Novel Planar Metamaterial with a Negative Refractive Index

Dongho Kim and Jaeick Choi

ABSTRACT—A new planar metamaterial (MTM) with simultaneous negative values of permittivity (ε) and permeability (μ) is proposed. Our MTM is composed of two identical copper patterns etched on both sides of dielectric laminate, which is very thin and easy to fabricate. Unlike conventional MTMs, the proposed structure shows a negative refractive index (NRI) behavior with respect to a normally incident wave. To explain the underlying principle of the NRI characteristics, an equivalent resonant circuit model based on surface current density distribution is investigated. An eigenmode analysis and a three-dimensional wave simulation for the stacked MTM prism are also performed to verify the existence of negative refraction. The experimental results from the transmission and reflection measurement ensure the validity of our design approach and show good agreement with the theoretically predicted effective medium parameters.

Keywords—Negative refractive index (NRI), metamaterial, effective medium parameter.

I. Introduction

Since a successful experiment of negative refraction with a rod and split-ring resonator (SRR), various metamaterials (MTMs) of negative permittivity (ε) or negative permeability (μ), such as a broadside SRR, axially symmetric SRR, or Ω-like SRR, have been investigated [1]-[3]. However, such MTMs are usually accompanied by two problems in measurement and application; one is the contact of the metal rods with the waveguide walls during refraction experiments, and the other is the bi-anisotropic properties of the SRRs [2], [3].

To solve the contact issue of the rods and the bi-anisotropy problem, an S-shaped resonator (SSR) was proposed [4]. The

SSR MTM successfully produces simultaneous negative ε and μ within a relatively wide frequency range.

Markeley and others proposed a planar negative refractive index (NRI) MTM in [5], which has conductive patterns orthogonal to the wave propagation direction, and its thickness is about 0.26 times that of the guided wavelength (λ_g). This MTM consists of narrow fishnet-grids and square patches that are connected with strips. The fabrication of this planar-type MTM is very simple; therefore, we can avoid an additional piling up process of individual cells using a hot-press technique to make "bulky" MTMs, which is needed for conventional non-planar MTMs.

In this letter, we present a new thin planar NRI MTM, which is about 0.06 λ_g thick. Our MTM is composed of metallic square loops and X-shaped cross poles which are printed on both sides of a thin dielectric substrate. We experimentally demonstrate that the proposed MTM has negative values of both ε and μ, showing good agreement with the theoretically retrieved effective medium parameters. The proposed MTM is very thin and easy to fabricate using the printed circuit board (PCB) technology of today and is readily applicable to various RF devices including antennas.

II. Design, Analysis, and Experimental Verification

The unit cell geometry of the proposed NRI MTM is shown in Fig. 1. It consists of copper square loops and centered X-shaped cross poles. Those copper patterns are printed on both sides of the dielectric substrate. The commercial Taconic RF-60A laminate, which has a relative permittivity (ε_r) of 6.15 and a loss tangent (tan δ_c) of about 0.002, is used for fabrication. The total thickness of the MTM board including the copper patterns is 3.245 mm, which is about 0.06 times the guided
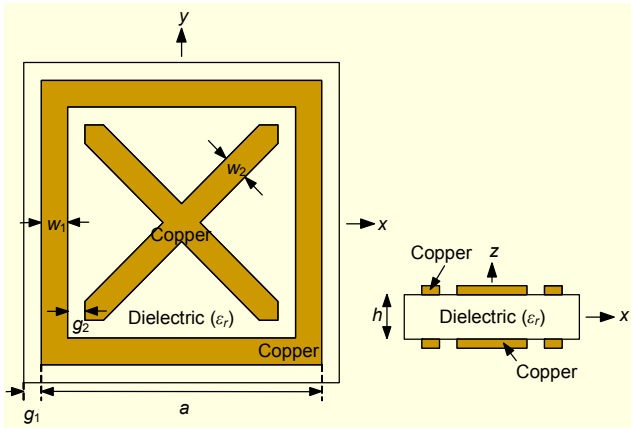
Fig. 1. Unit cell geometry of the proposed planar NRI MTM with a=18 mm, g_1=2 mm, g_2=w_1=0.5 mm, w_2=1.5 mm, h=3.175 mm, and ε_r=6.15.
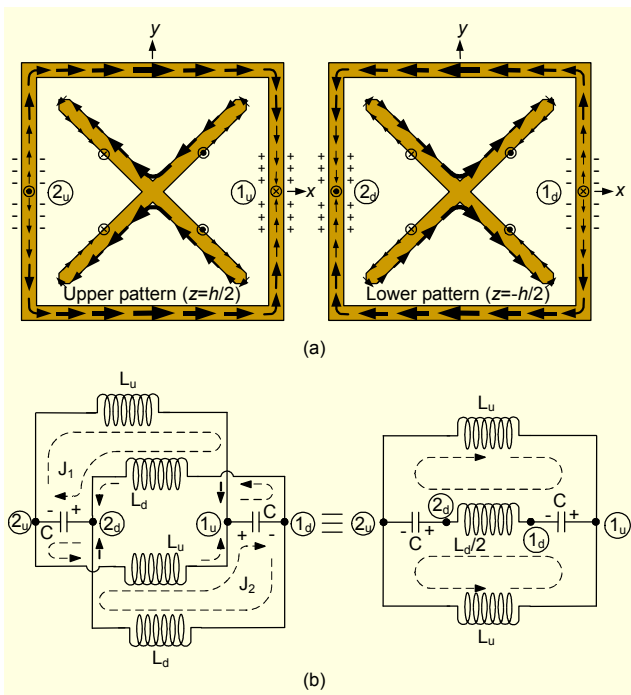

Fig. 2. (a) Flow of the conductive and displacement surface current density and (b) a representation of an equivalent resonant circuit of the loops to explain the negative μ response.

wavelength (λ_g) at 2.25 GHz.

Based on the distribution of conduction and displacement surface current densities, the equivalent circuit representation to conceptually explain the negative μ response of the proposed structure is shown in Fig. 2. First, we consider the effect of only the square loops. We depict the flow of the induced conduction current J_c at the upper and lower metallic patterns for an x-polarized incident plane wave in Fig. 2(a). The thicker and longer arrow means the stronger current density. Current J_c

starts from the point 2_u and flows through each arm of the loop to 1_u. When J_c arrives at 1_u, it runs toward the point 1_d on the lower loop in the form of displacement current J_d through the parasitic capacitor that is between the two points of 1_u and 1_d. Finally, after going through a similar way on the lower loop, J_c and J_d form a series resonant circuit, which is shown in Fig. 2(b). In Fig. 2(b), we can find that the loops work as a series resonant circuit, which yields the negative μ response. Though not shown here, it is easy to show that the X-poles will also produce another series resonant circuit, which is similar to those shown in Fig. 2(b). The negative ε is derived from the plasma-like behavior of each metal part of the loops and poles.

Dispersion diagram calculated from the simulated complex reflection and transmission coefficients of the unit cell is depicted in Fig. 3, where β_z means a propagation constant in the z-direction in the MTM. The second mode is an NRI passband that corresponds to about 2.1 GHz to 2.26 GHz. This relatively narrow NRI band can be widened by controlling the design parameters given in Fig. 1.

To more closely investigate the NRI behavior, we performed a three-dimensional full wave simulation using the commercial software of CST Microwave Studio, the result of which is given in Fig. 4. The MTM prism is composed by stacking 20 to 2 MTM cells from left to right, and the incline plane depicted as a broken line is tilted about 16.1° from the x-axis, which is equivalent to the incident angle of a plane wave. The experimental setup is very similar to the method used in [1], and the y-polarized plane wave impinges on the bottom face of the stacked MTM prism as shown in Fig. 4.

Simulation results show that the refracted beam, that is, the E_y-field, propagates toward a left-handed region with a
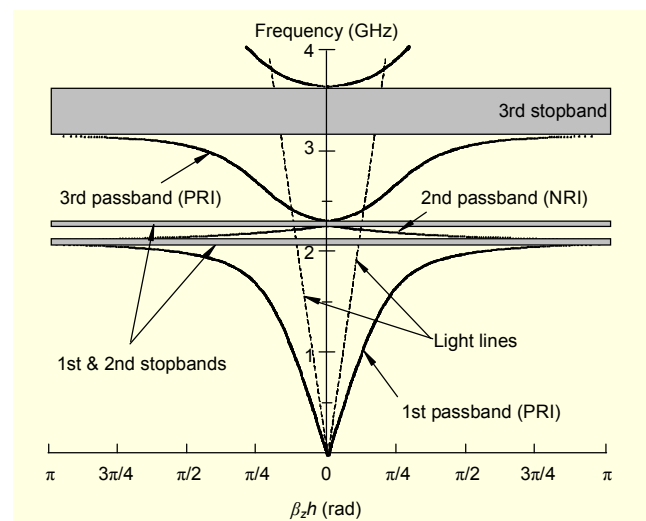

Fig. 3. Dispersion diagram of the planar NRI MTM computed from the reflection and transmission coefficients. PRI stands for a positive refractive index.
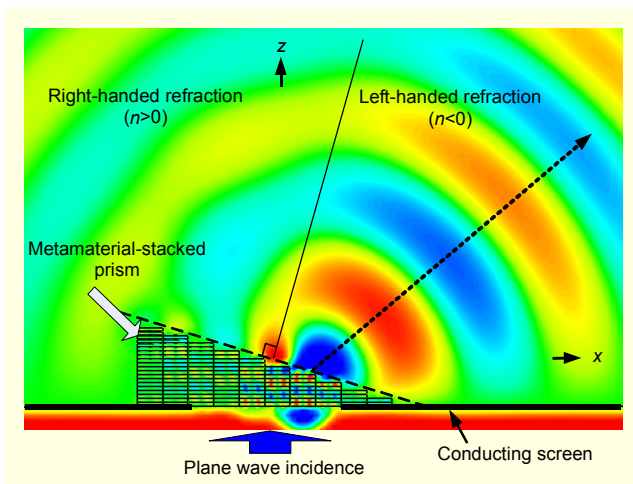
Fig. 4. Stacked-metamaterial-prism-based negative refraction simulation at 2.16 GHz.
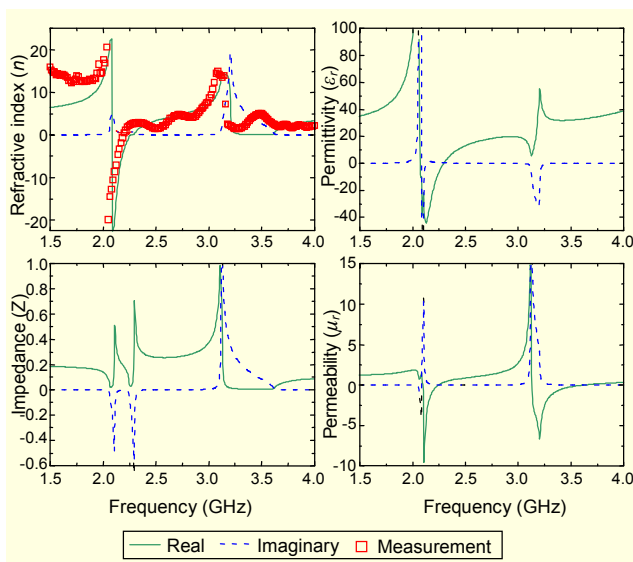

Fig. 5. Comparison of the measured and numerically retrieved effective medium parameters (time convention of $e^{-i\omega t}$ is assumed). Z is an impedance normalized by free space impedance.

negative refraction angle of -34.6°, which corresponds to a refractive index (n) of about -2.05. Consequently, two different approaches of the eigenmode analysis and the prism experiment verify that our MTM can produce both negative values of ε and μ in a specific frequency region.

For experimental verification of our design approach, we fabricated the proposed MTM board and measured its NRI properties. The measurement was performed using the MTM board consisting of 8×13 cells, which was placed between the two standard wideband horn antennas manufactured by ETS-Lindgren. The phase correction corresponding to the distance between the MTM board and the horn antennas was applied to

obtain the accurate complex scattering parameters. Figure 5 shows good agreement between the measured and predicted data, which was retrieved using the method reported in [6]. Four passbands and three stopbands also agree well with the eigenmode result shown in Fig. 3. These agreements confirm the validity of our design method and the NRI properties of our MTM structure. Losses are expected at some frequency bands, in which imaginary parts of n are not zero. However, in other regions with a zero imaginary part of n, losses are negligible, and there are only material losses.

III. Conclusion

A new planar-type MTM consisting of square loops and cross poles printed on both sides of a thin dielectric substrate was presented. The proposed MTM shows simultaneous negative permittivity (ε) and permeability (μ) properties in the specific frequency band, which were confirmed both by simulation and measurement. Our MTM is very thin and easy to fabricate; therefore, it can be directly applicable to various RF devices.

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