Tunable Dual-Band Negative Refractive Index Metamaterial Consisting of Ferrites and SRR-Wires

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Abstract

In this paper, we present a tunable dual-band negative refractive index metamaterial (NRIM), which composed of ferrite slabs, split ring resonators (SRR), and continuous wires. Numerical simulation shows that two pass-bands could be found in such structure, and the dual-band negative refractive indexes are demonstrated with the retrieved effective parameters based on the simulated scattering parameters. Taking advantage of the tunable permeability of ferrite slabs, we show these two negative refractive index passbands can be dynamically tunable by simply changing the magnetic bias.

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1. Introduction

Negative refractive index metamaterial (NRIM) predicted by Veselago [1] in 1960s has attracted considerable attention since the publication of Smith et al.’s initial paper [2], which demonstrated the existence of such medium. Much of the fascination arises from the unusual electromagnetic properties such as the reversals of both Doppler shift and Cherenkov radiation [1], enhancement of evanescent wave, and sub-wavelength resolution imaging [3]. Recently, some dual-band and multi-band NRIMs have been

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report at microwave and THz frequencies [4–6]. These NRIMs, however, are limited by inherent narrow bandwidths due to the resonant nature. In 2009, Ekmekci [7] reported a multi-band NRIM using micro-split SRR structure and the resonant frequencies could be shifted by changing the number of micro-splits, which was, however, still far from dynamically tunable. In this paper, a novel design for tunable dual-band NRIM consisting of ferrite slabs, split ring resonators (SRR), and continuous wires is presented. The validity of negative refractive index of separated SRR-wires and ferrites-wires structures have been demonstrated in previous well-known publications [2,8]. The new design presented in the paper is using the combination of SRR-wires and ferrites-wires structures to achieve dual-band resonances, and the two resonance frequency bands can be tuned by changing the magnetic bias.

2. Model and analysis

The unit cell of the combined ferrites based dual-band NRIM, with a cell dimension of 1.6 mm, is shown in Fig. 1(a). The SRR and wires are deposited in a Rogers TMM 4 ($\varepsilon_r = 4.5$, $\tan\delta = 0.002$) substrate of 0.6 mm separated 0.25 mm, by using standard optical lithography with a 0.017 mm copper thickness. And then the two sides of substrate are deposited with two ferrite slabs of 0.5 mm (A conventional ferrite is used in this paper and the saturation magnetization $4\pi M_s = 1830$ Gs, $\varepsilon_r = 13.8$, resonance beamwidth $\Delta H = 45$ Oe).

For the ferrite slabs under a transverse electromagnetic (TEM) wave propagated along the x-axis with the electric field along the y-axis and the magnetic field along the z-axis, and the dc magnetic bias acts on the ferrite slabs along the z-axis, as shown in Fig. 1(a). The effective permeability has been demonstrated previously in several references [8–10]. So combining the ferrite slabs to the well-known SRR magnetic resonance structures which exhibit negative permeability frequency band upper or under the negative band of ferrite slabs, one can expect that the two magnetic resonance bands should be appeared. On the other hand, for the continuous wires within the well-known SRR-wires NRIM, the negative permittivity band is broad covering both of the two negative permeability bands. So one can expect that the combined ferrites based NRIM can achieve the dual-band negative refractive index properties. Moreover, the two passbands can be shifted by changing the magnetic bias.

Fig. 1. (a) Schematic of the dual-band ferrites based NRIM unit cell. The structure sizes are shown in this figure in millimeters. (b) Simulated transmission and reflection characteristics of the ferrites based dual-band NRIM.
3. Numerical investigated results

For simulation and optimization, the unit cell is placed within a waveguide structure and excited by an EM wave with propagation vector \((\mathbf{k})\) along the \(x\)-axis, electric field vector \((\mathbf{E})\) along the \(z\)-axis and magnetic field vector \((\mathbf{H})\) along the \(y\)-axis, as shown in Fig. 1(a). The walls perpendicular to the \(z\)-axis and \(y\)-axis are modeled to be perfect E boundaries and perfect H boundaries, respectively. A magnetic bias acts on the ferrites along the \(z\)-axis.

First of all, the single-band NRIMs of SRR-wires and ferrites-wires structures are numerically demonstrated, respectively, to show the potential transmission bands. For SRR-wires structure, the width of the wire is 0.14 mm, and it runs the length of the unit cell. The outer ring length of the SRR is 1.4 mm and inner ring length is 1.1 mm, so the gap between the inner and outer rings is 0.05 mm, and both rings have a linewidth of 0.1 mm. The gap in each ring is 0.3 mm. The surrounding areas of the substrate are fictitious media \((\varepsilon_r = 13.8, \tan\delta = 0.0002)\) to compare the ferrite media. The simulated result shows that the single-band SRR-wires NRIM has a negative passband near 11 GHz. For ferrites-wires structure, the width of the wire is also 0.14 mm, and the surrounding areas of the substrate are ferrite media. A magnetic bias of 2 kOe acts on the ferrite slabs along the \(z\)-axis. The simulated result shows that the single-band ferrites-wires NRIM has a negative passband centered at 7.8 GHz. (The transmission characteristics of both the two single-band NRIMs are not shown in this paper)

![Fig.2. The effective electromagnetic parameters retrieved from simulated S-parameters](image-url)

(a) Effective impedance \(Z\)

(b) Effective refractive index \(n\)

(c) Effective permittivity \(\varepsilon\)

(d) Effective permeability \(\mu\)
Then, the combined dual-band NRIM as shown in Fig. 1(a) is simulated. All the parameters of the unit cell are the same as above mentioned. When the magnetic bias is also 2 kOe, the simulated results are shown in Fig. 1(b). It clearly shows that there are two passbands centered at 7.8 GHz and 11.2 GHz, respectively. Comparing the dual-band NRIM and the two single-band NRIMs, it can be known that there are few interactions between the ferrite slabs and SRR structures, except the little displacement of the second passband (the center frequency is shifted from 11 GHz to 11.2 GHz). This can be explained by the fact that the positive part of the effective permeability of ferrites upper the negative part is less than 1, so the resonance frequency of the SRR within the ferrite media, is higher than in the dielectric fictitious media.

To demonstrate the dual negative refractive index properties, the effective electromagnetic parameters are retrieved from the simulated S-parameters by using the retrieval method mentioned in reference [11], and shown in Fig. 2. From Fig. 2(a), it shows that the NRIM can transfer the EM waves in the above mentioned two passbands with small reflections. From Fig. 2(b), the effective refractive index is clearly negative in the two passbands of 5.5-8 GHz and 10-11.8 GHz. Then the effective permittivity and permeability are calculated by using the relations: $\varepsilon = n/Z$ and $\mu = n \cdot Z$ and the results are shown in Fig 2(c) and (d). The retrieved effective permittivity shows the typical anti-resonances near 6 GHz and 10.5 GHz, respectively. And the effective permeability shows also the typical magnetic resonances at 6 GHz and 10.5 GHz, respectively.

In the end, to show the tunable characteristic of the dual-band NRIM, the unit cell is further simulated in different magnetic biases ranged from 2 kOe to 2.8 kOe, and the transmission characteristic is shown in Fig. 3. It can be known that both of the two passbands are shifted. The first passband is shifted from 7.8 GHz to 9.4 GHz with the tuning rate of 2 MHz/Oe and the second passband is shifted from 11 GHz to 12 GHz with the tuning rate of 1.25 MHz/Oe. The bandwidth of the first passband is increased as the increase of magnetic bias and contrarily the bandwidth of the second passband is decreased.

![Fig. 3. The tunable characteristic of the dual-band NRIM in different magnetic biases](image-url)
4. Conclusions

In this paper, a tunable dual-band NRIM has been demonstrated. The schematic of the unit structure was firstly designed and then the transmissions, negative refractions, and tunability were numerically investigated, respectively. Such kind of NRIM had two separated passbands centered at 7.8 GHz and 11.2 GHz, provided by SRR-wires and ferrites-wires structures, respectively. And the two passbands can be simply shifted from 7.8 GHz to 9.4 GHz and 11GHz to 12 GHz, respectively, by changing the magnetic bias from 2 kOe to 2.8 kOe. The NRIM can be easily fabricated by using lithographic circuit board techniques and choosing the conventional ferrites. Therefore, it can be used to fabricate some dual-band metamaterial absorbers, cloaks, and antennas in our future works.

Acknowledgements

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