Design of Broadband and Low-loss Double Negative Electromagnetic Metameterials with Solid-State Arrangement

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***Abstract* - Split-ring resonators (SRRs) and continuous metallic wires were used to realize double negative materials (DNGs). In this paper, we discuss two kinds of DNG structures with different periodic arrangement. One is the conventional model with air separation, and the other is the solid-state structure. Full-wave simulations are used to analyze the effective medium characteristics and the figure of merit (FOM). Numerical simulation results show that the solid-state DNG metamaterials have the advantages of broadband and low-loss, which make them useful in industrial applications.**

***Index Terms* — Solid-state DNG metamaterials, low-loss, broadband, FOM.**

1. Introduction

Artificial electromagnetic new materials, such as electromagnetic bandgap (EBG), photonic crystals (PCs), and left-handed materials (LHM) or double negative materials (DNG), are broadly classified as *metamaterials*, which are typically created by using two- or three-dimensional periodic metallic and dielectric structures [1]. They have attracted significant research interest in recent years due to their unconventional properties, which are applicable to a wide range of electromagnetic devices, such as antennas, microwave circuits, radar, absorbing materials, cloaks, etc. Metamaterials are artificially engineered composite materials which exhibit special properties that are not found in nature and not observed in the constituent materials. A practical realization of such metamaterials, employing split-ring resonators (SRRs) and metallic wires, was first proposed by Pendry [2, 3] and achieved by Smith et al. [4, 5]. Then many other constructed DNGs by printing SRRs with different shapes and the wires on both sides of substrates [1]. However, those given DNGs have the drawbacks of high loss and narrow bandwidth. In this paper, we propose a solid-state double-sided DNG structure, which consists of SRRs and metallic wires with solid-state arrangement stacking by stacking on the two sides of the substrate. The DNG metamaterials can exhibit a low loss and broad double negative bandwidth.

2. DNG Model Based on SRRs and Metallic Wires

It is well known that the periodic model of split-ring resonators (SRRs) and metallic wires exhibit effective negative permeability and permittivity, respectively. The conventional structure of SRR unit cell is shown in Fig. 1(*a*), which obeys the Lorentz dispersive model and can produce the effective negative permeability. The continuous metallic wire is based on the Drude model and can produce the effective permittivity. Combining the SRR and wire that are printed on the two-side of the dielectric substrate, we can obtain double negative material characteristics. The conventional composite model is shown in Fig. 1(b), in which the substrate thickness is 1 mm, $\varepsilon_r = 4.2$, and $\tan\delta = 0.02$. In order to simulate the infinite periodic model in *x* and *y* directions, the substrate printed SRR and metallic wire is arranged in an air box, where the PEC and PMC boundary conditions are set in *x* and *y* direction of the box, respectively. Note that the DNG model shown in Fig. 1(b) is a conventional model which has the same periodicity in *x* and *y* direction. So the DNG structure is essentially constituted of dielectric boards separated by air, which is delicate to manipulate and has much loss. In this paper, we adjust the periodicity in *y* direction, as shown in Figs. 1(c) and (d), and thus the DNG metamateiral is a solid-state structure. The simulated results show that the figure of merit (FOM) of the solid-state effective medium can be significantly improved. Full-wave simulations were performed by utilizing Ansys HFSS, which is a high- frequency electromagnetic solver based on the finite element method.

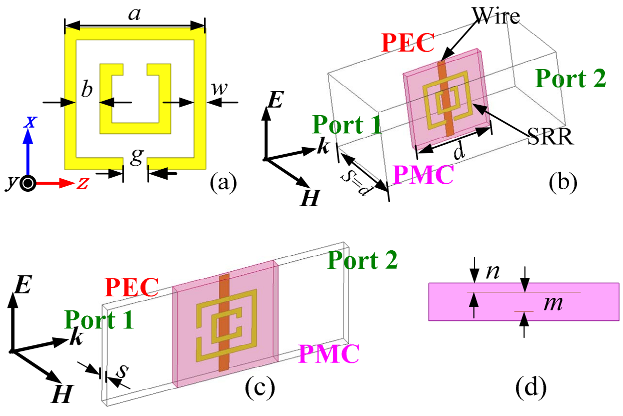

Fig. 1. (a) Unit cell of SRR with geometric dimensions *a*=3mm, *b*=0.5mm, *w*=0.25mm and *g*=0.5mm. (b) Schematic simulation model of SRR-Wire structure whose period in the *y* and *x* direction are both 5mm, geometric dimensions is *S*=*d*=5mm. (c) The width is 1mm in the *y* direction, geometric dimensions is *S*=1mm. (d) The top view of the solid-state unit cell given in (c), and the geometric dimensions is *m*=0.5mm and *n*=0.25mm.

3. Effective Medium Parameters Analysis

The DNG model is realized as an arrangement of dielectric and metallization properly oriented in space, which are therefore intrinsically inhomogeneous and microscopic. On the other hands, the unit cell themselves as well as their periodicity are very small compared to the operating wavelength. According to the effective medium theory, it is therefore legitimate to look for bulk permittivity and permeability, which is the macroscopic behavior of the medium. The retrieval algorithm is a bridge to connect the microscopic view and macroscopic view. Using the retrieval algorithm, we can extract the effective bulk properties of the macroscopic metamaterials from a set of parameters simulated or measured on the microscopic metamateials.

Smith *et al.* [6] proposed a retrieval procedure to obtain the effective electromagnetic parameters of DNG, i.e., the effective permittivity and the effective permeability. The idea was to model the metamaterial as an isotropic homogeneous slab, and calculate the effective parameters, ε and μ of the homogenous slab, from the measured or simulated metamaterial transmission (S_{21}) and the reflection (S_{11}) coefficients. The retrieval formulas are as follows [6]:

$$n=\pm\frac{1}{kd}\cos^{-1}\left[(1-S_{11}^2+S_{21}^2)/(2S_{21})\right] \qquad (1)$$

$$z=\pm\sqrt{\frac{(1+S_{11})^2-S_{21}^2}{(1-S_{11})^2-S_{21}^2}} \qquad (2)$$

$$\varepsilon_{eff}=\frac{n}{z},\quad \mu_{eff}=nz \qquad (3)$$

where k and d are wave vector in vacuum and the thickness of the slab, respectively. n is the refractive index and z is the normalized impedance. Using the full-wave simulation models shown in Fig. 1 and the above retrieval algorithm, we can obtain the effective medium properties of two kinds different periodic arrangement SRRs and metallic wires. The comparison of the effective medium parameters are shown in Fig. 2. It can be seen from Fig. 2(a) that the effective permittivity of two kinds of metamaterial models are negative in a specific frequency band, which have been shown to obey the Drude model. Fig. 2(b) show that the effective permeability are characteristic by the frequency-dispersive Lorentz model, which are negative in different frequency bands due to different periodic separation. For the conventional case, the bandwidth of negative permeability is from 8.78 to 9.24GHz, and for the solid-state case, the negative permeability bandwidth is from 5.96 to 7.02GHz. Although the working frequency band is not consistent, we can compare the relative bandwidth which reveals that the solid-state DNG metamaterial model has larger bandwidth, about 16%. In addition, the figure of merit (FOM), which is a factor to measure loss and defined as -Re(n)/Im(n). Fig. 2(c) shows the comparison of the FOM of two kinds of arrangement of DNG metamaterials. It can be seen that the solid-state model has more than twice as the conventional case. Therefore, this results reveal that the improved design for DNG metamaterials using solid-state arrangement can broaden the DNG bandwidth and has low-loss property.

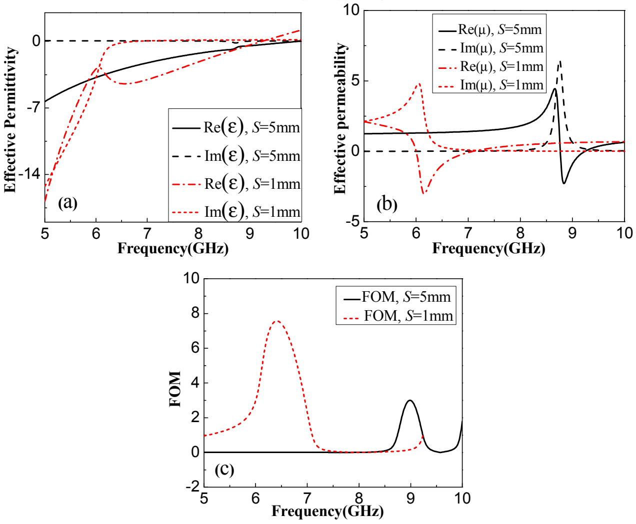

Fig. 2. Comparison of the effective medium parameters of the conventional air separation DNG with the solid-state DNG, (a) effective permittivity, (b) effective permeability, and (c) FOM.

4. Conclusion

This paper discussed the solid-state arrangement of DNG metamaterials using the SRRs and metallic wires elements. The results show that solid-state DNG can exhibit a low loss and broad double negative bandwidth, which is more useful in practical applications.

Acknowledgment

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