

A Combined WU-shaped NRI Metamaterial for Dual Band Microwave Application

Krishnan Sinha¹, Sikder Sunbeam Islam^{1,*}, Mohammad Jakir Hossain²

¹Department of Electrical & Electronic Engineering, International Islamic University Chittagong, Bangladesh

²Department of Electrical and Electronic Engineering, Dhaka University of Engineering & Technology, Bangladesh

Received November 3, 2019; Received December 2, 2019; Revised December 4, 2019

Copyright©2020 by authors, all rights reserved. Authors agree that this article remains permanently open access under the terms of the Creative Commons Attribution License 4.0 International License

Abstract In the field of electromagnetism, artificially constructed metamaterial has opened a new hope for the researchers. Metamaterial is developed artificially and not found available in nature. This composite material shows more irregular properties than the natural materials. Negative refractive index (NRI) is one of the exceptional properties of it. Therefore, many researchers have started investigation with this material. Some metamaterials found in literature have NRI properties but very few of them are found operating simultaneously in C-and X-band. In this study, a new combined WU-shaped NRI metamaterial unit cell is presented. Here, three different substrate materials have been adopted for sensitivity analysis. The used substrate materials are FR-4, Rogers RT6006 and Rogers RT6010 and their permittivity are 4.3, 6.15 and 10.2 respectively. Finite integration technique based numerical tool is adopted for all analyses. The electromagnetic properties are determined by Nicolson-Ross-Weir (NRW) method. Perfect electric-magnetic boundary condition is applied for simulation. The metamaterial unit cell exhibits negative refractive index (NRI) within C-band and X-band for all these substrate materials. C-and X-band are widely used for satellite and long distance communication. Moreover, the proposed material shows better effective medium ratio with increasing relative permittivity which ensures the materials proper operation and sensitivity for any applications.

Keywords Metamaterials, Negative Refractive Index, Permittivity, C and X-band

He proposed that this type of materials show the simultaneously negative permeability (μ) and negative permittivity (ϵ). The metamaterials are not found in naturally [1]. If a material shows simultaneously negative permeability and negative permittivity then the metamaterial is denoted as double negative (DNG) material or negative-reflective material. A double negative metamaterial is shown in [2] [3]. A metamaterial presents the negative of either epsilon (ϵ) or mu (μ) that is called single negative (SNG) metamaterials. These types of metamaterials are epsilon negative metamaterial (ENG) and mu negative metamaterial (MNG). An epsilon (ϵ) negative metamaterial and a Mu (μ) negative metamaterial are introduced in [4] and [5] respectively. After a long time of Veselago's suggestion, in 1996 J. B. Pendry was the first who showed a design of Thin-Wire which exhibits the negative permittivity [6]. The difficulty is to find a material which shows negative permeability (μ) naturally. For this reason, there are no experimental prove. At first, in 2000 Smith et al. reported experimental result of a new artificial metamaterials, which shows double negative property (both negative permeability and negative permittivity) [7]. In 2001, Shelby et al. determined the effective refractive index (η) by using Snell's law where it is negative in a frequency where both permittivity (ϵ) and permeability (μ) are simultaneously negative [8]. There are several shapes of metamaterials like spiral-shape [9], Triangular [10], S-shape [11], U-shape [12], V-shape [13] are introduced which exhibit their metamaterial properties at a certain frequency. However, all of them do not exhibit negative refractive index in C and X band. But the new proposed combined WU-shaped design shows a negative refractive index in C and X band.

1. Introduction

The metamaterial (MTM) is an artificial material which is first introduced by the scientist V. G. Veselago in 1967.

2. Design

The proposed combined-WU shaped metamaterial unit

cell design is displayed in the Figure 1. FR-4 is used as the substrate material which is popular substrate material. In which, dielectric constant (ϵ) and loss-tangent (δ) of FR-4 are 4.3 and 0.025 respectively. The current density of the unit cell at 3.145 GHz is given in Figure 2.

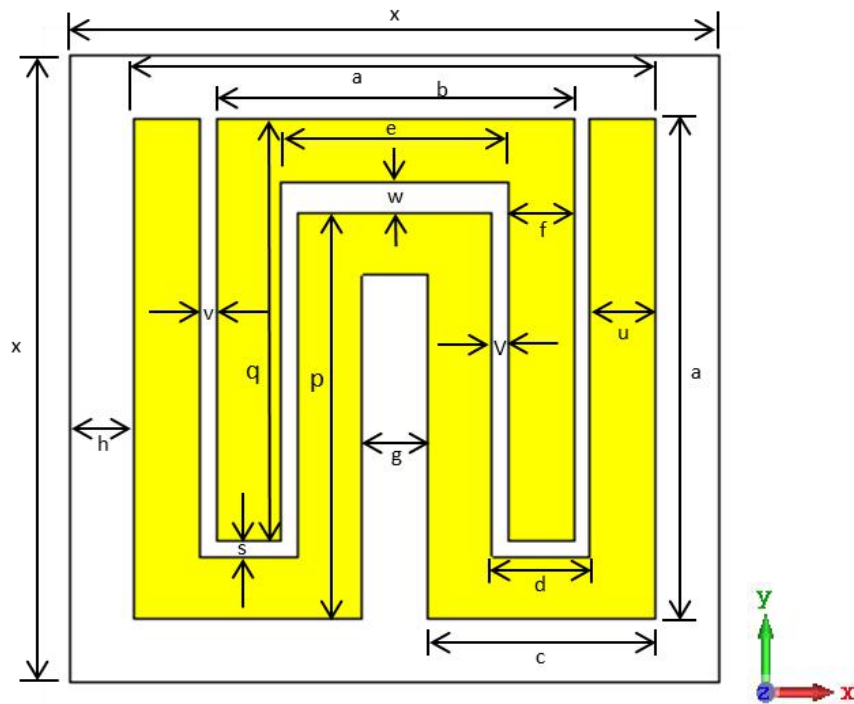


Figure 1. The new proposed metamaterials unit cell structure

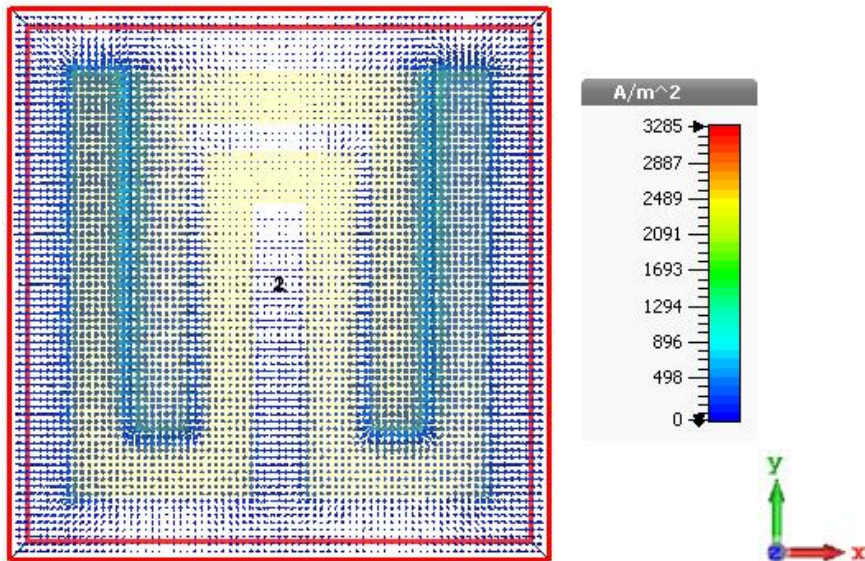


Figure 2. Current density of proposed unit cell at 3.145 GHz

Both the substrate length and width of the proposed design is $x = 10$ mm. The thickness of the substrate material is 1.6 mm. The structure of proposed combined-WU shaped metamaterial has been designed with two metal (copper) split square resonator, in which the shape of one strip is W-like and another is opposite U-like. All of the copper thickness is kept 0.035mm. Table 1. enlists the structural parameters of unit cell.

Table 1. Structural parameters in millimeter (mm) of the unit cell

Parameters of proposed unit cell	Value (mm)
a	8
b	5.5
c	3.5
d	1.5
e	3
f	1
g	1
h	1
p	6.5
q	6.75
s	0.25
u	1
v	0.25
w	0.5
x	10

The substrate material FR-4 of this design is replaced by another two substrate materials Rogers RT6006 and Rogers RT6010 where the dielectric constants are 6.15 and 10.2 respectively, and the loss-tangents of those substrate materials are 0.0027 and 0.0023 respectively. The proposed design's dimensions of the metamaterials using Rogers RT6010 and Rogers RT6006 as substrate materials are fixed which dimensions are used in the metamaterial using substrate material FR-4.

However, according to the resonance frequency, the effective medium ratio of the proposed combined-WU shaped negative refractive index metamaterial unit cell using substrate material FR-4 is $\lambda/x = 9.53895$, where λ is the wavelength. Other two proposed same designed metamaterial unit cells using Rogers RT6010 and Rogers RT6006 as substrate materials maintain an effective medium ratio approximately 13 and 11 respectively.

3. Methodology

For numerical investigation of the mentioned unit cell, the Computer Simulation Technology Microwave Studio (CST MWS) software is used for electromagnetic simulation. Using CST MWS and placing mentioned cell, transverse electromagnetic wave is propagated through proposed unit cell between two waveguide ports along

z-axis from +z to -z direction. On the x-axis and y-axis, perfect electric conductor (PEC) and perfect magnetic conductor (PMC) are applied respectively as boundary condition on waveguide. The S-parameters are S_{11} (reflection coefficient) and S_{21} (transmission coefficient) which are obtained after the simulator using the arrangement shown in Figure 3.

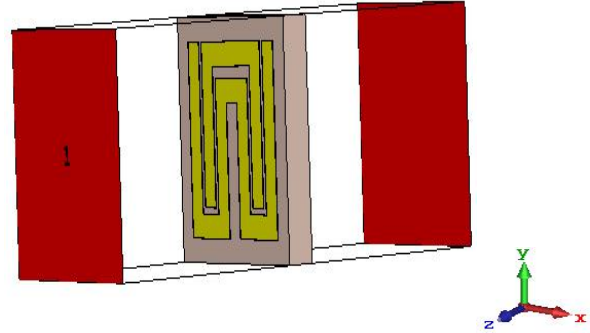


Figure 3. Simulation arrangement for calculating S-parameters by wave propagating through the z-axis

The same designed unit cells are fabricated on substrate materials FR-4, Rogers RT6010 and Rogers RT6006. The unit cell is simulated between the frequencies 1 to 12 GHz, which covers L, S, C, X band. In this paper, electromagnetic properties effective permeability (μ_r) and permittivity (ϵ_r) are determined by Nicolson-Ross-Weir (NRW) method and refractive index (η) is measured by the Direct-Refractive Index (DRI) method using simulated result of S_{11} and S_{21} of the proposed unit cell [14]. For analysis, the real values of all three parameters (ϵ_r , μ_r and η) are discussed. Equation (3) and (4) are used for extraction of effective permeability and effective permittivity respectively by using NRW method.

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

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

$$\mu_r = \frac{2}{jk_d} \frac{1-V_2}{1+V_2} \quad (3)$$

$$\epsilon_r = \frac{2}{jk_d} \frac{1-V_1}{1+V_1} \quad (4)$$

Where d and k_0 are the thickness of substrate and wave number in the free space respectively, Where ($k_0 = \omega/c$), the angular frequency is expressed as ω and the light speed in free space, $c = 3 \times 10^8$ m/s.

Here, the refractive index η is obtained by using the direct refractive index (DRI) using (5).

$$\eta = \frac{c}{j\pi d f} \left\{ \frac{(S_{21}-1)^2 - S_{11}^2}{(S_{21}+1)^2 - S_{11}^2} \right\}^{\frac{1}{2}} \quad (5)$$

Here, S_{21} and S_{11} are the S-parameters.

4. Results and Discussion

The results of effective permeability (μ), effective permittivity (ϵ) are found by using NRW method and refractive index (η) is found by using the DRI method for each same designed unit cell using FR-4, Rogers RT6006 and Rogers RT6010 as substrate material.

The simulated result of transmission coefficient, S_{21} for unit cell using FR-4 as substrate material is given in Fig. 4(a). The results of effective permeability, effective permittivity and refractive index are depicted in the Fig. 4(b), Fig. 4(c) and Fig. 4(d) respectively for the unit cell structure using FR-4.

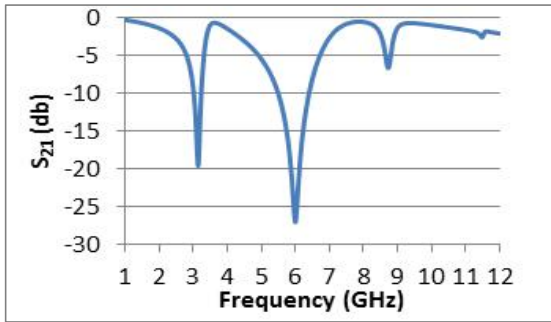


Figure 4(a). Simulated result of S_{21} in dB for using FR-4

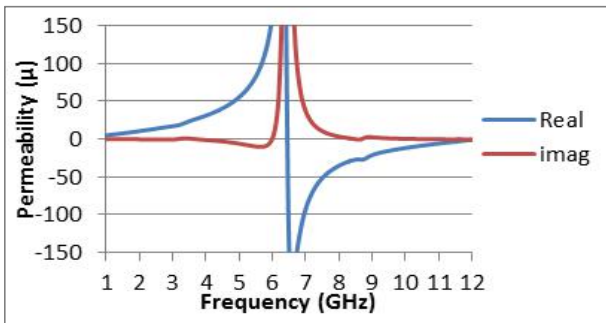


Figure 4(b). Effective permeability

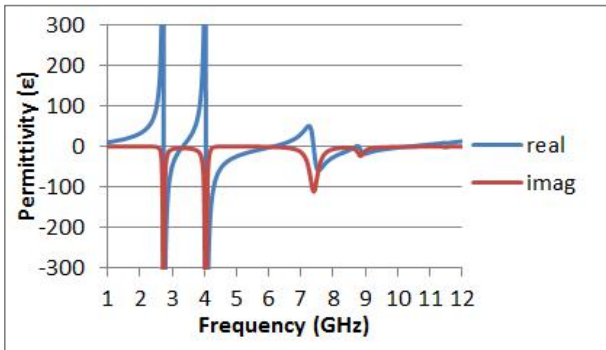


Figure 4(c). Effective permittivity

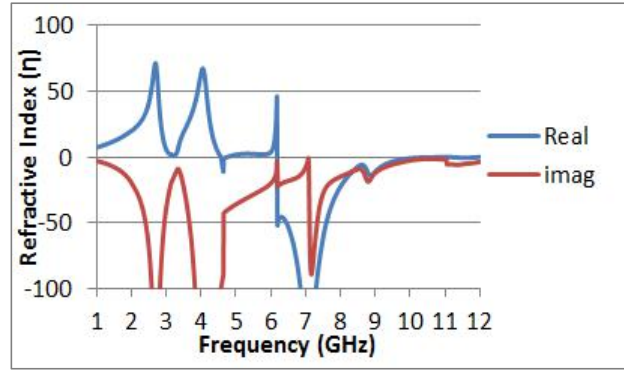


Figure 4(d). Refractive index

Fig. 4(b) shows the negative permeability from 6.456 to 12 GHz. Fig. 4(c) exhibits negative permittivity from 2.738 to 3.321 GHz, 4.047 to 6.115 GHz, 7.391 to 8.689 GHz and 8.799 to 10.328 GHz. Fig. 4(d) shows negative refractive index from 4.575 to 4.74 GHz and 6.192 to 11.956 GHz. Hence the proposed unit cell acts as a negative refractive index metamaterials from 7.391 to 8.689 GHz and 8.799 to 10.328 GHz where all the parameters are negative. Actually when the unit cell exists in a charging magnetic field, the structure gap acts like a capacitor and a charge is created in the gap. In the high frequency the created current in the gap lags the driving field and the negative permeability is formed for this reason. However, Negative refraction is achieved when energy and phase of wave flow oppositely due to the structure.

The simulated result of transmission coefficient S_{21} for unit cell using Rogers RT6006 as substrate material is given in Fig. 5(a). The results of the effective permeability, effective permittivity and the refractive index are depicted in the Fig. 5(b), Fig. 5(c) and Fig. 5(d) respectively for that same unit cell structure using Rogers RT6006.

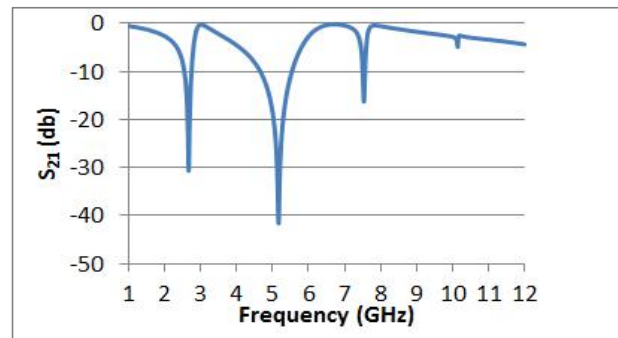


Figure 5(a). Simulated result of S_{21} in dB for using Rogers RT6006

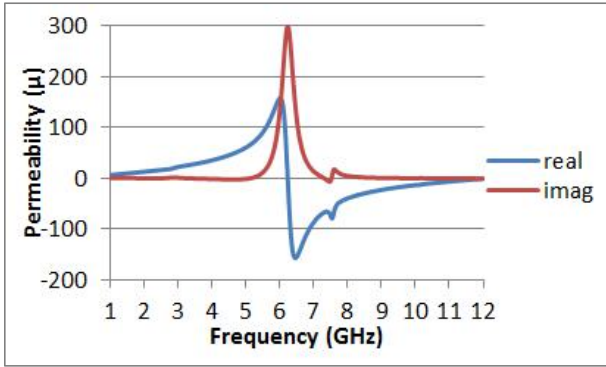


Figure 5(b). Effective permeability

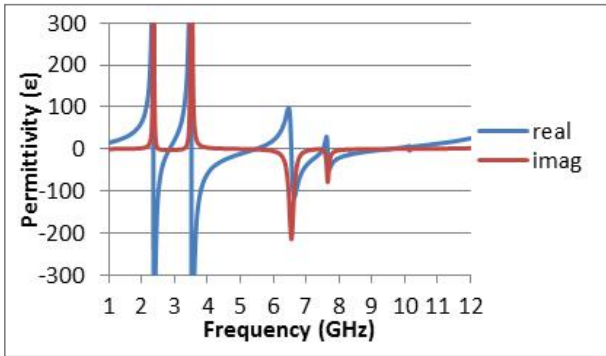


Figure 5(c). Effective permittivity

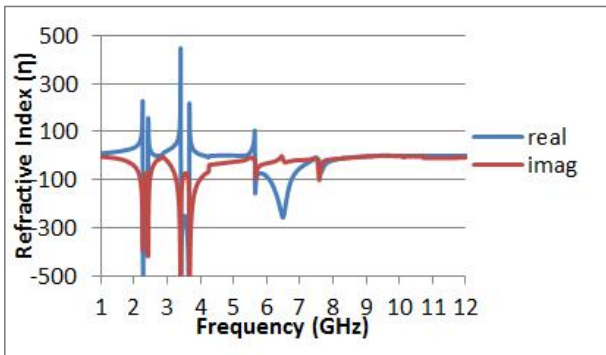


Figure 5(d). Refractive index

Fig. 5(b) exhibits the negative permeability from 6.236 to 12 GHz. Fig. 5(c) shows the negative permittivity from 2.364 to 2.837 GHz, 3.519 to 5.466 GHz, 6.555 to 7.501 GHz and 7.655 to 9.503 GHz. Fig. 5(d) shows the negative refractive index from 2.276 to 2.419 GHz, 3.42 to 3.662 GHz, 4.157 to 4.377 GHz, 5.653 to 9.393 GHz, 9.767 to 10.57 GHz and 10.944 to 11.802 GHz. Hence the proposed unit cell acts as a negative refractive index metamaterials from 6.555 to 7.501 GHz and 7.655 to 9.393 GHz where all the parameters are negative.

The simulated result of transmission coefficient S_{21} for unit cell using Rogers RT6010 as substrate material is given in Fig. 6(a). The Fig. 6(b), Fig. 6(c) and Fig. 6(d) represent the result of effective permeability, effective permittivity and refractive index respectively for proposed

unit cell structure using Rogers RT6010.

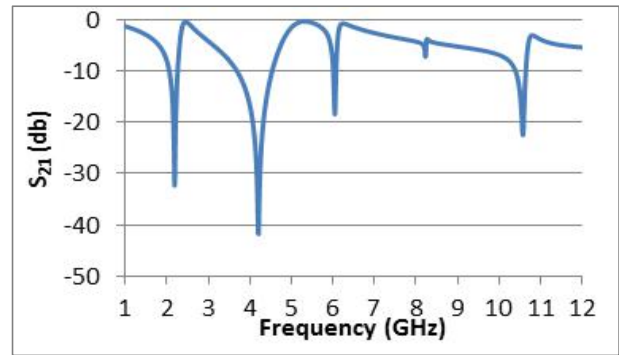


Figure 6(a). Simulated result of S_{21} in dB for using Rogers RT6010

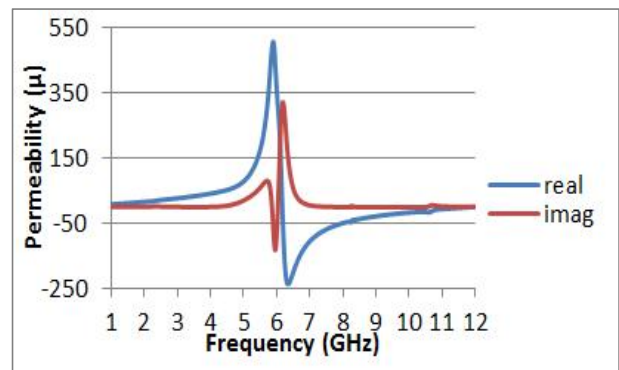


Figure 6(b). Effective permeability

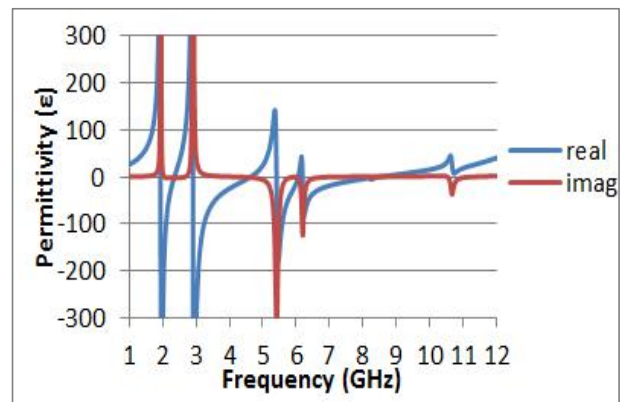


Figure 6(c). Effective permittivity

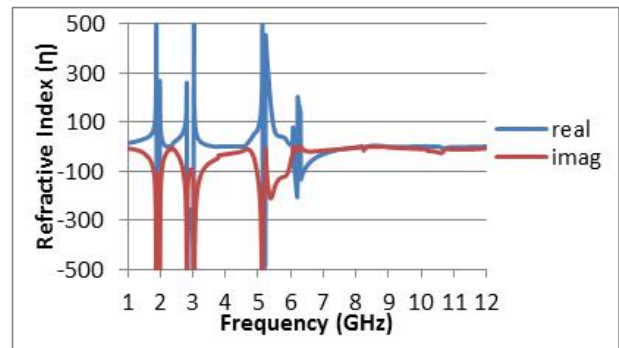


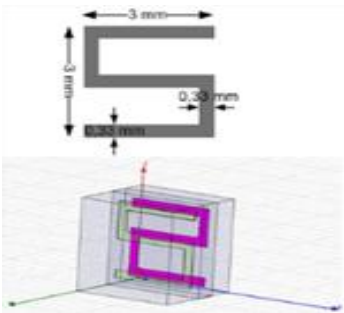
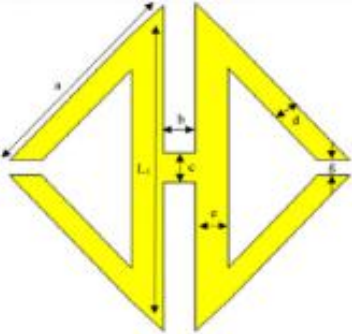
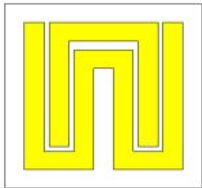


Figure 6(d). Refractive index

Fig. 6(b) expresses negative permeability from 6.181 GHz to 12 GHz. Fig. 6(c) shows the negative permittivity from 1.946 to 2.342 GHz, 2.914 to 4.63 GHz, 5.422 to 6.06 GHz and 6.192 to 8.546 GHz. Fig. 6(d) shows negative the refractive index from 1.891 to 1.979 GHz, 2.21 to 2.243 GHz, 2.826 to 3.024 GHz, 3.695 to 3.871 GHz, 4.267 to 4.52 GHz, 5.147 to 5.224 GHz, 6.082 to

6.203 GHz, 6.313 to 8.359 GHz, 8.92 to 9.91 GHz and 10.515 to 11.923 GHz. Hence the proposed unit cell acts as a negative refractive index metamaterials from 6.192 to 6.203 GHz, 6.313 to 8.139 GHz and 8.249 to 8.359 GHz where all the parameters are negative. Some previous design are given with frequency range and proposed combined WU-shape in Table 2.

Table 2. Comparison of the frequency of NRI among the some different designed metamaterial unit cell

Reference	Design	Frequency range of NRI	Band
A. Sethi [15]		2.5 G to 4.9524 GHz	S-band & X-band
R. A. Shelby [16]		10.05 to 10.95 GHz	X-band
H. Benosman [2]		15.67 to 17.43 GHz	Ku-band
M. J. Alam [17]		8.31 to 15.43 GHz and 17.43 to 18 GHz	X-band & Ku-band
New proposed design		7.391 to 8.689 GHz & 8.799 to 10.328 GHz	C-band & X-band

In Table 3, it is shown that the frequency ranges at which the effective permittivity, effective permeability and refractive index all three parameters are negative. The electric field and magnetic field of the material oscillate like sinusoidal shape when electromagnetic wave propagates through that material and its velocity depends on the electrical conductivity of the material which depends on the internal structure of that material. The relative speed of the electric signal passing through the material is changed according to the type of the interaction with internal structure. The transmission characteristics result depends on the changing of the electrical signal.

It is seen from the Table 3 that the proposed metamaterial shows NRI property in C-and X-band with different dielectric materials. It also holds the frequency band with increasing permittivity. Moreover, increasing bandwidth of NRI is found with increasing permittivity of dielectric materials.

Table 3. Frequency range of NRI metamaterials using three different substrates

Substrate	Permittivity	NRI Frequency (GHz)	Band
FR-4	4.3	7.391 – 8.689, 8.799 – 10.328	C, X
Rogers RT6006	6.15	6.555 – 7.501, 7.655 – 9.393	C, X
Rogers RT6010	10.2	6.192 – 6.203, 6.313 – 8.139, 8.249 – 8.359	C, X

5. Conclusions

The new designed metamaterial unit cell using different substrate materials exhibits the index of negative refraction (η) in certain area of C and X-band. This proposed NRI metamaterial unit cells using substrate materials FR-4, Rogers RT6006 and Rogers RT6010 cover C-band which band is used in far range radio communications and also covers X-band which is used in satellite communications, radar system and radio communication also. However, the material unit cell also reveals better effective medium ratio with increasing relative permittivity which ensures the materials proper operation and sensitivity for any applications. These properties make this new metamaterial unique and potential for electromagnetic paradigm.

REFERENCES

- [1] V. G. Veselago. The electrodynamics of substances with simultaneously negative values of ϵ and μ , *Soviet Physics Uspekhi*, Vol. 10, No. 4, 509-514, 1968.
- [2] H. Benosman and N. B. Hacene. Design and simulation of double "S" shaped metamaterial, *International Journal of Computer Science Issues (IJCSI)*, Vol. 9, No. 1, 534-536, 2012.
- [3] S. S. Islam, M. R. I. Faruque and M. T. Islam. Design and analysis of a new double negative metamaterial. *Journal of Microelectronics, Electronic Components and Materials*, Vol. 44, No. 3, 218-223, 2014.
- [4] S. S. Islam, M. R. I. Faruque and M. T. Islam. An Object-Independent ENZ Metamaterial-Based Wideband Electromagnetic Cloak. *Scientific Reports* 6, 33624; doi: 10.1038/srep33624 (2016).
- [5] S. S. Islam, M. R. I. Faruque, M. T. Islam, T. Alam. A new mu-negative metamaterial, *Proceedings of 2nd International Conference on Electrical Information and Communication Technology (EICT)*, 269-272, 2015.
- [6] J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs. Extremely low frequency plasmons in metallic mesostructures, *Physical Review Letters*, Vol. 76, No. 25, 4773-4776, 1996.
- [7] D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith. Metamaterial electromagnetic cloak at microwave frequencies, *Science*, Vol. 314, 977-980, 2006.
- [8] R. A. Shelby, D. R. Smith, and S. Schultz. Experimental verification of a negative index of refraction, *Science*, Vol. 292, 77-79, 2001.
- [9] J. D. Baena, R. Marques, F. Medina, and J. Martel. Artificial magnetic metamaterial design by using spiral resonators, *Physical Review B*, Vol. 69, 0144021-0144025, 2004.
- [10] M. R. I. Faruque and M. T. Islam. Novel design of triangular metamaterial for electromagnetic absorption in human head, *Progress in Electromagnetics Research*, Vol. 141, 463-478, 2013.
- [11] H. Chen, J. Huangfu, L. Ran, X. Zhang, and K. Chen. Left-handed materials composed of only S-shaped resonators, *Physical Review E*, Vol. 70, 0576051-0576054, 2004.
- [12] B. Gallas, K. Robbie, R. Abdeddaïm, G. Guida, J. Yang, J. Rivory, and A. Priou. Silver square nanospirals mimic optical properties of U-shaped metamaterials, *Optics Express*, Vol. 18, No. 16, 16335-16344, 2010.
- [13] E. Ekmekci and G. Turhan-Sayan. Investigation of permittivity and permeability for a novel V shaped metamaterial using simulated S parameters, *Proceedings of 5th International Conference on Electrical and Electronics Engineering*, 2007.
- [14] S. S. Islam, M. R. I. Faruque and M. T. Islam. A new direct retrieval method of refractive index for the metamaterial, *Current Science*, Vol. 109, No. 2, 337-342, 2015.
- [15] A. Sethi and R. Rajni. Determination of electromagnetic parameters of a new metasurface comprising of square loop, *Journal of Engineering Science and Technology*, Vol. 13, No. 1, 048 – 057, 2018.
- [16] R. A. Shelby, D. R. Smith, S. C. Nemat-Nasser, and S. Schultz. Microwave transmission through a two-dimensional, isotropic, left-handed metamaterial, *Applied Physics Letters*, Vol. 78, No. 4, 489- 491, 2001.
- [17] M. J. Alam, M. R. I. Faruque, R. Azim, and M. T. Islam. Depiction and analysis of a modified H-shaped double-negative meta atom for satellite communication, *International Journal of Microwave and Wireless Technologies*, Vol. 10, No. 10, 1-11, 2018.