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NEGATIVE INDEX MATERIAL COMPOSED OF MEANDER LINES AND SRRS

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Abstract—A compact meander-line resonator is proposed in this paper, which could provide negative permittivity with a small unit-to-wavelength ratio. The meander-line structure is simple to be designed and is convenient to be controlled. Negative index materials (NIM) are realized using units composed of meander lines and split-ring resonators (SRRs), which have simultaneously negative permittivity and permeability in a specified pass band with relatively low loss. Simulation results show the identified properties of the meander-line resonator and NIM.

1. INTRODUCTION

In 1968, Veselago first predicted the novel electromagnetic properties of substance with simultaneously negative permittivity and permeability [1]. Thirty years later, Pendry pointed out that long metallic wire lattices had effectively negative permittivity and split ring resonators (SRRs) had effectively negative permeability in specified frequency bands [2, 3]. Smith et al. then successfully realized the first negative index material (NIM) sample at microwave frequencies [4]. Researches on the properties and applications of such metamaterials have become much more popular inspired by this work [5–14]. Some alternative structures also have been designed to realize NIM [15–19].

In the first NIM sample, each SRR works as a magnetic resonator, with a dimension much smaller than the wavelength. SRR has great magnetic response to the incident wave near the resonant frequency, and hence produces negative permeability in this special frequency band. But to create negative permittivity, the metallic wire array must be long enough. The metallic wires are continuous between neighbor cells and hence the wire length is comparable with the wavelength. This results in a serious disadvantage of dispersion and application problems since the electromagnetic properties of such artificial NIM would change according to the block size. When we cut the long wire at terminals of each unit cell to make each cell resonate individually, the frequency band of negative permittivity will be too higher. In some alternatively electric resonators, horizontal wires are introduced to increase the cut capacities to reduce the electric resonant frequency [17]. However, in these cases, the capacities between unit cells become the dominant elements that affect the resonance, and then the energy is mainly concentrated in the gaps. In such a case, the electric resonators still act as a whole.

In this paper, we propose a simple meander line resonator, an alternative electric resonator which could lower the resonant frequency effectively and provide negative permittivity by each unit individually. Electromagnetic properties of such meander lines are discussed. We then realize NIM using meander line resonators and SRRs. Theoretical and simulation results show that such NIM particles have a relatively small unit-to-wavelength ratio and loss.

2. MEANDER LINE STRUCTURE

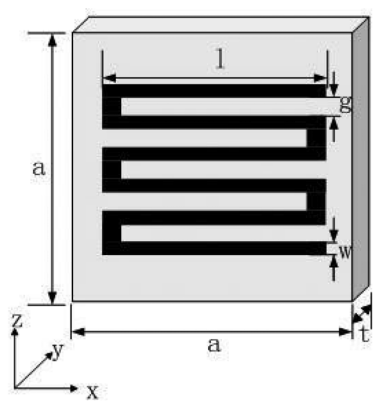


Figure 1. The meander line model.

The meander line structure, shown in Fig. 1, is an electric resonator due to the oscillation of currents induced in the perpendicular wires which are parallel to the incident electric field. The electric response of a meander line is similar to that of a cut wire. According to a Lorentz model, the effective permittivity has been shown to be [20]

$$\varepsilon_{eff} = 1 - \frac{\omega_{ep}^2 - \omega_{e0}^2}{\omega^2 - \omega_{e0}^2 + i\gamma\omega}\,, \quad (1)$$

where ω_{ep} is the plasma frequency of metal wires, ω_{e0} is the electric resonant frequency and γ represents the dissipation of plasmon's energy in the metallic wire. For continuous wires, the resonant frequency is zero, and for cut wires, it moves to a high frequency because the interruptions in wires will introduce depolarization field. In a meander line case, in order to reduce the resonant frequency to a target range, we increase the equivalent inductance by folding wire in one unit cell, instead of adding capacities between neighbor cells.

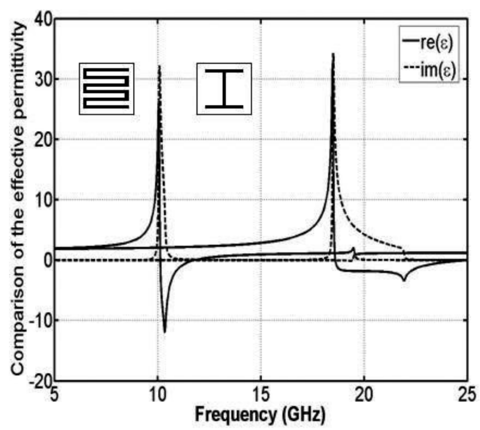


Figure 2. Comparison of the effective permittivities between a meander line and a cut wire with only two horizontal wires at the ends. The resonant frequency of a meander line is much lower.

Equation (1) indicates the effective permittivity to be negative in the range from ω_{e0} to ω_{ep}. To test the identities, we use Ansoft HFSS 10 for a full-wave simulation. In the simulation model, thick copper patterns are stuck on substrate of F4B. Electromagnetic wave propagates along the x axis, and the polarization direction is parallel to the z axis. Fig. 2 shows the comparison of the effective permittivity between a meander line and a cut wire with only two horizontal wires at the ends, using retrieval algorithm [21, 22]. In this comparison, model dimensions are chosen as $a = 3.333\,\text{mm}$, $l = 2.8\,\text{mm}$, $w = 0.15\,\text{mm}$, and $g = 0.2\,\text{mm}$. It is obvious that the negatively effective permittivity exists in a specified frequency range, which is much lower than that of the simple cut wire. This frequency range becomes narrower and sharper as well, because of its higher resonant intensity. Such a meander line resonator has an electric size about one ninth of wavelength in vacuum.

Large distances between neighbor cells are designed to reduce the capacities and guarantee each meander line to resonate individually. The simulation results show that the energy is mainly focused in the middle of the meander line, not in the capacities between neighbor cells in polarization direction, as shown in Fig. 3.

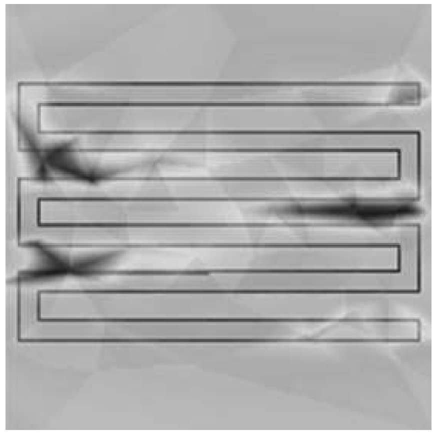
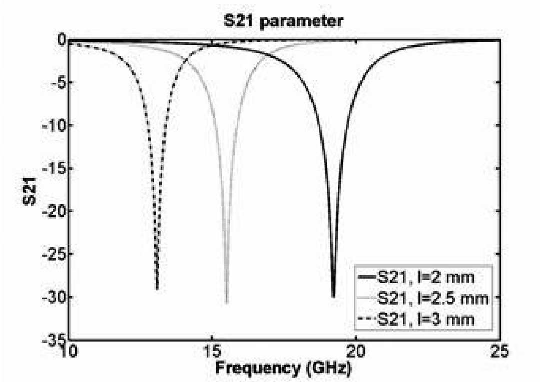


Figure 3. Electric energy distribution in a unit cell of meander line.

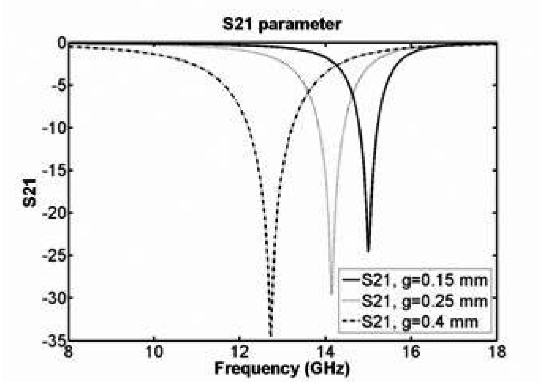
It is also noted that the number of horizontal arms in one unit should be even, so as to offset the induced electric field which is orthogonal to the incident field.

We can control the properties of meander line resonators by varying the dimension. Three dominant dimensions are the length of horizontal wires (defined as l in Fig. 1), the width of wires (defined as w in Fig. 1) and the gap between wires (defined as g in Fig. 1). The length of wires mainly decides the equivalent inductance of the structure. Once it grows, the inductance increases, making the resonant frequency lower down. The gap between wires affects the resonant frequency as well, since the gap size influences the inductance of the perpendicular wires. When the gap size increases, the resonant frequency decreases. The width of wires also influences the equivalent inductance. By widening the wires, we could decrease the inductance and increase the resonant frequency. Some simulation results have proved these analyses, as shown in Fig. 4.

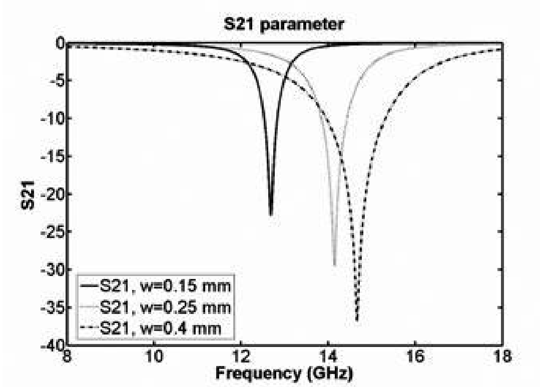
Properties of substrate also affect the resonance significantly. The resonant frequency varies obviously when the relative permittivity or the thickness of the substrate is changed. In this paper, F4B is chosen as the substrate for our structures, considering the fabrication and expense.



(a)



(b)



(c)

Figure 4. S parameters of the meander-line resonator, in which the dimension of length, gap and width are defined in Fig. 1. (a) With different values of l. (b) With different values of g. (c) With different values of w.

3. NIM PARTICLE COMPOSED OF MEANDER LINE AND SRR

To design negative index material, we first design meander lines and SRRs separately. We fix both unit sizes to be 3.333 mm, and tune their dominant dimensions to make them resonate at similar frequencies. For SRR, the cut gap (defined as c in Fig. 6) mainly affects the resonant frequency. There are several ways to combine the two structures. One way is to assign them side by side, as shown in Figs. 5(a) and 5(b), will double the unit sell size in one direction. Another way is to assign them back to back on each side of a substrate, as shown in Fig. 5(c), will cause terrible interaction. If we use a thicker block of substrate, the interaction reduces, but the loss increases. We finally place them on two separate substrate blocks, as shown in Fig. 6. The distance between two blocks is half the unit size, in order to remain the unit size in every direction.

A fine sweep of parameters has been used to get some feasible groups of dimensions. To match the impedance and have a relatively small electric size, dimensions should be further optimized. After analysis of scattering parameters and retrieved indexes, groups of

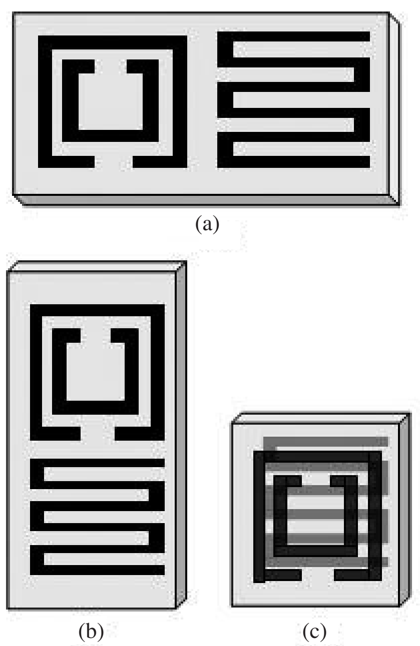


Figure 5. Different ways to combine the meander line and SRR.

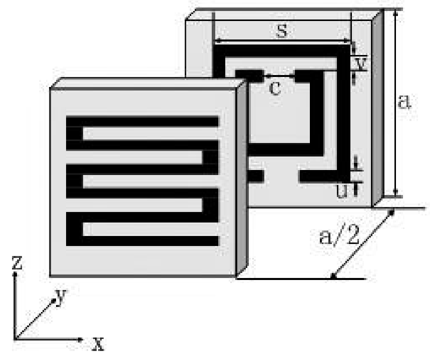


Figure 6. A NIM unit combined composed of meander line and SRR.

relatively optimal dimensions are determined. It is noticed that the electromagnetic response is not very sensitive when the dimensions varies a little, which is an advantage in applications. In the following part of the paper, for the meander line, we choose $a = 3.333$ mm, $l = 2.92$ mm, $w = 0.15$ mm, and $g = 0.2$ mm; and for SRR, we choose $a = 3.333$ mm, $s = 2.8$ mm, $c = 0.75$ mm, $u = 0.25$ mm, and $v = 0.25$ mm. The copper thickness is 0.018 mm, and the thickness of F4B substrate is 0.5 mm.

For either the meander line resonator or SRR, there is a stop band around the resonant frequencies. When we compose them together, the stop band disappears, leaving a pass band in the same frequency range, as shown in Fig. 7. The S_{21} parameter of such a NIM particle varies from −0.85 dB to −2.58 dB. A retrieval result proves the negatively effective permittivity, permeability, and index of refraction in the frequency range from 9.75 GHz to 10.6 GHz, as shown in Fig. 8. The real part of the impedance approaches unit in that range, which indicates the reflection is insignificant. The imaginary part of impedance represents the loss, which should be zero in an ideal case. In Fig. 8, it varies around zero in the frequency band we focus on, and the loss mainly comes from the substrate loss.

More simulation results have been given to demonstrate the novel properties of negative index materials. We assign four unit cells of such NIM particles along the propagating direction, and observe the scattering parameters, as shown in Fig. 9. The pass band remains in the region from 9.9 GHz to 10.4 GHz, with the transmission coefficient no less than −3 dB and the reflection coefficient below −10 dB. We remark that the loss existing in the pass band could be cut down if we use a low-loss substrate.

When an electromagnetic wave propagates in NIM, it is known

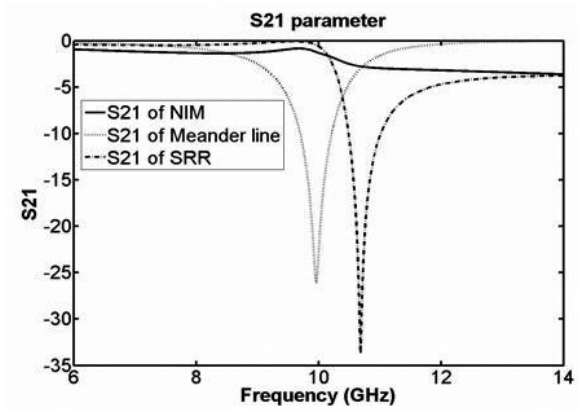


Figure 7. The comparison of S_{21} parameters of a NIM particle, a meander line and a SRR.

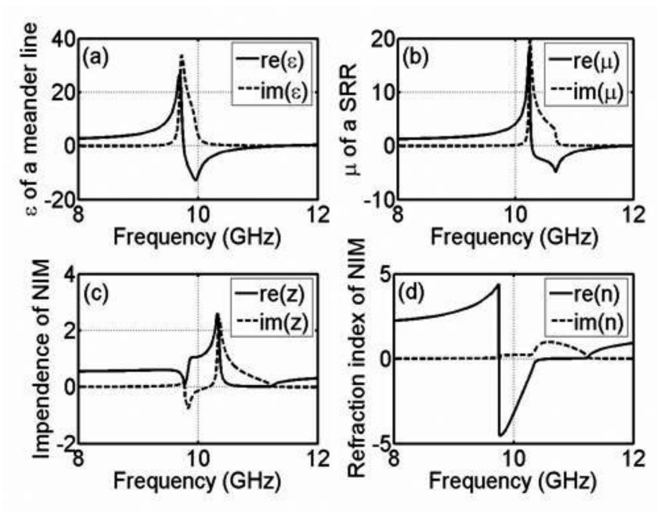


Figure 8. (a) Effective permittivity of the meander line. (b) Effective permeability of SRR. (c) Normalized impedance of the NIM particle. (d) Refraction index of the NIM particle.

that the wave number is negative and the phase distributes reversely along the propagating direction, which are abnormal to the natural materials. Fig. 10 shows the phase distribution of electric field along the propagating direction at the frequency of 10.2 GHz. NIM particles are arranged from 0 to 13.332 mm in the horizontal axis. It is obvious the phase shift in NIM distributes oppositely to that in vacuum. When

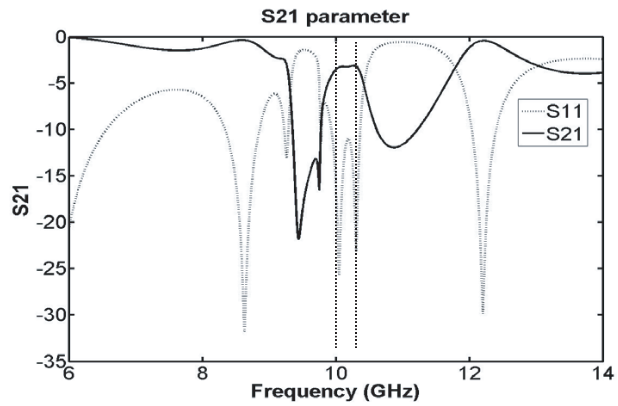


Figure 9. S parameters of four NIM particles. The pass band of negative index is marked.

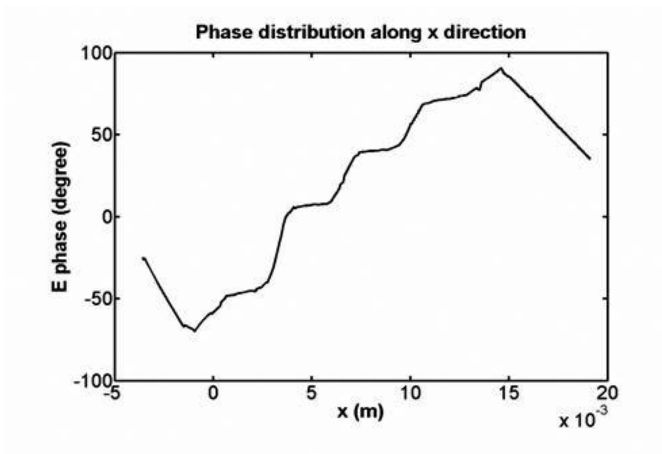


Figure 10. The phase distribution of electric field along the propagating direction at the frequency of 10.2 GHz.

we animate the electromagnetic field in HFSS, we could observe the electromagnetic wave propagating 'backward'.

4. CONCLUSIONS

A new meander line resonator has been presented in this paper. It could effectively lower down the electric resonant frequency and resonate individually. The structure is very simple to be controlled and is convenient for placing with other structures. By combining meander lines and SRRs, we could realize NIM at microwave frequencies with a relatively low loss. When we use substrate with lower dielectric loss, the loss will be reduced further.

ACKNOWLEDGMENT

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