Positive-Negative-Positive Metamaterial Consisting of Ferrimagnetic Host and Wire Array

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Abstract **─** The positive-negative-positive metamaterial consisting of ferrimagnetic host and wire array is presented in this paper. Such metamaterial possesses three pass bands resulting from the interactions between the ferrimagnetic host and the wire array. The necessary parameter conditions are theoretically investigated and then the transmission and refraction properties are demonstrated by numerical method. The results show that the metamaterial exhibits three transmission peaks at frequencies of 7.1 GHz, 10.9 GHz, and after 15.5 GHz, respectively. The refraction directions at corresponding frequencies show that the metamaterial indeed exhibits positive-negative-positive refractive characteristics. Such metamaterial offers the potential applications, such as, multiband band pass filter, wavelength divider, and coupler.

Index Terms **─** Ferrimagnetic host, metamaterial, positive-negative-positive refraction.

I. INTRODUCTION

Metamaterial [1], so-called negative index material (NIM) or double-negative (DNG) material with simultaneously negative permittivity ε and permeability μ, has attracted more attention since the publication of Smith et al.'s initial paper [2], which demonstrated the existence of such a medium. Much of the fascination arises from the unusual electromagnetic properties, such as, reversals of both Doppler shift and Cherenkov radiation [1], enhancement of evanescent waves, and sub-wavelength resolution imaging [3], etc. Most of metamaterials are realized by artificial metallic structures with metallic plasma resonance, such as, using wires to provide negative permittivity and using split-ring resonators (SRR) to provide negative permeability [2], [4–6].

Some researchers, recently, proposed another metamaterial composed of ferrimagnetic host and wires [7–10]. The ferrimagnetic metamaterial, however, can also exhibit positive-negative-positive refractive characteristics at microwave frequencies that have not been discussed in previous published papers [7–10]. This characteristic is significantly different from other metamaterials [2], [4–6]. Metamaterials consisting of cut wires and SRR can exhibit a transmission band in a special frequency region with a negative refractive index characteristic and exhibit big loss below and above the negative frequency region. These metamaterials may also possess the positive-negative-positive refractive characteristic; but the two-side transmission bands of these metamaterials are not indistinctly shown due to the big loss and the metallic structure multiband metamaterials are limited in a narrow band or not at all tunable.

Since the multiband metamaterials offer potential applications, such as multiband pass filters, wavelength dividers, and couplers, it should be discussed further in this paper. The necessary parameter conditions of the positive-negative-positive metamaterial must be found out first by analyzing the theoretically effective electromagnetic parameters. And then the positive-negative-positive refractive characteristic is investigated numerically. Finally, some conclusions are provided.

II. THEORETIC ANALYSIS

The previous works show that the metamaterial consisting of a ferrimagnetic host and wire array can achieve negative refraction in given frequency band when a plane electromagnetic wave propagates to the surface of the sample under applied magnetic field [10]. It can be found that such metamaterial can also exhibit three pass bands due to the interactions between the ferrimagnetic host and wire array. Therefore, this paper mainly focuses on such characteristics that have not been reported previously.

The single unit cell of original model [7], of the ferrimagnetic metamaterial, is shown in Fig. 1. The conducting region is within the circle of radius r_1. The region between r_1 and r_2 is filled with a dielectric insulator. The region surrounding the cladded wire is filled with ferrimagnetic material. All of these sizes are much smaller than the free-base wavelength λ_0 at the central frequency, 11 GHz. The whole structure has infinite size in the *x* and *z* directions. An EM wave propagates along the *y* axis with the electronic field along the *z* axis and the magnetic field along the *x* axis, and a dc applied magnetic field acts on the ferrimagnetic host along the *z* axis.

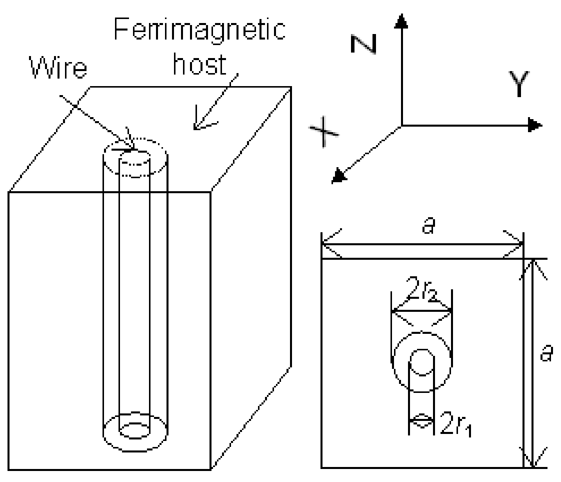

Fig. 1. Single unit cell (left) and top view (right) of the positive-negative-positive metamaterial composed of ferrimagnetic host and wire array.

This model presented here is the same as [7], so the effective permeability, μ_{eff}, and permittivity, ε_{eff}, of the metamaterial can be obtained from the following expression [7]:

$$\frac{\mu_{eff}}{\mu_0} = \frac{(H+M_S)^2 - (\omega/\mu_0\gamma)^2}{H(H+M_S) - (\omega/\mu_0\gamma)^2}, \quad (1)$$

$$H = H_0 - i(\frac{\omega}{\mu_0\gamma})(\frac{\Lambda}{\mu_0\gamma M_S}), \quad (2)$$

$$\frac{\varepsilon_{eff}}{\varepsilon_0} = \frac{\varepsilon_f}{\varepsilon_0} - \frac{\sigma_{eff}/\omega\varepsilon_0}{i + (\frac{\omega a^2 \sigma_{eff}}{2\pi})\left(\mu_0 \ln(\frac{r_2}{r_1}) + \mu_{eff}\left(\ln(\frac{a}{r_2}) - 1.06\right)\right)}. \quad (3)$$

Here M_S is saturation magnetization of ferrimagnetic host, H_0 is dc applied magnetic field, γ is gyromagnetic ratio, and Λ is a phenomenological damping parameter describing losses intrinsic to the ferrimagnetic host [7]. ω is angle frequency, ε_f is permittivity of ferrimagnetic host, ε_0 and μ_0 are permittivity and permeability of air, respectively, and σ_{eff} is effective conductivity of wire array. In the process of obtaining the effective permeability and permittivity, we have assumed that the EM wave propagates perpendicular to wires with the electronic field parallel to it and the magnetic field perpendicular to it, and a dc applied magnetic field acts on the ferrimagnetic host along the wires. Therefore, one can use the effective parameters shown in equations (1) – (3) to express the properties of the magnetic material and wire array [11, 12].

As shown in Ref. [7], Dewar claimed that the parameter values must be chosen properly so that such metamaterial can achieve a negative refraction. However, such metamaterial can, also, achieve three transmissions with positive-negative-positive refractive characteristics by redesigning the parameter values. This property can be used to explain why there are some unexpected pass bands in ferrimagnetic host based tunable metamaterials as shown in our previous paper [10].

To design a positive-negative-positive metamateial at microwave frequencies, the effective electromagnetic parameters are analyzed firstly. It can be calculated simply from equations (1) and (2) by using the following ferrimagnetic material's parameter values: $M_S = 2 \times 10^5$ A/m, $H_0 = 1.39 \times 10^5$ A/m, and $\Lambda = 1 \times 10^9$. The big phenomenological damping parameter Λ presented here is used to display clearly the real part of μ_{eff} and the ferromagnetic resonance (FMR) frequency f_{FMR} [4]. For a general quality ferrimagnetic host, the Λ may be 10 – 20 times smaller than the above values. The parameter values presented above are used to show a microwave frequency metamaterial. These values can also be used for particular metamaterials [10]. The calculated μ_{eff} is shown in Fig. 2(a) (black lines). However, the ε_{eff} is difficult to satisfy the expected result, in which the composite medium must show positive-negative-positive refractive characteristics, due to the complex expression in equation (3). Here the Matlab software is used to numerically calculate and optimize the parameter values of showing expected three pass bands.

Since the copper wires are used to calculate the effective permittivity in this paper, and the copper wire's skin depth δ is much smaller than the wire radius. So the effective conductivity of the wire array is given by [7]

$$\sigma_{eff} = \frac{\sigma 2\pi r_1 \delta}{a^2}, \; \delta = \sqrt{\frac{2}{\mu_0 \sigma \omega}}. \qquad (4)$$

Here σ is conductivity of copper wire. Hence, the parameter values of effective permittivity ε_{eff} are optimized finally and the calculated result is shown in Fig. 2(a) (grey lines with dots). The effective complex propagative constant k calculated from the ε_{eff} and μ_{eff} with $k=2\pi f\cdot(\varepsilon\varepsilon_0\cdot\mu\mu_0)^{1/2}$ is also shown in Fig. 2(b). The optimized parameters are shown as follows: $\varepsilon_f = 4\varepsilon_0$, $a = 2.4 \times 10^{-3}$ m, $r_1 = 2 \times 10^{-5}$ m, $r_2 = 1.5 \times 10^{-4}$ m. Therefore, the normalized electrical size (periodic size/wavelength ratio) of the designed metamaterial at the central frequency is about 0.088.

From Fig. 2(a), it can be known that in the frequency range of 9.6 GHz – 11.8 GHz both the μ_{eff} and ε_{eff} are negative, while in the ranges of 6.4 GHz – 7.7 GHz and after 14.5 GHz both the μ_{eff} and ε_{eff} are positive. This means that the EM waves can be transferred in the three frequency ranges with positive-negative-positive refractive characteristics. As shown in Fig. 2(b), the imaginary parts, which imply the loss in such metamaterial, of the propagative constant k in the ranges of 6.4 GHz – 7.7 GHz and 9.6 GHz – 11.8 GHz are larger than in the range of after 14.5 GHz. So the losses in the first two ranges are larger than the third range.

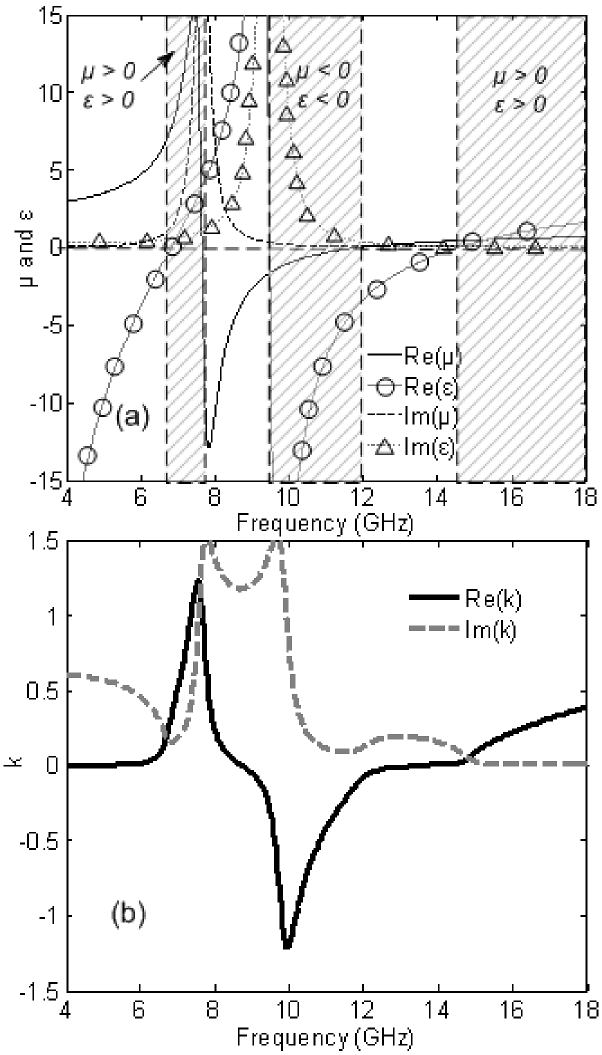

Fig. 2. (a) The effective permeability (black lines) and the effective permittivity (grey lines with dots) calculated from the equations (1)-(4). (b) The effective complex propagative constant k calculated from the ε_{eff} and μ_{eff} with $k=2\pi f\cdot (\varepsilon\varepsilon_0\cdot\mu\mu_0)^{1/2}$.

Why have the three pass bands appeared? Dewar has proved that the negative permeability of ferrimagnetic host would damage the negative permittivity property of wire array unless the wires are cladded with dielectrics [12]. And the thickness of cladding is crucial for appearing negative refraction and other characteristics. Therefore, one can design the parameter values so that the effective permittivity has both positive and negative values in the frequency band of negative permeability [see Fig. 2(a)], resulting in a positive-negative-positive metamaterial.

III. SIMULATION

In this section, the positive-negative-positive refractive characteristic of the above analyzed metamaterial is numerically demonstrated by utilizing a commercial finite-element based electromagnetic solver (HFSS, Ansoft) with the parameter values mentioned above.

To simulate the transmission properties in a broad frequency band (4 GHz – 18 GHz), a planar waveguide system (inserted in Fig. 3) with a cross section of 48 × 8 mm^2 is used. The metamaterial slab, with two layers, is put in the middle of the planar waveguide and the two side walls are Master and Slave Boundaries. So the simulated model has infinite boundary in the *x* and *z* directions. It is the same as the theoretical model and a dc applied magnetic field acts on the ferrimagnetic host along the wires.

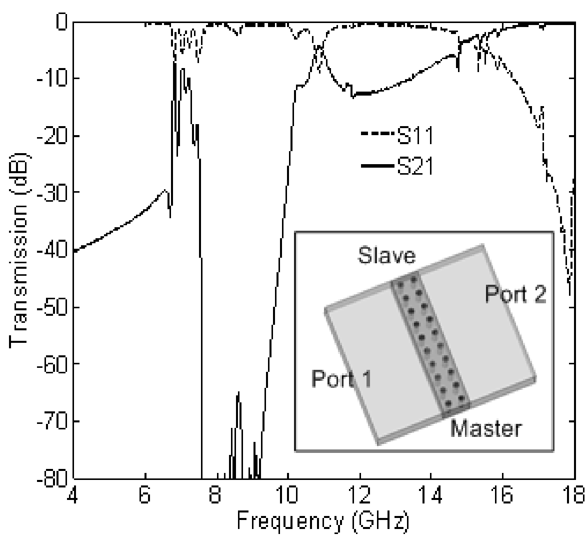

Fig. 3. Numerically simulated transmission properties of the ferrimagnetic metamaterial. The magnitudes of S_{11} (dotted line) and the S_{21} (solid line) are presented. The simulated model is also inserted in this figure.

Figure 3 shows the simulated transmission properties of the ferrimagnetic metamaterial in a broad frequency band. It can be seen that the metamaterial slab exhibits three transmission pass bands in the ranges of 6.7 GHz – 7.5 GHz, 10.2 GHz – 11.5 GHz, and after 15 GHz with transmission peaks at 7.1 GHz, 10.9 GHz, and 15.5 GHz, respectively. Moreover, the transmission amplitude values (S_{21}) at 7.1 GHz and 10.9 GHz are smaller than the value after 15.5 GHz, and the reflection values at 7.1 GHz and 10.9 GHz are larger than the value after 15.5 GHz. The smaller transmission values in the first two ranges result from the larger imaginary part of the effective propagative constant *k* shown in Fig. 2(b). The larger reflections in the first two ranges are due to the mismatch between metamaterial and air. These simulated results, shown in Fig. 3, agree with the theoretical results shown in Fig. 2, very well. When we change the number of layers, the transmission characteristic is not changed except for a small loss in such metamaterials (This result is not shown in this paper).

Moreover, the three pass bands of the ferrimagnetic metamaterial can be tuned by changing the dc applied magnetic field. The tunability is the particular characteristic of the ferrimagnetic metamaterial and has been discussed in Ref. [10], so it is not discussed in this paper.

Generally, to investigate a new metamaterial, most researchers would retrieve the effective parameters with the method proposed by Smith et al. [12] from the scattering parameters. In this paper, however, we do not retrieve the effective parameters, but directly investigate the refraction properties of the metamaterial at the three peak points shown in Fig. 3. The schematic of refraction system and the model of the prism sample are shown in Fig. 4(a). The wedge of the prism sample presented here is 18.43°, and a dc applied magnetic field, also, acts on the ferrimagnetic host along the wires. The incident beam impinges onto the sample at normal incidence with a Gaussian intensity profile tailored by side absorbers. For this condition of excitation, the electromagnetic wave undergoes refraction at the second tilted interface.

Figure 4(b)-(d) show the maps of the normalized electric field magnitude at various frequencies calculated at the mid-plane between the top and bottom perfect E conductors. The black arrow and the dash-dot line indicate the direction of the refracted beam and the normal to the second tilted interface, respectively. For frequencies of 7.1 GHz and 15.5 GHz [Fig. 4(b) and 4(d)], it can be seen that the angles of the two refracted beams are in the positive direction with respect to the normal as expected for a positive dispersion branch. At 10.9 GHz [Fig. 4(c)], the peak of the refracted beam is directed along a negative angle with respect to the normal and is consistent with the negative branch. Moreover, the refracted power at 15.5 GHz [Fig. 4(d)] is much higher than the refracted powers at 7.1 GHz and 10.9 GHz [Fig. 4(b) and 4(c)]. That is because the losses and reflections at 7.1 GHz and 10.9 GHz are larger than those at 15.5 GHz [see Fig. 3]. These refraction phenomena at different frequencies agree with the theoretical results shown in Fig. 2 and the simulated three pass bands characteristic shown in Fig. 3, very well.

In the numerical results presented above, there is no spatial dispersion that has been discussed in [13, 14]. This is because the one-dimensional wire array has infinite length along the *z* direction and periodic boundary in the *x* direction.

This model is, also, the same as the theoretical analysis mentioned in section II. Furthermore, Pendry [3] discussed that three-dimensional wire array should be coated with some magnetic materials for reducing the spatial dispersion to achieve negative permittivity [15]. However, he has, also, shown that there is no spatial dispersion for the condition when the electric field is parallel to one of the three sets of wires. In this paper, the ferrimagnetic magnetic material is used to provide the negative permeability. So this is not the same condition and therefore, there is no spatial dispersion.

IV. CONCLUSION

In this paper, a positive-negative-positive metamaterial consisting of ferrimagnetic host and wire array is discussed. The necessary parameter conditions of such metamaterial are investigated theoretically. Then the three transmission passbands property and the positive-negative-positive refraction phenomena in different frequencies are numerically investigated. Both the theoretical and numerical results show that the metamaterial exhibits a positive-negative-positive refractive characteristic. Since such metamaterial has very small normalized electrical size of 0.088, it shows the potential applications such as novel multiband band pass filter, wavelength divider, and coupler, etc. Moreover, the arbitrary controllability of effective permeability and permittivity in the ferrimagnetic metamaterial and the tunability of operating frequency open a way to design an invisible cloak and absorber at arbitrary frequencies.

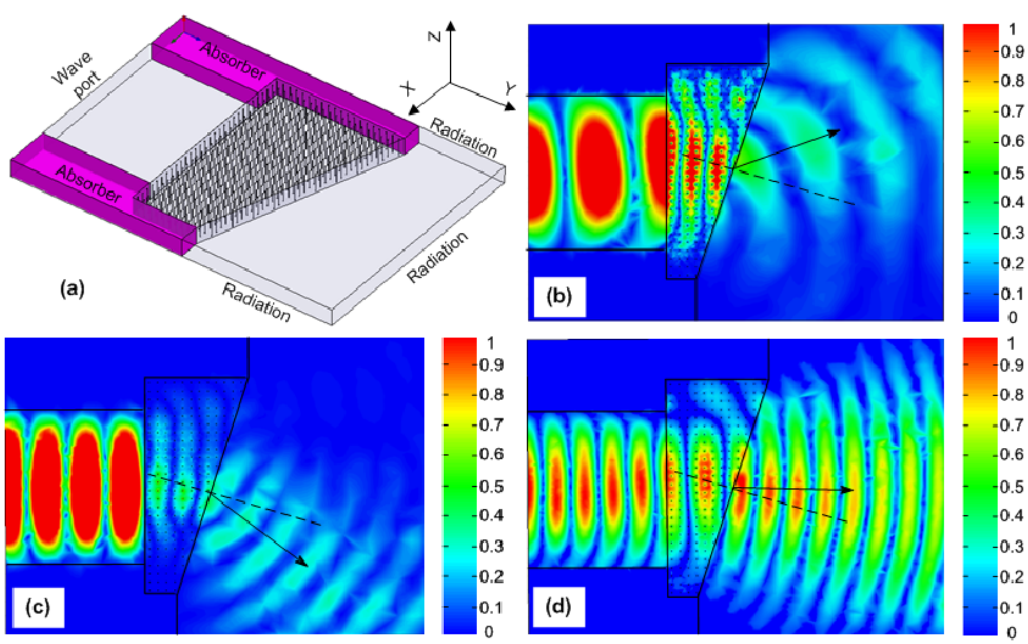

Fig. 4. (a) Schematic of the refraction system and numerically demonstrated refraction phenomena of the metamaterial in different frequency points: (b) 7.1 GHz; (c) 10.9 GHz; (d) 15.5 GHz.

ACKNOWLEDGMENT

This work was supported by the National Nature Science Found of China under Grant Nos. 60571024, 60771046, and 60588502.

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