Metamaterial based microwave devices

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Abstract

We studied metamaterial based microwave devices and investigated the effect of electrical size of the constituting elements on the device performance. First, we identify and characterize the suitable subwavelength resonators that are used to create metamaterials. We continued by demonstrating electrically small, metamaterial loaded monopole and patch antennas, miniaturized microwave absorbers, and flat metamaterial lenses with increased resolution.

1. Introduction

Response of a medium to an incident wave is determined by the fundamental parameters: electric permittivity (ε) and magnetic permeability (μ). At any narrow frequency band of the electromagnetic spectrum the concept of metamaterials enables us to design a medium with the desired electromagnetic response. Metamaterial media can have negative permittivity, permeability, and an index of refraction. Particles composed of non-magnetic metal and dielectric substrates were used as the unit cell of the metamaterials. Subwavelength resonators provide the magnetic response and thereby a medium with negative permeability. A rather small electrical size is of importance for the performance of the metamaterial loaded devices such as antennas, absorbers, lenses, and subwavelength apertures.

2. Deep subwavelength resonators

The most common negative permeability medium element is a split ring resonator (SRR): a metallic flat ring with a split etched on the substrate [1]. The typical electrical size of the SRR is $\lambda_0/10$, where λ_0 is the free space wavelength at the magnetic resonance frequency. Spiral resonators form a good example of the utilization of the available space with proper metal geometry. These particles are well known in microwave engineering as lumped inductors.

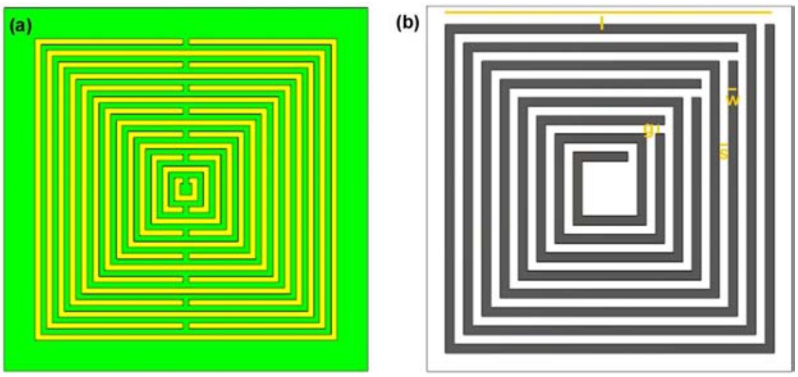

Fig. 1: Geometry and parameters of multi-split ring resonators (MSRR) and multi-spiral resonators (MSR).

We studied electrically small negative permeability medium particles that can be fabricated via the standard planar substrate based fabrication techniques and can be packed into one-, two- and threedimensional arrays for the metamaterial applications [2, 3]. The particles are multi-split ring resonators (MSRRs), spiral resonators (SRs) and multi-spiral resonators (MSRs). The MSR states a compromise between the electrical size and resonant response strength.

The geometry and parameters of the MSRR and MSR particles are shown in Fig. 1. The substrate used in our particles was Rogers RT/Duroid 5880 with $\varepsilon_r = 2.0$ and $\tan\delta = 0.0009$. The thickness of the substrate was t = 381 μm and deposited copper thickness was h = 18 μm. The particle parameters were as follows: width of the strips was w = 60 μm, separation between the strips was s = 60 μm, the split width was g = 60 μm, side length of the MSRR was l = 3.12 mm and MSR was l = 2.16 mm. The number of rings was N = 13 and number of turns was N = 9 for the MSRR and MSR respectively. The strength of the resonant response was larger than 20 dB for the both particles. The electrical size of the MSRR and MSR were $\lambda_0/25$ and $\lambda_0/35$, respectively. Both particles are designed to operate at around 4 GHz.

3. Metamaterial loaded antennas

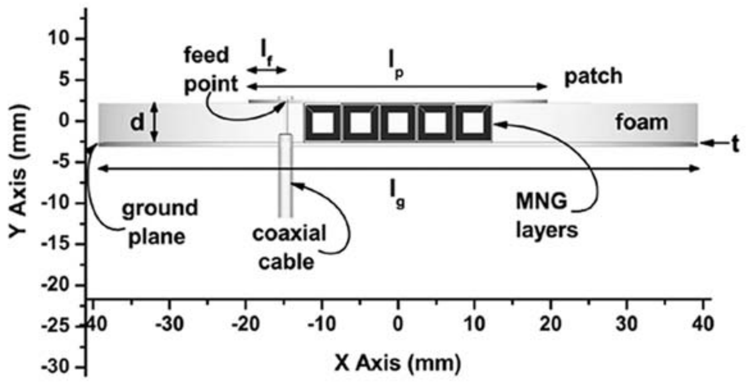

Fig. 2: Geometry of a loaded circular patch antenna.

We demonstrated loaded monopole antennas and circular patch antenna with the resonators. The loaded antennas operate at wavelengths that are much larger than their sizes. By loading the monopole antennas via subwavelength resonators, we obtained electrically small antennas of dimension λ /10. The efficiencies of these antennas were larger than %40. Secondly, circular patch antennas were loaded properly with a μ-negative medium as shown in Fig. 2. Choosing a proper mode of operation we obtained an efficient subwavelength patch antenna, whose radiation properties are as good as the standard dimension patch antenna.

4. Metamaterial based miniaturized absorbers

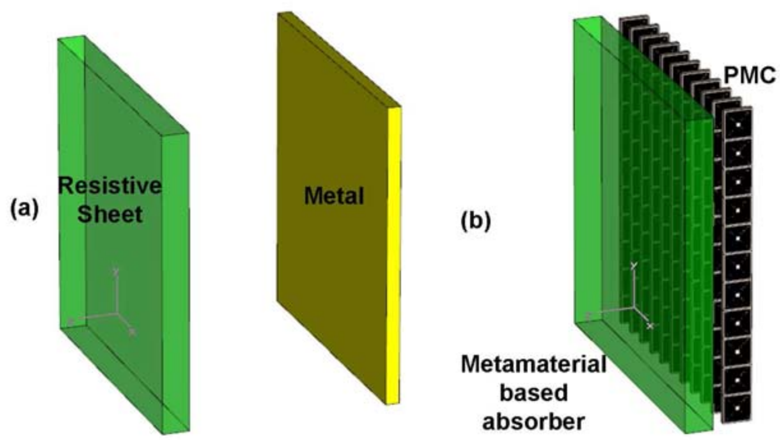

Fig. 3: Schematic of the absorbers (a) Salisbury Screen (b) Deep subwavelength resonator array loaded absorber.

The simplest microwave absorber, Salisbury Screen, was composed of a 377 Ohm resistive sheet and a metal plane placed a quarter-wavelength apart. Instead of the metal plane, we used an artificial perfect magnetic conductor: deep subwavelength resonator array. As we placed the array close to the resistive sheet at the resonance frequency the structure behaved as a narrow band absorber. Schematic of the absorbers are shown in Fig. 3. The advantages over the regular Salisbury screen are the lack of metal plane and reduced electrical thickness. We also investigated the effect of artificial perfect magnetic conductor thickness on the operation bandwidth.

5. Flat metamaterial lens and subwavelength imaging

We designed deep subwavelength resonator based double negative lenses by incorporating continuous wires on the back face of the substrates. By the qualitative effective medium theory analysis, we considered the transmission response of four different unit cell structures and concluded whether the composite metamaterial medium (CMM) was double negative. By shorting the gaps of the MSRR, we introduced the multi-closed ring resonator (MCRR) on which there are no circulating currents and at the operation frequency MCRR acts like an electric dipole. We obtained the transmission spectra of the MSRR media. The media are transparent up to 3 GHz and a stop-band for the MSRR-only medium was observed. This gap was not present at the MCRR transmission data, indicating its magnetic origin. Next, we considered the ε-negative wire-mesh medium. Its plasma frequency was designed to be at around 10 GHz. Even the wire-only medium might have negative ε below the plasma frequency, the composite metamaterial acts as a different plasmonic system. The MSRRs of the composite metamaterial kick in the effective permittivity and cause a downward shift of the wire-only medium plasma frequency. Therefore, instead of just considering the wire-only medium transmission response, we should also take into account the transmission response of the MCRR and wire composite (CCMM). We designed the medium parameters in such a way that the plasma frequency of the CCMM was around 8 GHz. We can guarantee thereby that the CMM medium is ε-negative below 8 GHz. Finally, we concluded that the transmission peak at around 4 GHz, was due to the double negative nature of the CMM medium.

We investigated the effect of electrical size of metamaterial elements on the subwavelength imaging. Metamaterial lenses composed of MSRRs and MSRs were studied in terms of subwavelength imaging. We tried to prove that as the electrical size of the metamaterial ingredients decrease the subwavelength resolution ability of flat lens increases.

6. Conclusion

We studied metamaterial based microwave devices: metamaterial loaded electrically small monopole and patch antennas, miniaturized microwave absorbers, and flat metamaterial lenses. Loading with a layer of MSRs, we obtained an efficient subwavelength patch antenna, whose radiation properties are as good as the standard dimension patch antenna. We placed a subwavelength resonator array back to a 377 Ohm resistive sheet and obtained an electrically small absorber appropriate for stealth applications. We investigated a limitation of subwavelength imaging: electrical size of constituting negative permeability medium elements.

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ISBN 978-0-9551179-6-1