in Fig.1(b), only a tiny transmission passband appears in the forbidden band of wires [Fig.3(a)]. The passband refers to the left-handed property since double negative medium permits the propagation of microwave according to Maxwell's equations.

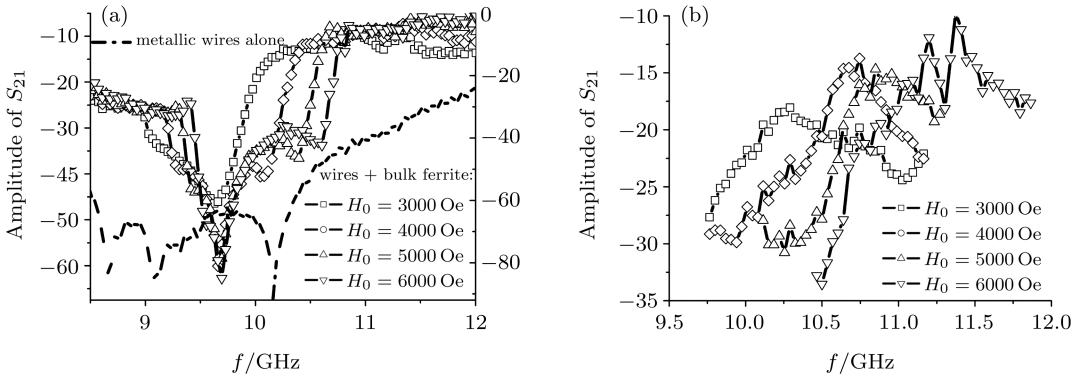


Fig.3. Amplitude of S_{21} for the composite structure consisted of ferrite slab and copper rods under different magnetic field; (a) $d = 0$ mm, (b) $d = 2$ mm. The dashed curve shown in Fig.3(a) is the amplitude of S_{21} for metallic wires alone.

As suggested by Pendry,[5] periodic metallic wires can generate negative permittivity within a wide region below the plasma frequency ω_p, which has a Drude form as

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + \mathrm{i}\gamma)} \tag{1}$$

with

$$\omega_p^2 = \frac{ne^2}{\varepsilon_0 m_{\mathrm{eff}}}, \tag{2}$$

$$m_{\mathrm{eff}} = \frac{\mu_0 \pi r^2 e^2 n}{2\pi} \ln(a/r), \tag{3}$$

where γ is a damping term, ε_0 and μ_0 respectively refer to permittivity and permeability of free space, r is the wire's radius, a is the size of unit cell, n is the active electron density, e is the electron charge, m_{eff} is effective mass of electron. When the wires are in a magnetic environment instead of vacuum, the relative permeability of the environment μ_r should be introduced into Eq.(3)

$$m_{\mathrm{eff}} = \frac{\mu_0 \mu_r \pi r^2 e^2 n}{2\pi} \ln(a/r). \tag{4}$$

From Eq.(4), it can be concluded that $\mu_r < 0$ will result in a negative m_{eff}, so $\varepsilon(\omega) > 0$ no matter $\omega < \omega_p$ or $\omega > \omega_p$. That is to say that MNG environment destroys the negative permittivity of metallic wires. The plasma resonance of metallic wires depends on the wires' self-inductance. When the metallic wires are in MNG environment, the electrons in wires behave capacitively, so the negative permittivity disappears.

The discussions above are based on the assumption of isotropic homogeneous medium. When transverse electromagnetic mode (TEM) is used, an isotropic medium is not necessary for left-handed property. For example, negative μ_x alone is enough to realize a one-dimensional LHM, such as the first LHM made of SRRs and metallic rods.[8] By designing the proper anisotropic structure, the negative influence of MNG medium on the wires plasma can be reduced. If the magnetic field induced by the MNG medium acts on the metallic wires while it does not destroy the wires' self-inductance, the LHM can be made.

The permeability of a ferrite magnetized along the z-direction can be described as

$$\bar{\bar{\mu}} = \begin{pmatrix} \mu & -\mathrm{i}\kappa & 0 \\ \mathrm{i}\kappa & \mu & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{5}$$

where $\mu = 1 + \dfrac{\omega_{\mathrm{m}}\omega_{\mathrm{h}}}{\omega_{\mathrm{h}}^2 - \omega^2}$; $\kappa = \dfrac{\omega\omega_{\mathrm{m}}}{\omega_{\mathrm{h}}^2 - \omega^2}$, $\omega_{\mathrm{h}} = \gamma H_0$ and $\omega_{\mathrm{m}} = 4\pi\gamma M_{\mathrm{s}}$ (γ is the gyromagnetic ratio, and M_{s} is the magnetization of saturation). Under the ideal condition, μ_z is positive and all the magnetic flux lines are held in the sample and any current is not excited in the surrounding wire, so the ferrite will not influence the wires' plasma resonance. In the real experiment, the leaky magnetic flux lines at the ends of ferrite samples can also excite current in the wires and go against the self-inductance. In this experiment, copper wires are placed to one side of the ferrite slab instead of being embedded in it, so the left-handed behaviour is not suppressed entirely and a weak transmission peak appears.

Because the induced magnetic field in copper wires decays rapidly with the rise of distance, introducing a buffer layer can decouple the direct electromagnetic interaction between ferrite and copper wires. Consequently, the left-handed behaviour of the composite can be enhanced. In order to reduce the negative influence of ferrite on the copper wires' plasma, a nonmagnetic insulating layer, 2 mm-thickness plexiglas, is inserted between the bulk ferrite and copper wires. Therefore, a notable left-handed transmission passband is observed [Fig.3(b)].

The distribution of magnetic field around the ferrite can also be modified by the sample's shape anisotropy. A sample with stronger anisotropy can restrict magnetic flux lines more efficiently. Figure 4 shows the transmission spectra of the array of slim ferrite rods under different bias magnetic fields. Similar to the bulk ferrite sample, ferrite rods' array can also produce negative permeability at FMR frequency. Moreover, when the same bias field is applied, the FMR frequency of slim rods is much higher than that of ferrite slab due to stronger anisotropy of ferrite rods.

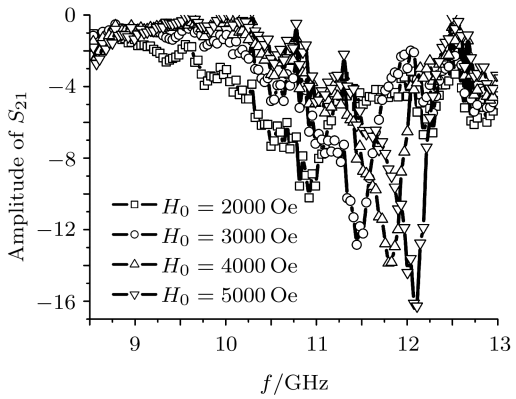


Fig.4. The amplitude of S_{21} for the ferrite rods' array under different magnetic fields.

Subsequently, slim ferrite rods were substituted for bulk ferrite in the composite structure, where each ferrite rod ($3\times4\times10\,\mathrm{mm}^3$) is tightly stuck to a copper wire [Fig.1(c)]. The transmission spectra of the composite consisting of ferrite rods and copper wires are shown in Fig.5. There is an obvious left-handed transmission peak in transmission spectrum, and the characteristic frequency can be tuned by bias field. It is indicated that the substitution of slim ferrite rods for bulk ferrite slab remarkably enhances the left-handed property. The microwave properties of this composite are also simulated through CST microwave studio. A transmission passband appears in the transmission spectrum of the structure under a bias field of 3000 Oe, as shown in Fig.6(a), and the electric field distribution at the characteristic frequency under plane wave incident from the left is shown in Fig.6(b). It can be seen that the wave-fronts propagate backward in the composite material. The simulated results agree with the experimental data very well, which gives a support to the experimental results of left-handed property.

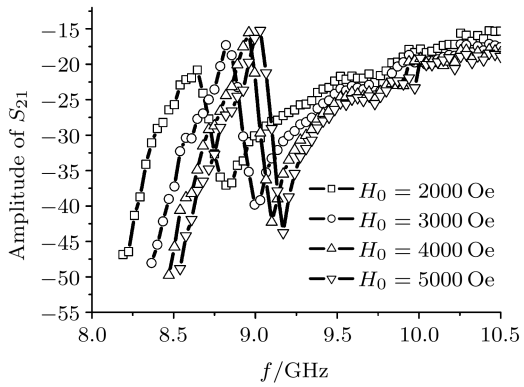


Fig.5. Amplitude of S_{21} for the composite structure consisted of ferrite rods and metal wires ($d = 0\,\mathrm{mm}$).

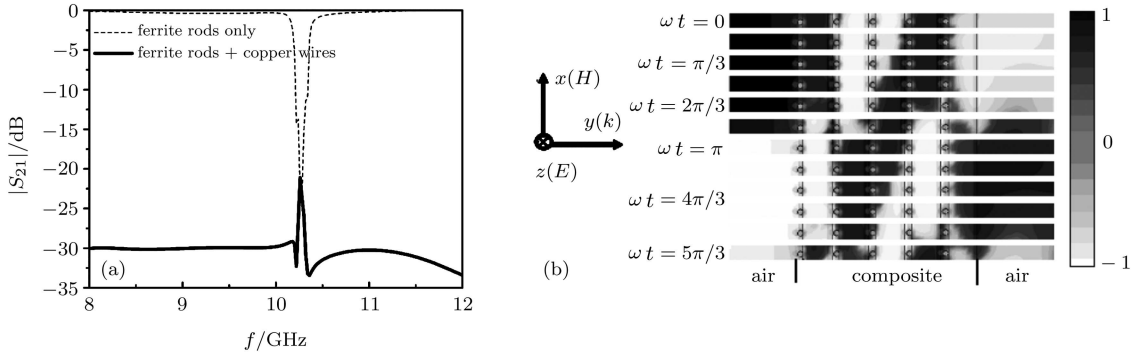


Fig.6. (a) Simulated transport parameters for the composite structure consisted of ferrite rods and metallic wires ($d = 0\,\mathrm{mm}$). (b) Electric field E_z in the midplane at the frequency of 10.4 GHz, the wave is incident onto the structure from left, the magnitude of the field is in log scale.

4. Conclusions

An LHM consisting of ferrite and copper wires has been demonstrated and methods to alleviate the negative influence of ferrite on copper wires' plasma resonance have also been proposed. Inserting a buffer layer or substituting bulk ferrite by slim ferrite rods, either way, can alleviate the electromagnetic interaction between ferrite and copper wires. It is well known that inserting buffer layer is disadvantageous to the miniaturization of LHM, while in the composite structure ferrite rods and metallic wires can be stuck closely to each other, which greatly promotes the development of LHM with close-packed unit cells. If special processing technology, such as orientation in magnetic field, is used to enhance the anisotropy of sample, it becomes more convenient to prepare LHMs.

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