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Design of a New Low Cost Metamaterial Structure

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Abstract

In this paper a new volumetric three dimension metamaterial design has been proposed. The structure consists of spherical balls of stainless steel and substrate of Bakelite. The structure is simulated from 1 to 20 GHz and show negative refractive in this range. Reflection and transmission coefficient (s-parameter) is used to calculate the effective permittivity and permeability of the structural. Refractive index of the structure is then calculated using effective permittivity and permeability of the structural. Due to negative refractive index it exhibits several unusual properties like focusing of light even with flat surfaces. This material can be easily incorporated with microstrip antennas to get highly directional beam patterns by using it as a substrate.

Keywords: *Metamaterial, epsilon negative media, Mu-negative media, Negative refractive index material, patch antenna*

1. Introduction

Metamaterial are artificially design material having negative electric and magnetic permeability. Metamaterial was first named and explained by Prof. V.G. Vaselego in 1968 [1]. He theoretically derived the properties of the metamaterial and showed that this type of material has negative electric and magnetic permeability. After its theory, in 1999 Pendry *et al.*, [2] first time demonstrated that periodic array of nonmagnetic conductor split rings shows negative effective permeability. In 2000 Smith *et al.*, [3] proposed a structure which has both electric and magnetic permeability negative. The structure has negative refractive index with respect to vacuum thus they called it a left hand medium. The structure consists of nonmagnetic split ring and continuous wires. The conducting wire provided electric field resonance and thus negative value of electric permittivity and split ring provided magnetic field resonance thus negative value of magnetic permeability.

Since then metamaterial in form of various structures has been proposed by researchers for different applications. The main applications of metamaterial in microwave region are miniaturization and performance improvement of microwave component, filter and antennas [4-7]. Different shape of the unit cell that are proposed for different application are split ring, triangular split ring, spiral ring, omega shaped, infinite shaped, fishnet, fan shaped split ring resonator and elliptical split ring resonator [5-8]. They all design using noble metal like silver and gold because they have negative permittivity at optical frequency. The shapes are designed on different substrates like RT5880, FR4 and glass using different fabrication technique which depends on the size and requirement. The fabricated metamaterial are than analyzed and using its reflection and transmission coefficient, effective material parameters are calculated by retrieval method [9] or Nicholson-Ross-Weir (NRW) technique [7]. In Retrieval technique proposed by smith et al., they use scattering data to identify refractive index (η) and impedance (z) of the structure from which electric permittivity $\varepsilon=\eta/z$, and the magnetic permeability $\mu=\eta*z$ are calculated.

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In designing metamaterial some researchers also develop different techniques for tuning metamaterial resonant frequency. A common approach for tuning metamaterial resonant frequency is changing its geometry parameter like size of outer and inner ring of SRR, conductor width, dielectric thickness [5, 8]. Evren *et al.*, proposed an idea of tuning metamaterial resonant frequency using RF MEMS switches in the gap of split ring resonator [8]. Sabah *et al.*, proposed a technique of mechanical tuning of metamaterial resonant frequency by varying substrate thickness in the direction of wave propagation [5].

In this paper design and simulation of a new type of structure is presented which exhibit negative refractive index. The structure consists of a spherical steel ball placed inside a Bakelite substrate. The structure has been simulated on HFSS and s-parameter values (S11 and S21) thus obtained was used to calculate refractive index.

2. Design

Micro-wave metamaterials are fabricated with PCB by making different metal architecture [4-8, 10].To design a material having metamaterial property; one has to design a unit cell which is periodically repeated in the structure to give the desired value of permeability and permittivity [2-3]. Metamaterial affects EM wave by having structure smaller than the wavelength and the dimension of the unit cell is restricted by frequency range in which material is analyzed or use. The dimension condition for a unit cell is given in equation 1.

$$a \ll \lambda \qquad (1)$$

The design of the structure developed in this work is shown in Figure 1 to Figure 4. The unit cell dimension is 2mm X 2mm. It consists of a steel ball of radius 0.5 mm which is inserted in a Bakelite substrate (ε = 4.7) of thickness 2.22 mm.

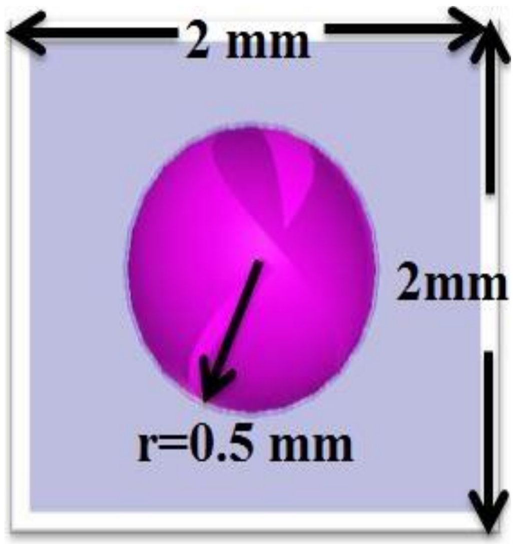

Figure 1. Unit

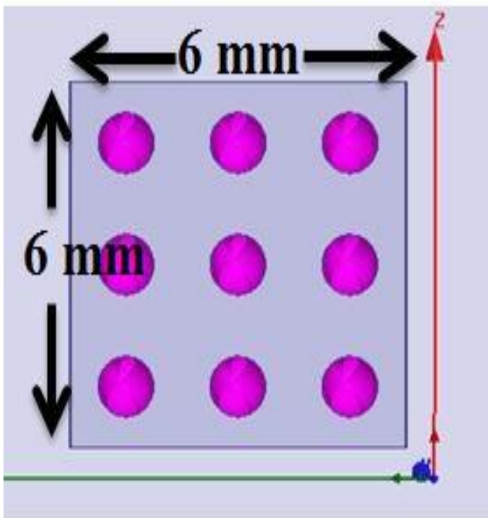

Figure 2. Top View

Dimension of the unit cell is taken around 1/10th of the wavelength. If the condition of equation 1 were not obeyed, there would be the possibility that internal structure of the medium could diffract as well as refract radiation, which leads to an undesired result. Figure 3 and 4 show structure in which nine unit cells is placed and simulate.

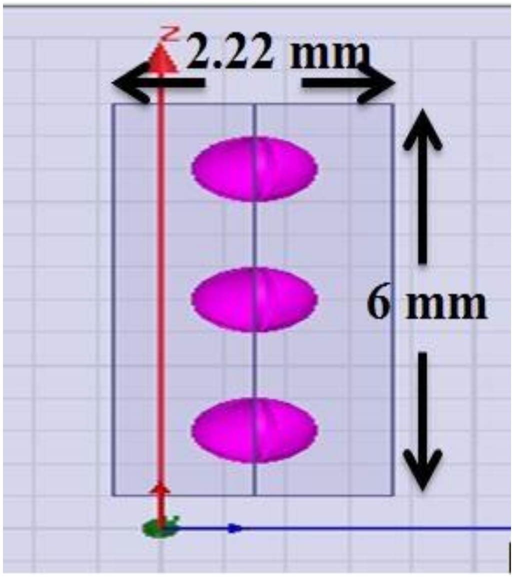

Figure 3. Side View

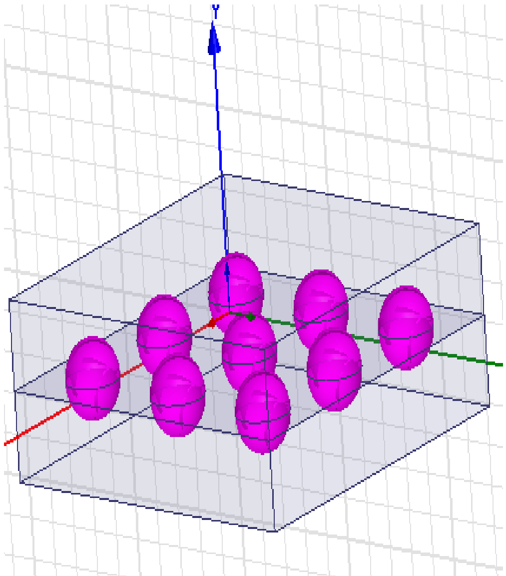

Figure 4. Three Dimension View

3. Calculation

Substrate is placed at the mid of the waveguide and then s parameter is measure at the port. Effective permittivity ε_r and effective permeability μ_r can be calculated using Nicholson-Ross-Weir (NRW) technique. NRW method is programmed in MATLAB to obtain the plots.

The effective permittivity ε and effective permeability μ is calculated as:

$$v1=s11+s21 \quad (2)$$

$$v2=s21-s11 \quad (3)$$

S11 and s21 are transmission and reflection coefficient respectively.

$$\mu_r = \frac{2}{jkh}\frac{1-v2}{1+v1} \quad (4)$$

$$\varepsilon_r = \frac{2}{jkh}\frac{1-v1}{1+v1} \quad (5)$$

Here h is thickness or height of substrate in the direction of wave propagation and k is wave number which is given as:

$$k=\frac{2\pi}{\lambda} \quad (6)$$

Using ε and μ we can calculate the refractive index as:

$$\eta = \pm\sqrt{\mu\,\varepsilon} \quad (7)$$

For $\mu_r < 0$ & $\varepsilon_r < 0$

$$\eta = -\sqrt{\mu\varepsilon} \quad (8)$$

4. Result

Plot of s11(dB) and s21(dB) is shown in Figure 5, which shows that the proposed structure resonates at 4.2 GHz, 6.5 GHz, 8.7 GHz, 10.8 GHz, 13 GHz and 15 GHz frequencies. Figure 6 shows the effective permittivity and permeability of the material. Both effective permittivity and permeability is negative in frequency is range 6.4 GHz to

8.3 GHz, 10.8 GHz to 13 GHz and 15.3 GHz to 16.9 GHz. Real and imaginary part of the refractive index is plotted in Figure 7. It is shown from the plot of refractive index that, refractive index is negative in frequency region where the μ & ε is negative. Table 1 shows the frequency region in which the refractive index is negative and maximum refractive index in negative.

Table 1

Frequency Range (GHz)	Frequency of maximum Refractive Index (GHz)	Maximum Refractive Index in Range (negative)
2-4.2	2.2	-24.36
6.4-8.2	6.8	-8.243
10.8-13	11.1	-4.883
15.2-17	15.3	-4.564

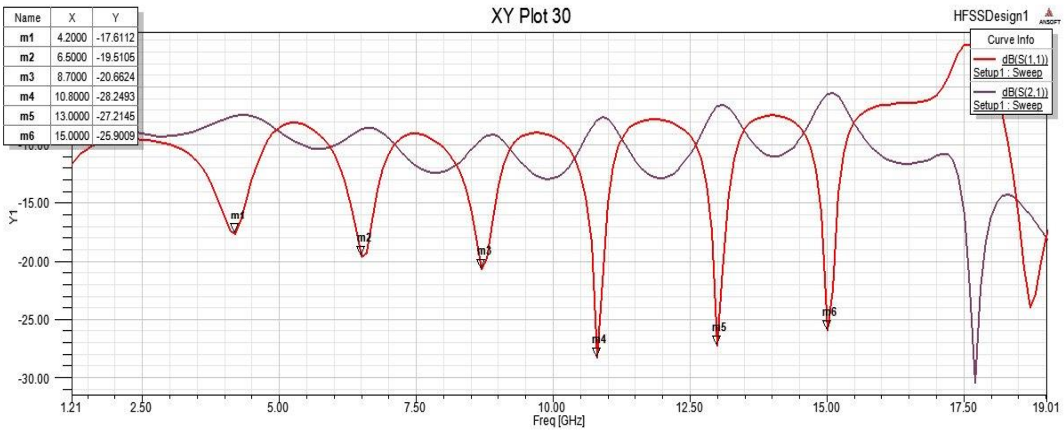

Figure 5. Plot of s11(dB) and s21(dB)

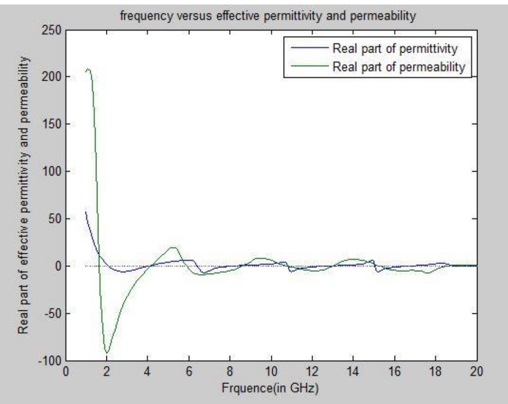

Figure 6. Frequency versus Effective μ_r and ε_r

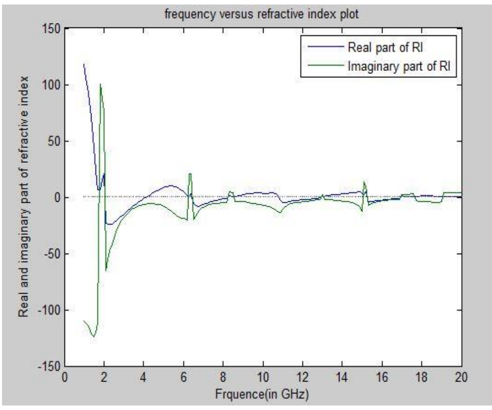

Figure 7. Frequency versus Refractive Index Plot

5. Conclusion

A new low cost metamaterial structure has been designed and its performance with given physical parameters has been analyzed. The results show that it has a negative refractive in the desired range. This metamaterial when used as a substrate of a patch antenna, shows improvement in its bandwidth and radiation pattern. The performance of the metamaterial is best shown in frequency range 10.8 GHz to 13 GHz. Low cost materials, Bakelite and steel balls have been used to design the metamaterial structure. The developed metamaterial can be incorporated in microwave components and antennas for performance improvement.

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