Transmission and Reflection Properties of Composite Double Negative Metamaterials in Free Space

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***Abstract*—We report free space transmission and the first reflection measurements of a composite double negative (DNG) metamaterial, also known as a left-handed material (LHM). The metamaterial composes of the split-ring-resonators and discontinuous thin wires. Very high transmission values of the metamaterial are observed within a frequency range for which both effective permeability and permittivity are expected to be negative.**

***Index Terms*—Metamaterials, photonic bandgap, plasma frequency, split ring resonator.**

I. INTRODUCTION

COMPOSITE metamaterials (CMMs) have inspired great interest due to their unique physical properties and novel applications of these materials [1]–[6]. Two important parameters, electrical permittivity ε and magnetic permeability μ, determine the response of the material to the electromagnetic radiation. Usually, ε and μ are both positive in ordinary materials. While ε could be negative in some materials (for instance, ε posses negative values below plasma frequency of metals), no natural materials with negative μ are known. However, for certain structures which are called left-handed materials (LHM), both the effective permittivity ε_{eff} and permeability μ_{eff} possess negative values. In such materials the index of refraction, n, is less than zero, and therefore, phase and group velocity of an electromagnetic (EM) wave can propagate in opposite directions such that the direction of propagation is reversed with respect to the direction of energy flow [7]. This phenomena is called negative index of refraction and it was first theoretically proposed by Veselago in 1968, who also investigated various interesting optical properties of the negative index structures [7].

A negative permittivity medium can be obtained by arranging thin metallic wires periodically [8], [9]. The continuous wire structure behaves like a high-pass filter which means that the effective permittivity will take negative values below the plasma frequency [8]. However, for discontinuous wire structures, the negative permittivity region does not extend to zero frequency, and there appears a stopband around the resonance frequency.

On the other hand, a negative effective magnetic permeability medium is difficult to obtain. In 1999, Pendry *et al.* have suggested that an array of split ring resonators (SRRs) might exhibit a negative effective magnetic permeability for frequencies close to the resonance frequency of these structures [10]. By combining these SRRs and thin wires, Smith *et al.* reported the first experimental demonstration of left-handed metamaterials [1]. This was later followed by direct measurement of negative index of refraction [3]. All of these measurements were performed in a waveguide chamber which limited one of the dimensions of the LHM structures to a maximum of three cells. Recently, Ziolkowski and Heyman investigated wave propagation in double negative (DNG) composite metamaterials [4].

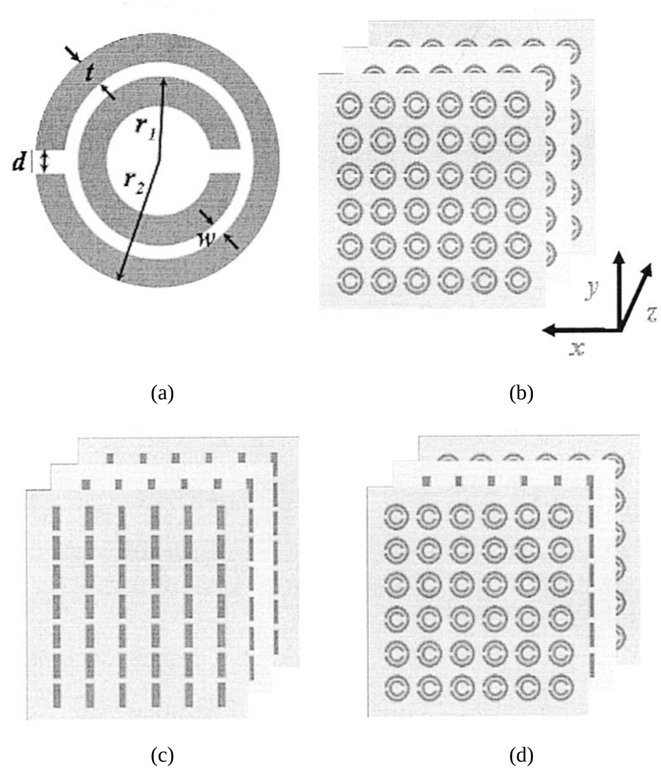

Fig. 1. (a) A single copper SRR with parameters $r_1 = 2.5$ mm, $r_2 = 3.6$ mm, $d = w = 0.2$ mm, and $t = 0.9$ mm. Schematic drawing of (b) the negative μ medium, (c) the negative ε medium, and (d) the composite DNG metamaterial.

In this paper, we report the transmission and reflection properties of DNG composite metamaterials in free space. To our knowledge, this is the first reflection measurements of composite metamaterials reported in scientific literature.

II. SPLIT RING RESONATORS

The negative permeability medium that consists of periodical arrangement of copper SRRs is constructed on a circuit board [5]. The board has a refractive index of 2.1 and a thickness of 1.5 mm. The details of the single SRR structure is shown in Fig. 1(a). It consists of two rings separated by a gap, which

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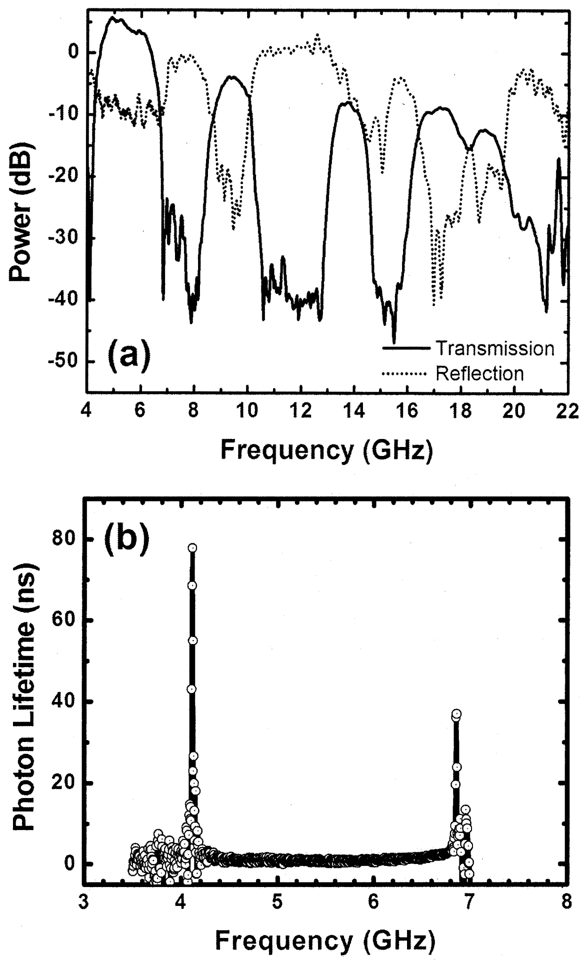

Fig. 2. (a) Measured broad-range transmission and reflection spectra of the SRR medium along x direction in free space. The transmission spectrum exhibits series stopbands and passbands. The negative permeability regions do not allow the propagation of electromagnetic waves through the SRR structure. (b) Measured delay time, photon lifetime, as a function of frequency. The delay time increases rapidly as we approach the band edges.

is similar to the SRR structures in [1]. Fig. 1(b) displays the stacked negative μ medium with parameters $N_{\rm x} = 15$, $N_{\rm y} = 15$, and $N_{\rm z} = 20$ units cells along each direction. The periodicity along x, y, and z axes are $a_{\rm x} = 9.3$ mm, $a_{\rm y} = 9$ mm, and $a_{\rm z} = 6.5$ mm. The transmission, reflection, and phase measurements are performed in free space by using an HP 8510C network analyzer and microwave horn antennas having various sizes for different portions of the frequency spectrum [5]. For all measurements, EM waves propagate along the x direction. The electric field polarization is kept along the y axis, and magnetic field polarization is kept along the z axis. The distance between the horn antennas is kept at 40 cm for all measurements to get rid of near field effects.

The measured transmission and reflection characteristics of the SRR medium are displayed in Fig. 2(a). The data shows that the structure has four significant pass bands, along with four stopbands throughout the spectrum. For the first passband, the transmission is measured to be higher than unity. As we have a passive structure with no gain, this can be explained by the lensing effect and the spatial dispersive properties of our structure along with the experimental error due to the overall size of

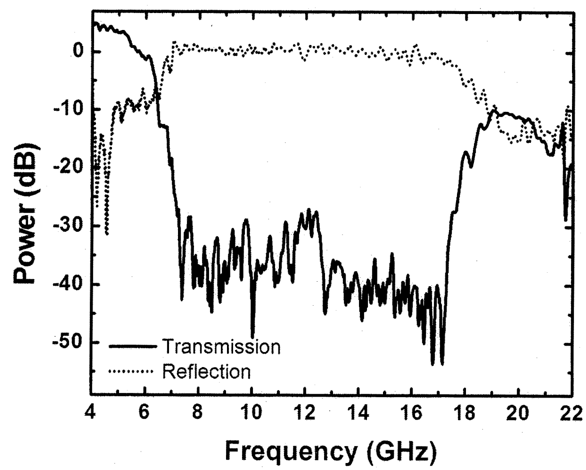

Fig. 3. Measured transmission and reflection characteristics of the thin wire medium. The transmission spectrum exhibits a wide stopband extending from 7 to 18 GHz. The lower passband is observed due to discontinuous nature of the wires. The reflection data also indicates the strong rejection of electromagnetic waves from the crystal for the negative permittivity region.

the crystal (which is around a few wavelengths at these low frequencies). The magnitude of transmission of the passbands decrease for higher order passbands. While the second passband has a peak transmission of $-$ 5 dB, this reduces to $-$ 10 dB for the fourth passband. The measured reflections at the first and second stopbands are measured to be near unity. So, we can safely claim that these structures perfectly reflect the EM waves for the lower stopbands. However, the measured reflection for the higher stopbands is around $-$ 5 dB which is well below unity. This suggests that the EM waves are partially scattered within the structure at the higher stopbands. The measured photon lifetime for the first passband, which is derived from phase measurements, is plotted in the inset of Fig. 2(b). Photon lifetime corresponds to the propagation time of the EM waves inside the metamaterial [11]. Hence, group velocity is inversely proportional to the photon lifetime. The photon lifetime and its physical interpretations have been rigorously studied by Ohtaka *et al.* [12]. As shown in the figure, the delay time significantly increases near the band edges. The photon lifetime near the lower edge of the first passband is $\sim$ 80 ns, which is 160 $\times$ larger than the time required for the EM waves to propagate along the structure. So, the SRR structure reduces the speed of light at this frequency by a factor of 160. For the upper edge, the lifetime is $\sim$ 40 ns, which corresponds to a 80 $\times$ reduction for the speed of light.

III. Thin Wires

The thin wire crystal is constructed by depositing discontinuous wire strips, of height 8.65 mm, on the circuit board [see Fig. 1(c)]. The thickness of the stripes is 0.9 mm and the gap between the two stripes is 0.35 mm. As shown in Fig. 1(c), the thin wire stripes with parameters $N_{\rm x} = 15$, $N_{\rm y} = 15$, $N_{\rm z} = 20$ units cells are stacked along each direction. The periodicity along x, y, and z axis are $a_{\rm x} = 9.3$ mm, $a_{\rm y} = 9$ mm, and $a_{\rm z} = 6.5$ mm, respectively.

The measured transmission and reflection characteristics of the thin wire structures are displayed in Fig. 3. In contrary to the

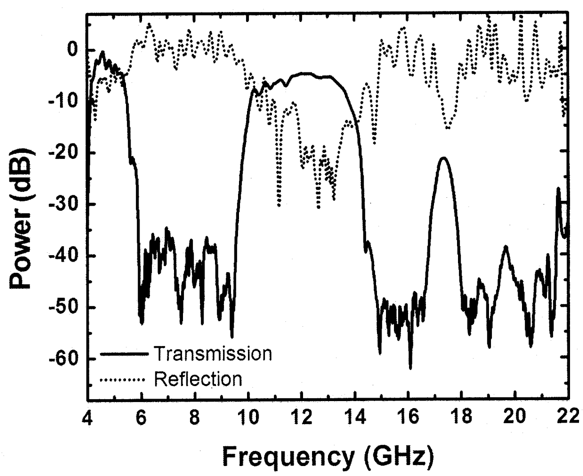

Fig. 4. Measured transmission and reflection spectra of the DNG composite metamaterials. Relatively high power, − 4.5 dB, is measured between frequencies 9.5 and 14.5 GHz in which both effective permittivity and permeability have negative values. The reflection spectrum also has average − 20 dB rejection throughout this region.

continuous wire structures [8] that exhibit a stopband with no lower edge, the present configuration exhibits a stopband with a well-defined lower edge due to the discontinuous nature of the wires. The stopband of the discontinuous thin wire structure extends from 6 to 18 GHz. The transmission of the structure for the lower passband is higher than unity. This high transmission again can be explained by the lensing effect and the crystal size restrictions described earlier. The transmission of the structure for the higher passband is measured to be less than − 10 dB. The reflection measurement indicates that all of the incident EM waves are reflected back from the structures within the stopband. So, the structure behaves like a good mirror throughout the stopband. For the passband region, the measured reflection is near − 15 dB. As the transmitted power is also low at these frequencies, we can conclude that the EM waves can not efficiently couple into propagating modes and strongly scatter within the structure.

IV. Composite Metamaterials

The composite structure is constructed by stacking the SRR and wire mediums periodically as shown in Fig. 1(d). The periodicity along z direction is $a_z = 6.5$ mm, the same as in SRR and wire mediums. The measured transmission and reflection properties of the composite metamaterial are displayed in Fig. 4. There appears a broad passband extending from 9.6 to 14.3 GHz. The average transmission within the passband is around − 4.5dB, corresponding to a transmission − 0.3 dB for each unit cell. This transmission is significantly higher than the previously reported composite metamaterial transmission properties [1], [5], [13]. As can be seen from Figs. 2 and 3, in this frequency range, both effective permeability and permittivity are negative. Since if only one of the constitutive parameters is negative and the other is positive we would have evanescent waves rather than propagating waves in the medium. So, the structure can be named as a DNG metamaterial [4]. The reflection of the double-negative structure within this frequency range is quite low. This shows that most of the EM waves penetrate into the DNG composite medium, and we have a certain amount of scattering loss at these frequencies[14], [15]. The reflection of the structure is around unity for the first stopband region, which suggests that the composite structure acts as an almost perfect mirror for these frequencies.

V. Conclusion

In summary, we investigated the transmission and reflection properties of the composite metamaterials at microwave frequencies in free space. A transmission amplitude of − 0.3 dB per unit cell is achieved throughout the DNG region. To our knowledge, this is the highest transmission characteristics reported for a composite metamaterial structure. Moreover, we observed that the delay time increases very rapidly near the SRRs band edges.

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