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DETERMINATION OF ELECTROMAGNETIC PARAMETERS OF A NEW METASURFACE COMPRISING OF SQUARE LOOP

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Abstract

In the present work, the reflection and transmission coefficients of new metasurface consisting of square loop structures have been analyzed to determine the electromagnetic parameters. In order to analyze the metasurface, a block of 3X3 cells has been placed centrally in a waveguide with a well defined boundary conditions and excitations which is a representative of infinite number of unit cells. The simulation results show that the effective permittivity and effective permeability of metasurface are negative simultaneously in the desired frequency range. The negative refractive index is confirmed by the overlapped region of negative effective permittivity and effective permeability.

Keywords: Metasurface, Square Loop, Negative permittivity, Negative permeability.

1. Introduction

Metamaterials (MTM) are exotic smart materials that exhibit the properties that are not available naturally. They are designed by uniting numerous components composed of different materials and are arranged repeatedly at smaller wavelengths. These materials formulate their properties from these newly designed structures and not from their constituents [1]. The MTMs are new materials that demonstrate unnatural qualitative response functions. These materials exhibit negative permeability (μ) and negative permittivity (ε) and can be classified into four categories relative to permeability and permittivity: Double negative (DNG) medium, Epsilon negative (ENG) medium, Mu negative (MNG) medium and Double positive (DPS) medium. Double negative mediums are the mediums in which the material has the permittivity and permeability less than zero simultaneously. Such mediums are also termed as Left Handed Mediums (LHM) [2].

Nomenclatures

C	Side of inner square, mm
c	Speed of light in free space, m/s
d	Thickness of substrate, mm
G	Gap between two square loops, mm
k_o	Wave number in free space
L	Side of outer square, mm
S_{11}	S-Parameter for reflection
S_{21}	S-Parameter for transmission

Greek Symbols

ε	Permittivity
ε_{eff}	Effective permittivity
μ	Permeability
μ_{eff}	Effective permeability
ω	Angular frequency

Abbreviations

DNG	Double Negative
DPS	Double Positive
DR	Direct-Retrieval
EM	Electromagnetic
ENG	Epsilon negative
FEM	Finite Element Method
HFSS	High Frequency Structure Simulator
Img	Imaginary Part
LHM	Left Handed Medium
MATLAB	Matrix Laboratory
MNG	Mu negative
M-NRI	Metamaterial Negative Refractive Index
MTM	Metamaterials
NRW	Nicolson-Ross-Weir
PEC	Perfect Electric Conductor
PMC	Perfect Magnetic Conductor
Re	Real part
SRR	Split Ring Resonators
TR	Transmission Reflection
TW	Thin-Wire

Metamaterials is a generous category of fabricated materials that may be constructed to manipulate electromagnetic (EM) features of host medium in accordance with the requirements of the system [3, 4]. Due to their extraordinary features, these materials have attracted a lot of researchers to use them in the field of miniaturization of antennas [5], with enhanced directivity [6], controlled beam-width and beam scanning [7].

Veselago, in 1968 [8], made a notable invention by introducing the first DNG medium which simultaneously exhibited negative values of permittivity and permeability. But this invention of artificial materials was merely a theoretical assumption and three decades later, Pendry et al. acknowledged his work by proposing thin-wire (TW) periodical structure that exhibited negative effective permittivity [9]. It was also indicated in [10] that an array of split ring resonators (SRR) can be used to achieve negative magnetic permeability. The DNG mediums provide numerous exceptional EM properties such as negative refractive index which was confirmed experimentally by Pendry and Smith [11-13], and vigorous optical movements [14-17]. Various researchers proposed different shapes of SRR like edge-coupled SRR [18], spiral resonators [19] and triangular-SRR [20]. Comprehensive attempts have been made to get simultaneous negative permittivity and permeability in microwave, terahertz, infrared and visible frequency ranges [21-24]. Metamaterials with negative refractive index has various applications such as M-NRI (Metamaterial- Negative Refractive Index) for antennas, superlens, wireless power transfer and biomedical applications [25-26].

The permittivity and magnetic permeability are the basic characteristic quantities that govern the advancement of electromagnetic waves in matter being the only parameters of a substance that appear in the dispersion equation [8]. The measurement of these complex parameters is not required only for scientific but also for industrial applications [27]. The extraction of these parameters is one of the necessary functions for characterizing the metamaterial and because of the increasing importance of metamaterial; the extraction of its effective parameters has acquired quite much consideration by the researchers.

Metasurface is the surface equivalent of the three-dimensional metamaterial and can be extended by the arrangement of small scatterers or holes in a two-dimensional pattern at a surface. Various approaches for efficient extraction of parameters of metasurfaces including Transmission-Reflection (TR) method, Direct-Retrieval (DR) Method, Nicolson-Ross-Weir (NRW) method etc., have been used [28-30] in past. In this paper a new Left handed metasurface structure of square loop cells is modeled and simulated using Finite Element Method (FEM) based Ansoft High Frequency Structure Simulator (HFSS) software to prove the negative refractive index of the material.

This paper is organized in five sections. Section 1 discusses the introduction and previously done work. Section 2 describes the proposed design of LHM structure. Section 3 presents simulation methodology of LHM cells with suitable boundary conditions and excitations. Section 4 presents the numerically analyzed results and discussions. Section 5 gives the conclusion of the paper.

2. Proposed Design of LHM Structure

The proposed left handed metasurface structure consisting of 3×3 square loops is depicted in Fig. 1(a), whereas the geometry and dimensions of a single unit cell is shown in Fig. 1(b). Table 1 enlists the geometrical dimensions of square loop unit cell. The proposed structure is designed on a Rogers RO4350 substrate with permittivity 3.66, dielectric loss tangent 0.004 and a thickness of 1.524 mm.

The unit cell is a square loop and has each outer side equal to 6 mm and the side of the inner cut is 2 mm. The square loop metasurface is designed on one side of the substrate and ground plane on the other side.

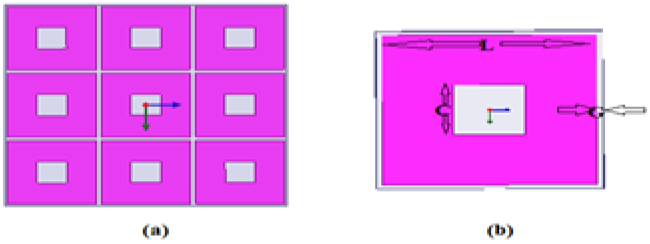

Fig. 1. Geometry of (a) 3×3 cell structure, (b) Unit cell.

Table 1. Dimensions of LHM unit cell structure.

	Parameter	Unit (mm)
1.	Side of outer square (*L*)	6
2.	Side of inner square (*C*)	2
3.	Gap between two square loops (*G*)	0.35

3. Simulation Methodology of LHM in Waveguide

The proposed metasurface unit cell is simulated with HFSS by putting it in a waveguide as illustrated in Fig. 2. The perfect magnetic conductor (PMC) and perfect electric conductor (PEC) are applied as boundary conditions on waveguide. The two wave ports are assigned along each of the substrate line on the x-faces from -x to x direction as shown in Fig. 2.

The S-Parameters, i.e., Reflection coefficient, S_{11} and Transmission coefficient, S_{21} are obtained from the above arrangement. Then these values are exported to Microsoft excel and Nicolson-Ross-Weir (NRW) approach is applied to retrieve μ_{eff} and ε_{eff} [31-32] and MATLAB code is written to implement Eqs. (1) to (4).

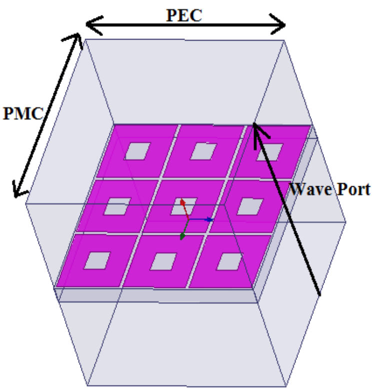

Fig. 2. Boundary conditions of the proposed LHM structure.

$$V_1 = S_{21} + S_{11} \quad (1)$$

$$V_2 = S_{21} - S_{11} \quad (2)$$

$$\mu_{eff} = \frac{2}{jk_{\circ}d}\frac{1-V_2}{1+V_2} \quad (3)$$

$$\varepsilon_{eff} = \frac{2}{jk_{\circ}d}\frac{1-V_1}{1+V_1} \quad (4)$$

Here, S_{11} is the S-Parameter for reflection and S_{21} is the S-Parameters for transmission through the structure respectively, d is the thickness of the substrate, $k_{\circ}$ is wave number in free space $(k_{\circ} = \omega/c)$, ω is the angular frequency and c is the speed of light in free space, c=3×10^8 m/s. By putting the value of V_1 and V_2 in Eqs. (3) and (4), μ_{eff} and ε_{eff} can be obtained.

4. Results and Discussions

A full wave simulation of the proposed LHM unit cell in a waveguide is performed with EM solver. The model is executed to verify its features after applying appropriate boundary conditions and excitations. The transmission and reflection parameters are plotted in order to validate the performance of the proposed metasurface.

4.1. Transmission and reflection parameters

Reflection coefficient can be represented as the fraction of the complex amplitude of the reflected wave and the transmitted wave. The transmission coefficient can be represented as the fraction of the amplitude of the complex transmitted wave and incident wave at a point of discontinuity in the transmission line. Figure 3 illustrates the reflection coefficient, S_{11} and the transmission coefficient, S_{21} of the proposed LHM structure with respect to frequency. It can be observed from the plot that there is a strong reflection at 38.0965 dB below 0 dB at 4.8632 GHz. This reveals that the proposed LHM structure resonates at 4.8632 GHz.

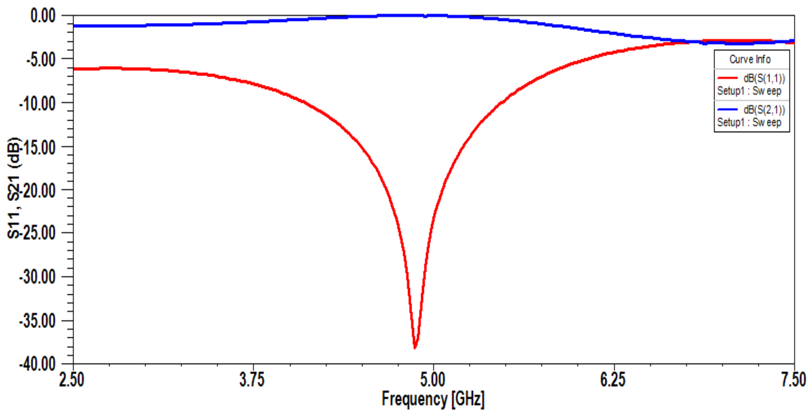

Fig. 3. Reflection coefficient (S_{11}) and transmission coefficient (S_{21}).

Reflection and transmission coefficients are in the form of a complex ratio. So, in order to evaluate the negative characteristics of permittivity and permeability of the proposed square loop structure, this complex ratio is split into real and imaginary parts. Real (Re) and Imaginary (Img) parts of S_{11} and S_{21} are depicted in Figs. 4 and 5 respectively.

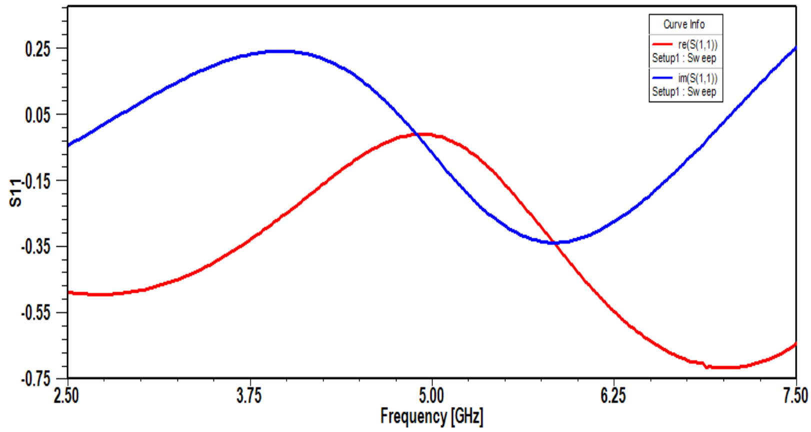

Fig. 4. Real and Imaginary parts of S_{11}.

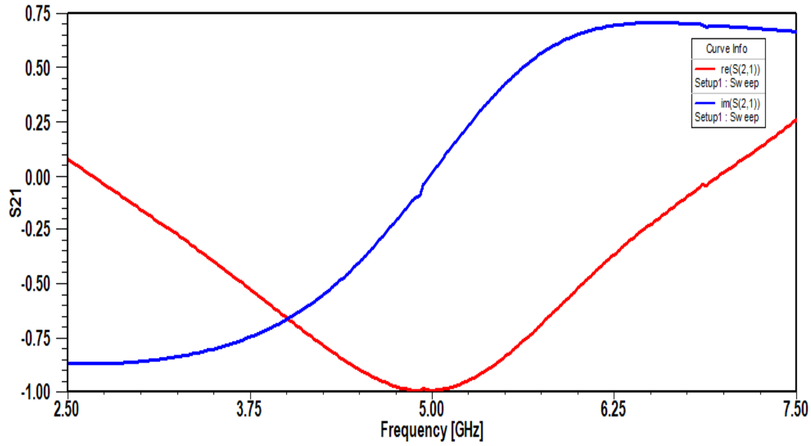

Fig. 5 Real and Imaginary parts of S_{21}.

The magnitude of any coefficient depicts the combined amplitude of the real and imaginary parts whereas the phase of any coefficient depicts the combined relative proportion of real and imaginary parts. The magnitude and phase of the S_{11} of the proposed LHM with respect to frequency are depicted in Fig. 6. The magnitude of the reflection coefficient should be between 0 and 1. The magnitude and phase of S_{21} of the LHM structure are revealed by Fig. 7.

Metasurfaces possess negative μ and ε and thus have negative refractive index, i.e., the reversal of snell's law. Due to this negative refractive index, the group and phase velocities of electromagnetic wave appear in opposite direction, i.e., the direction of propagation is reversed with respect to the energy flow direction. This interesting property of metasurface is validated by the reversal of phase of reflection and transmission coefficient at particular frequencies.

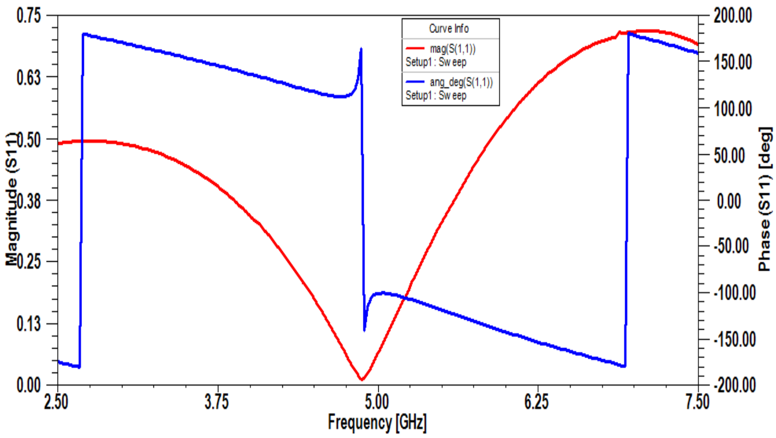

Fig. 6. Magnitude and Phase of Reflection coefficient (S_{11}).

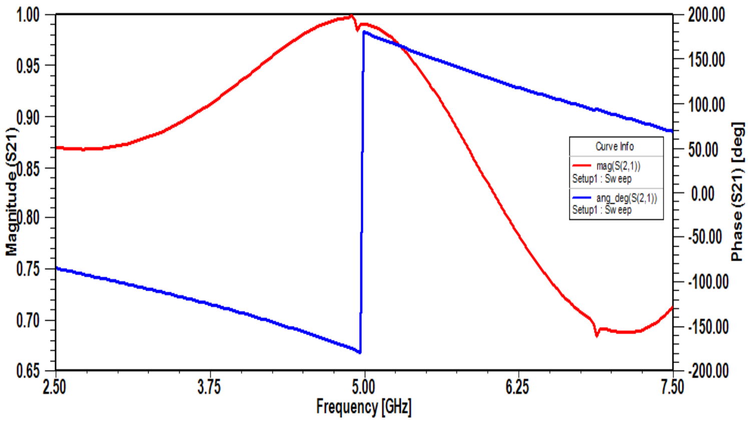

Fig. 7. Magnitude and Phase of Transmission coefficient (S_{21}).

4.2. Effective permeability and Effective permittivity

Figures 8(a) and 8(b) depict the real and imaginary parts of permeability and permittivity respectively. For evaluating effective permittivity and effective permeability, a MATLAB code is generated. The values of S_{11} and S_{21} are then exported to MATLAB. Finally, Eqs. (3) and (4) are implemented and μ_{eff} and ε_{eff} are calculated so as to verify the properties of metasurface.

The metamaterial theory states that the condition of negative real part of μ_{eff} and ε_{eff} for the proposed LHM design. It can be observed from the plots that the values of permittivity and permeability are below zero for the proposed structure. Figure 8(c) depicts the real part of permeability and permittivity respectively. The negative real part of permeability lies between 2.5-5.144 GHz, whereas the real part of permittivity lies between 2.5 GHz to 4.9524 GHz. Figure 8(c) depicts that the proposed LHM design exhibit simultaneous negative permittivity and permeability in the range of 2.5 GHz to 4.9524 GHz. Hence the proposed LHM structure exhibits negative refraction in 2.5 GHz to 4.9524 GHz frequency range.

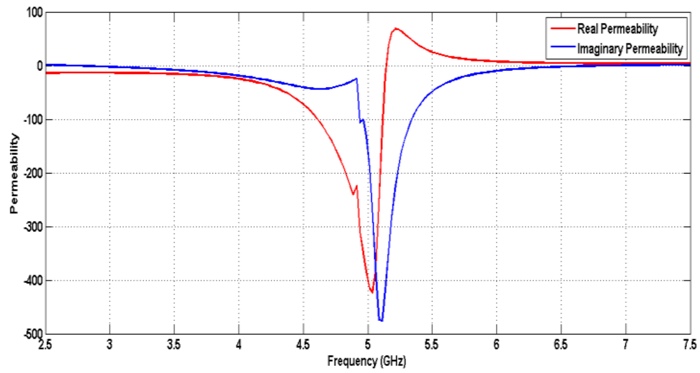

Fig. 8(a). Real and Imaginary parts of permeability.

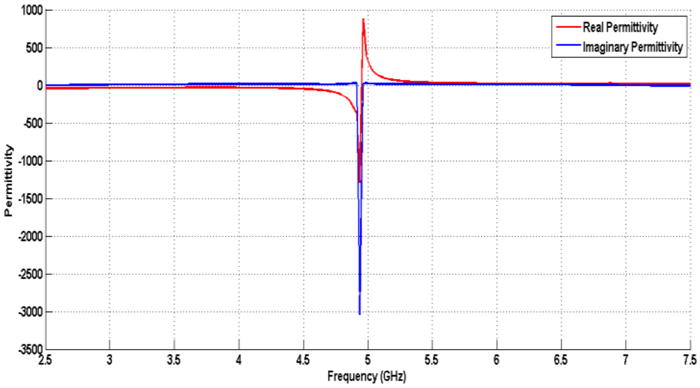

Fig. 8(b). Real and Imaginary parts of permittivity.

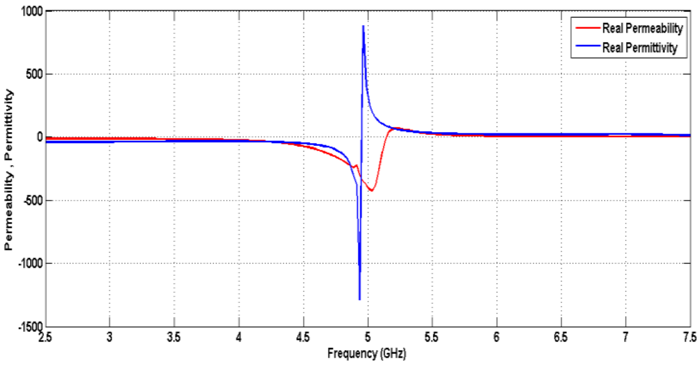

Fig. 8(c). Real parts of Permeability and permittivity.

5. Conclusions

The properties of metasurface are confirmed by using S_{11} and S_{21} of the proposed LHM structure of square loop cells. The structure shows simultaneous negative permittivity and negative permeability in the range of 2.5-4.9524 GHz. Negative index of refraction is also observed in this frequency range. Proposed square loop structure is a form of a tuned circuit consisting of inductance and capacitance and as a result it has a resonant frequency. This is the frequency where the capacitive and inductive reactance cancels each other out. Here, the proposed square loop structure resonates at 4.86 GHz, which lies in the region of negative refractive index. This work can be extended and used periodically as a superstrate for microstrip patch antenna or circular patch antenna to achieve improved performance characteristics.

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