A new double ш-shaped compact negative refractive index metamaterial for wideband applications

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Article Info	ABSTRACT
	This paper analyzed the new compact design and negative refractive index (NRI) metamaterial for wideband applications. The proposed metamaterial exhibits NRI and wideband characteristics of the x-axis wave propagation. It displayed the NRI property at the frequency of 1.54 GHz and wideband from 1.26 GHz to 7.08 GHz frequency (L, S, and C band). Moreover, the response of the 1×2 horizontal and 2×1 vertical array structure showed the wideband frequency in the 7.17 GHz to 13.62 GHz and 1.46 GHz to 9.53 GHz, respectively. Electromagnetic simulation software called CST has been used to design the metamaterial unit cell. The metamaterial has been displayed the multi-band characteristics such as L, S, C, X and K_u bands with negative index material properties.

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1. INTRODUCTION

Metamaterial is an engineered material structure that has some unique electromagnetic properties that not found in the nature. Thus, metamaterials are artificially constructed that called left-handed metamaterials. They can exhibit the negative permittivity ($\varepsilon < 0$), negative permeability ($\mu < 0$) and the negative refractive index, Snell's law, etc. In 1968, Russian scientist Victor Veselago first time explained about this material property. It had some different properties compared with the conventional materials [1]. Almost 30 years later, in 2000 Smith et al. [2] practically demonstrated a composite material with negative metamaterial characteristics. These unique characteristic materials can be used in more important fields, namely sensor design, EM absorption, SAR reduction, filter design, antenna design, and invisibility cloaking operation. A metamaterial is called double-negative (DNG) material when the effective permittivity (ε) and permeability (μ) are negative. If any of them of permittivity and permeability is negative, then the material called single negative (SNG) material. Some unit cell structure with metamaterial properties and double band electric atom with double split ring resonators are explained in literature [3-5]. There are some metamaterials structures have been proposed such as, Malik et al. with 25×25 mm^2 rectangular "U-shape" metamaterial that can display double negative properties for the various array structures [6].

Hossain et al. suggested a meta-atom, the dimention of the meta-atom was $12 \times 12 \times 1.6$ mm^3 with EMR (10.55) [7]. Zhou et al. designed a "double Z-Shape" metamaterial structure with double negative properties and the dimension of 8.5×8.5 mm^2 whereas the EMR was 4.80 [8]. Islam et al. suggested an "H shape" metamaterial structure with the size of 30×30 mm^2. This structure was shown the NRI properties at 0.5 GHz and 0.3 GHz frequency with small EMR (3.65) [9]. Rizwan et al. designed an "F-shape" metamaterial structure with NRI that were applicable of K and K_u bands [10]. Zhou et al. designed an

"S-shape" chiral metamaterial. The dimension of the metamaterial was 15×15 mm^2 with X and K$_u$ band application [11]. Hossain et al. proposed a modified multiple hexagonal unit cell structure. The dimension of the structure was $11 \times 10 \times 1.6$ mm^3 and the EMR was 13.84 [12]. Hossain et al. designed a "G-Shape" a new wideband double negative metamaterial and the dimension was $12 \times 12 \times 1.6$ mm^3 whereas the EMR was 11.90 [13]. Hasan et al. proposed a "Modified Z-shape" double-negative miniaturized metamaterial for wideband operation. The dimension of the structure was $10 \times 10 \times 1.6$ mm^3 and the EMR was 3.98 [14]. Abhishek et al. designed dual band metamaterial unit-cell structure with dimension was $7.5 \times 7.5 \times 0.787$ mm^3 and the EMR was 7.14 [15]. Hossian et al. proposed a "double C-shape" metamaterial structure dimension of $12 \times 12 \times 1.6$ mm^3 and the EMR was 9.62 [16]. Abbott et al. designed a compact capacitive loading design to improve the effective medium ratio [17]. In 2010 Fabio Urbani et al. proposed a "diamond-shaped" metamaterial unit-cell for X-band only and the EMR was too small 1.2 [18]. Karamanos et al. designed a compact double negative metamaterial unit cell with EMR 6.9 [19]. Nabila Abdul Jaffar et al. designed a metamaterial-base antenna for non-invasive hyperthermia cancer treatment [20]. Bashar et al. proposed a dual band modified split square resonator metamateraial structure [21]. Adamu et al. designed a metamaterial antenna employing SSR and CSRR for WLAN application [22]. Hossain et al. designed a "combination of double T- and double U-shaped split ring resonators with square split ring resonator" metamaterial in the microwave range, whereas the size of the published design structure was $10.5 \times 12 \times 1.6$ mm^3 that was large compared to proposed design structure [23].

In this paper, the design of "double Ш- shaped" with a split square resonator metamaterial unit cell structure exhibits the multi-band characteristics of L, S, C, X and K$_u$ bands with wideband frequency of 1.26 GHz to 7.08 GHz (5.62 GHz), 7.17 GHz to 13.62 GHz (6.45 GHz), 1.46 GHz to 9.53 GHz (8.07 GHz) for the X-axis wave propagation. The different types of array structure such as 1×2 horizontal, and 2×1 vertical were described in this paper. The proposed compact design of metamaterial unit cell also displayed the negative refractive index properties at 1.53 GHz, 1.68 GHz, 6.16 GHz, 6.045 GHz resonance frequencies. In this paper, the size of the suggested unit cell structure is $9.6 \times 9.6 \times 1.6$ mm^3, which is more compact than the reference metamaterial structure with the terms of EMR (20.29). Electromagnetic simulation software called CST has been used to design the metamaterial unit cell structure for multi-band application.

2.   DESIGN AND METHODOLOGY

The NRI metamaterial unit cell is a two-layer copper substance with "double Ш-shape" and split square resonator printed on the FR4 lossy material substrate. The dimension of the substrate is $9.6 \times 9.6 \times 1.6$ mm^3 and thickness of 0.035 mm with permittivity, $\varepsilon = 4.3$, permeability, $\mu = 1$, and loss tangent, $\delta = 0.025$. The metamaterial unit cell's parameters are L = 9 mm, W = 9 mm, W$_1$ = 0.5 mm, W$_2$ = 0.5 mm, W$_3$ = 0.5 mm, L$_1$ = 5.8 mm, L$_2$ = 7 mm g$_1$ = 0.4 mm, g$_2$ = 0.4 mm, g$_3$ = 0.6 mm, g$_4$ = 0.5 mm.

In this paper, electromagnetic simulation software called CST has been utilized to obtain the NRI and wideband properties of the metamaterial unit cell structure. The structure is placed in between the positive and negative waveguide ports along the X-axis wave propagation to execute the NRI and the wideband operation where Y-axis and Z-axis represent perfect electric conductor (PEC) and perfect magnetic conductor (PMC) respectively for boundaries. To simulate S-parameters, a frequency domain solver is used where 1001 sample frequencies have been taken. The simulation was performed between the frequency ranges of 1GHz to 15GHz. The proposed metamaterial unit cell's formation diagram is shown in Figure 1.
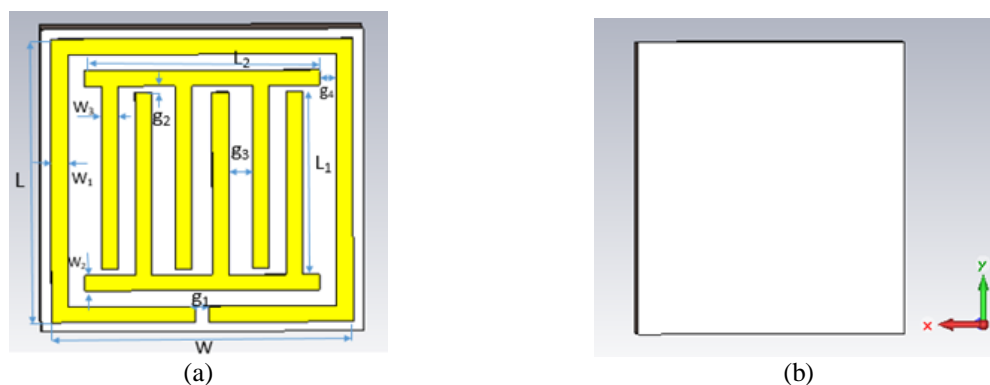

| (a) | (b) |

Figure 1. The sketch diagram of the proposed unit cell structure, (a) Front side, (b) Back side

3.   RESULTS AND DISCUSSION

Generally, Direct-Retrieval method [24], Direct Refractive Index method and the Nicolson-Rose-Weir (NRW) method are used to extract the effective parameters [25]. In this case, both (real and imaginary) values of permittivity (ε), permeability (μ) and refractive index (n) are determined from the simulated complex S-parameters such as reflection coefficient (S_{11}) and transmission coefficient (S_{21}). This paper analyzes the X-axis wave propagation and the different types of array structure such as 1×2 horizontal and 2×1 vertical array respectively.

3.1.   Analysis of EM wave propagation for the X-axis

The metamaterial unit cell structure is between the positive and negative waveguide ports along the X-axis wave propagation where Y-axis and Z-axis represent perfect electric conductor (PEC) and perfect magnetic conductor (PMC) respectively for boundaries. Figure 2(a) showed the simulated configuration and 2(b) showed the magnitude of S-parameters with X-axis wave propagation. The reflection coefficient (S_{11}) displays the maximum resonance at the 1.3 GHz and 7.13 GHz frequencies. Since the transmission coefficient (S_{21}), the maximum resonances at 1.54 GHz, 8.46 GHz, 12.33 GHz frequencies. Whereas the structure depicts the operation bands are L, S, C and X bands. Figure 3(a) and (b) display the effective permittivity and effective permeability with real and imaginary curves for X-axis wave propagation. Figure 3(a) shows the real value of negative permittivity from 1.38 GHz to 6.99 GHz, and 12.95 GHz to 14.98 GHz. The real value of negative permeability from 1.34 GHz to 1.46 GHz, 6.29 GHz to 7.13 GHz and 7.67 GHz to 13.94 GHz are shown in the Figure 3(b). Figure 3(c) exhibits the negative refractive index with both curves (real and imaginary) for the X-axis wave propagation. The real values of negative refractive index are indicated from 1.37 GHz to 6.99 GHz and 12.56 GHz to 14.04 GHz. The metamaterial unit cell exhibits the NRI property at 1.53 GHz and the wideband at the frequencies of 1.26 GHz to 7.08 GHz (5.62 GHz bandwidth).
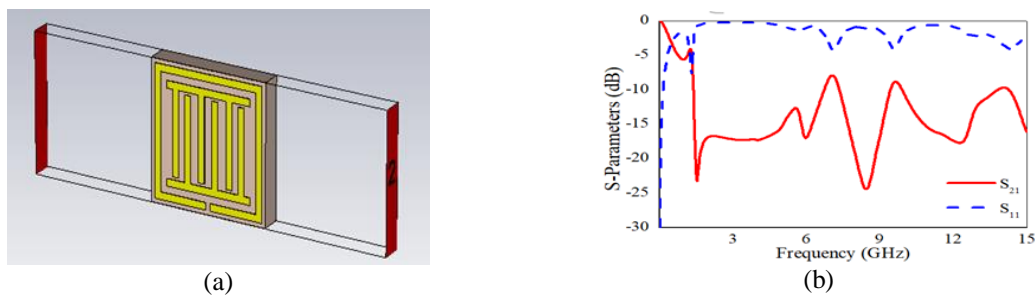

| (a) | (b) |

Figure 2. (a) Simulation setup, (b) Numerical S-parameters
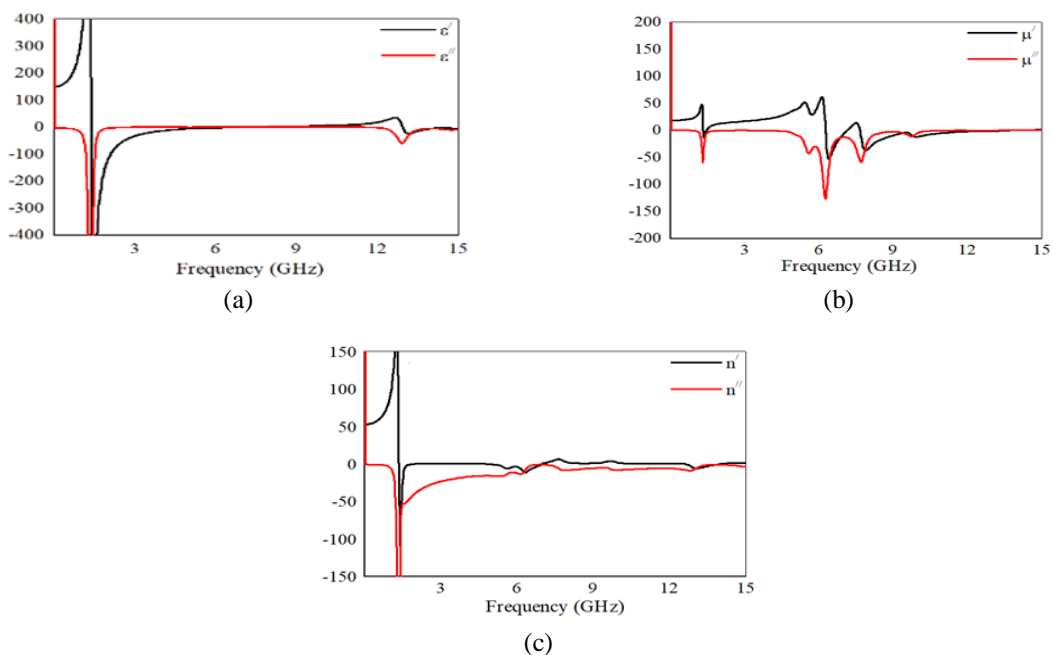

| (a) | (b) |

(c)

Figure 3. Real and imaginary curve of (a) Effective permittivity, (b) Effective permeability,
(c) Effective refractive index for the X-axis wave propagation

3.2. Analysis of 1×2 horizontal array of the metamaterial unit cell structure

Figure 4(a) shows simulation setup for 1×2 horizontal array which is formed in the same substrate as basic unit cell structure and Figure 4(b) displays the numerical S-parameters in 1×2 horizontal array structure. The reflection coefficient (S_{11}) displays the maximum resonance frequencies at 1.13 GHz and 9.42 GHz. The maximum peak of the resonance frequencies are 1.53 GHz, 6.07 GHz, and 10.86 GHz in the transmission coefficient (S_{21}). The applicable bands are L, S, C, X and K_u bands. Figure 5(a) and 5(b) represents the effective permittivity and effective permeability with real and imaginary curves for 1×2 horizontal array structure. In the Figure 5(a), the real values of negative permittivity from 0.84 GHz to 6.51 GHz, 7.17 GHz to 7.35 GHz and 13.41 GHz to 15 GHz are illustrated. Figure 5(b) shows the real value of the negative permeability of 1.07 GHz to 1.32 GHz, 6.95 GHz to 14.1 GHz and Figure 5(c) exhibits the negative refractive index with the real and imaginary curves for the 1×2 horizontal array. The real values of the relative negative refractive index of 0.96 GHz to 1.3 GHz, 1.53 GHz to 5.01 GHz, 5.91 GHz to 6.29 GHz, 6.98 GHz to 8.27 GHz, 9.36 GHz to 9.62 GHz, 10.59 GHz to 11.37 GHz and 13.26 GHz to 14.27 GHz. The structure of the 1×2 horizontal array exhibits the NRI resonant at 6.05 GHz and the wideband of 7.17 GHz to 13.62 GHz (6.45 GHz bandwidth).
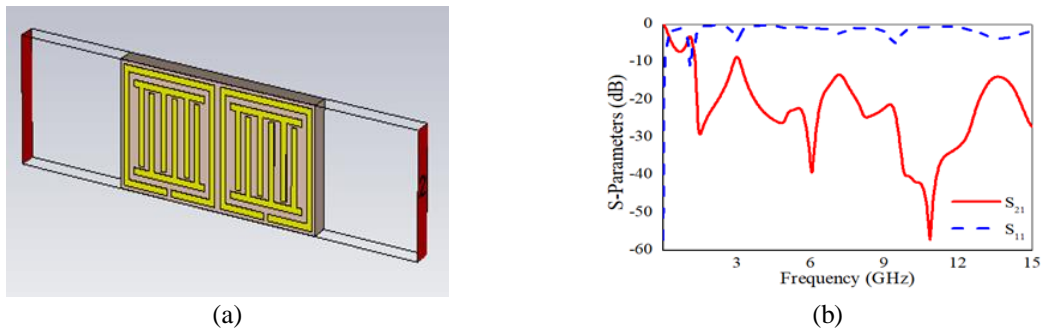

(a)　　　　　　　　　　　　　　(b)

Figure 4. (a) Simulation setup for 1×2 horizontal array,
(b) Numerical S-parameters in 1×2 horizontal array structure
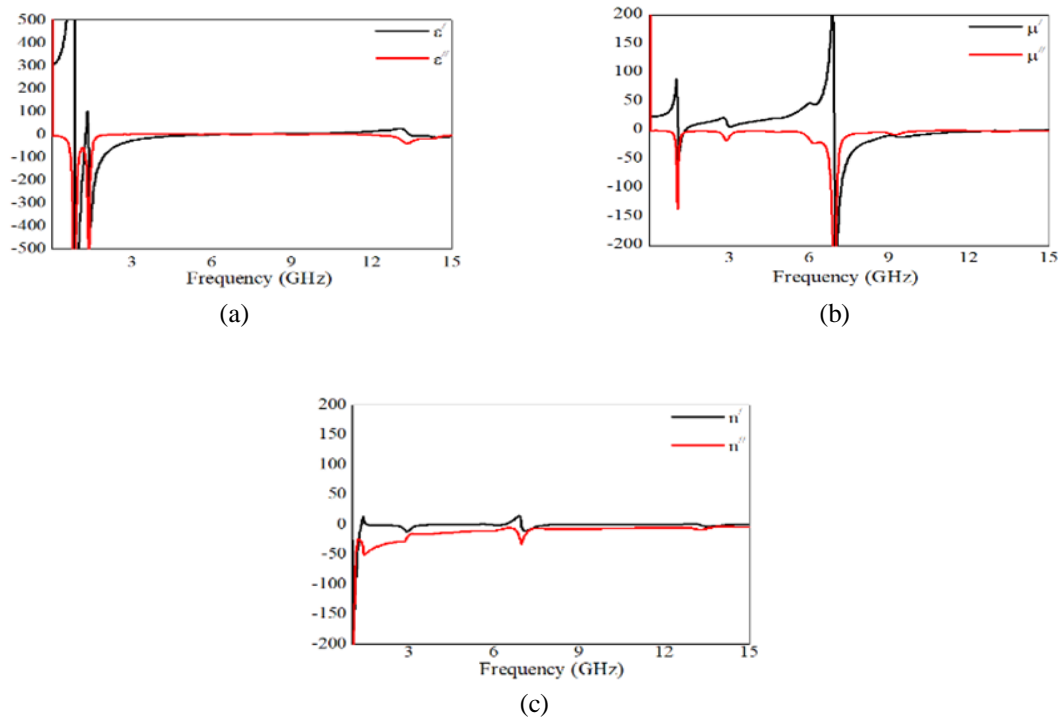

(a)　　　　　　　　　　　　　　(b)

(c)

Figure 5. Real and imaginary curve of (a) Effective permittivity, (b) Effective permeability,
(c) Effective refractive index for the 1×2 horizontal array

3.3. Analysis of 2×1 vertical array of the metamaterial unit cell structure

Figure 6(a) indicates the simulation arrangement for 2×1 vertical array which is formed in the same substrate. Figure 6(b) shows the numerical S-parameters in the 2×1 vertical array structure. The reflection coefficient (S_{11}) displays the maximum deep of the resonance at 1.33 GHz and 9.49 GHz. The maximum deep of the resonance frequencies at 1.69 GHz, 7.56 GHz, and 12.09 GHz in the transmission coefficient (S_{21}). However, the represented bands are L, S, C, X and K_u bands. Figure 7(a) and 7(b) demonstrates the effective permittivity and effective permeability with real and imaginary curves. The real values of negative permittivity from 1.37 GHz to 6.98 GHz, 12.96 GHz to 15 GHz are shown in Figure 7(a). Figure 7(b) exhibits the real values of the negative permeability of 1.49 GHz to 1.58 GHz, 6.45 GHz to 6.95 GHz and 7.26 GHz to 13.95 GHz. Figure 7(c) represents the negative refractive index with both curves (real and imaginary) for the 2×1 vertical array. The real values of the relative negative refractive index of 1.39 GHz to 2.88 GHz, 3.05 GHz to 6.99 GHz, 12.47 GHz to 14.01 GHz. The structure of the 2×1 vertical array exhibits the NRI property at 1.68 GHz and the wideband of 1.46 GHz to 9.53 GHz (8.07 GHz bandwidth). Comparison among previous configurations and proposed configurations as shown in Table 1.
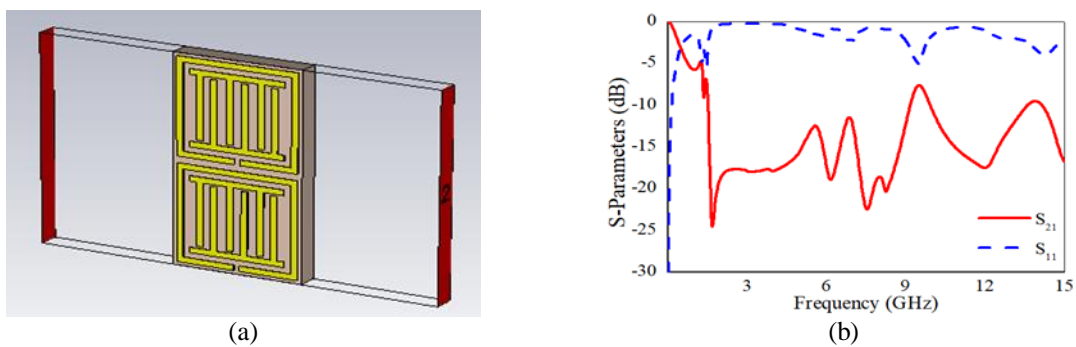

(a)   (b)

Figure 6. (a) Simulation setup, (b) Numerical S-parameters curve of 2×1 horizontal array structure

(a)   (b)
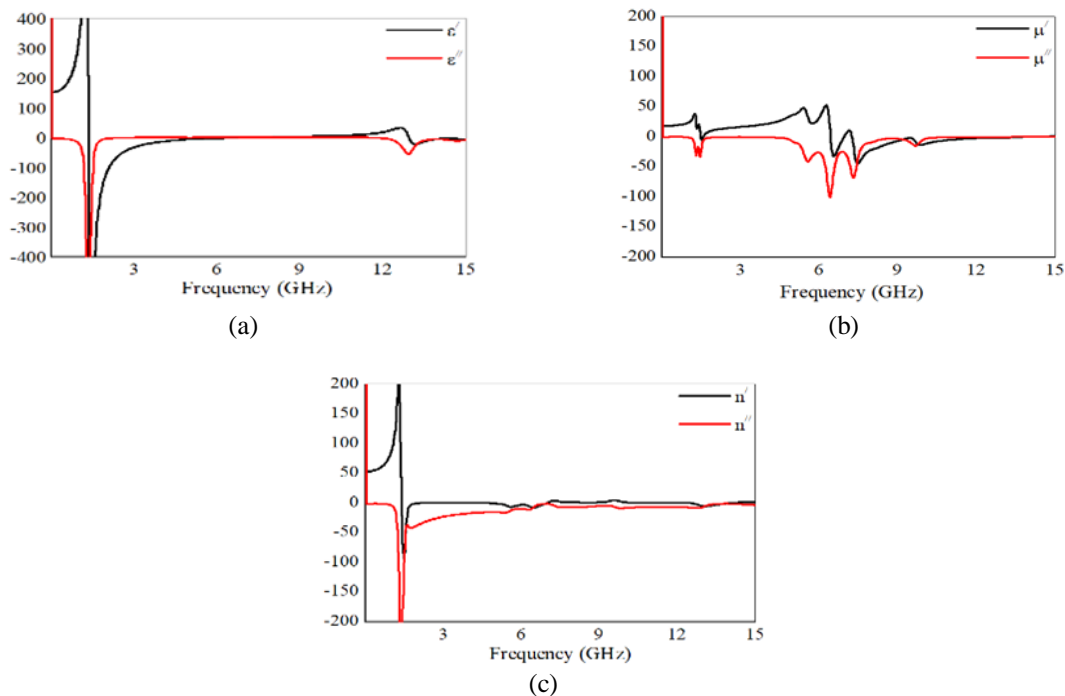

(c)

Figure 7. Real and imaginary curve of (a) Effective permittivity, (b) Effective permeability,
(c) Effective refractive index for the 2×1 vertical array

Table 1. Comparison among previous configurations and proposed configurations

Author's name	Dimension (mm³)	Applicable band	Unit-cell shape	Metamaterial type	EMR	Year
Islam et al. [9]	30×30×1.6	(2-15) GHz	H -shape	LHM	3.65	2014
Hossain et al. [13]	12×12×1.6	(0.5-6) GHz	G-shape	NIM	11.90	2015
Zhou et al. [8]	8.5 × 8.5	(6-12) GHz	Double Z shape	LHM	4.80	2015
Hasan et al. [14]	10×10×1.6	(2-14) GHz	Modified Z	SNM	3.98	2016
Hossain et al. [7]	12×12×1.6	(1-15) GHz	Double C	NIM	10.55	2017
Hossain et al. [12]	11×10×1.6	(1-18) GHz	Modified Hexagonal	LHM	13.84	2018
Proposed unit cell	9.6×9.6×1.6	(1-15) GHz	Double Ш	NIM	20.29	---

4. CONCLUSION

The proposed double Ш-Shaped compact metamaterial unit cell structure designed on FR4 substrate material for NRI and wideband operation. It showed the NRI property at 1.54 GHz resonance frequency and 5.62 GHz bandwidth for X- axis wave propagation. Moreover, the analysis on 1×2 horizontal and 2×1 vertical array structure respectively exhibited the wideband of 6.45 GHz (7.17 GHz to 13.62 GHz) and 8.07 GHz (1.46 GHz to 9.53 GHz) that indicated L, S, C, X, and K_u bands. This metamaterial unit cell structure displayed the higher EMR (20.29) compare to the mentioned metamaterial unit cell design structure. Electromagnetic simulation software called CST was been utilized to analysis the metamaterial unit cell structure. The proposed metamaterial is applicable for satellite communications, GPS, radar, long distance radio telecommunications, military telemetry, mobile phones (GSM).

REFERENCES

[1] V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ," *Soviet Physics Uspekhi*, vol. 10, no. 4, pp. 509-514, 1968.

[2] D. R. Smith, et al., "Composite medium with simultaneously negative permeability and permittivity," *Physical Review Letters*, vol. 84, p. 4184, 2000.

[3] A. Sarkhel, et al., "A compact metamaterial with multi-band negative-index characteristics," *Applied Physics* A, vol. 122, pp. 1-10, 2016.

[4] B. Zarghooni and T. A. Denidni, "New compact metamaterial unit-cell using SIR technique," *IEEE Microwave and Wairless Components Letters*, vol. 24, no. 5, pp. 315-317, 2014.

[5] J. D. Baena, et al., "Equivalent-circuit models for split-ring resonators and complementary split-ring resonatorscoupled to planar transmission line," *IEEE transections on Microwave Theory Techniques*, vol. 53, no. 4, pp. 1451-1461, 2005.

[6] A. Malik, et al., "Design of a novel two rectangular U-shaped double negative metamaterial," in *International conference on Informatics, Electronics and Vision (ICIEV)*, Dhaka, Bangladesh, pp. 1-6, 2013.

[7] M. J. Hossain, et al., "An effective medium ratio obeying meta-atom for multiband applications," *Bulletin of the polish academy of sciences technical science*, vol. 65, no. 2, pp. 139-147, 2017.

[8] H. Zhou, et al., "A novel double-incidence and multi- band left-handed metamaterials composed of double Z-shaped structure," *Journal of Materials Science: Materials in Electronics*, vol. 27, pp. 2534-2544, 2016.

[9] S. S. Islam, et al., "The design and analysis of a novel split-H-shaped metamaterial for multi-band microwave application," *Materials*, vol. 7, pp. 4994-5011, 2014.

[10] M. Rizwan, et al., "Dual-band tunable negative refractive index metamaterial with F-Shape structure," *Central European Journal of Physics*, vol. 12, pp. 578-581, 2014.

[11] Z. Zhou and H. Yang, "Triple-band asymmetric transmission of linear polarization with deformed S-shape bilayer chiral metamaterial," *Appled Physics A*, vol. 119, pp. 115-119, 2015.

[12] M. J. Hossain, et al., "Effective medium ratio obeying wideband left-handed miniaturized meta-atoms for multi-band applications," *Journal of Electronic Materials*, vol. 47, pp. 1859-1870, 2018.

[13] M. I. Hossain, et al., "A New Wide-Band Double-Negative Metamaterial for C- and S-Band Appli- cations," *Materials*, vol. 8, pp. 57-71, 2015.

[14] M. M. Hasan, et al., "A new compact double-negative miniaturized metamaterial for wideband operation," *Materials*, vol. 9, no. 10, p. 830, 2016.

[15] A. Sarkhel, et al., "A compact meta-atom for dual band negative permittivity metamaterial," *Microwave and Optical Technology Letters*, vol. 57, no. 5, pp. 1152-1156, 2015.

[16] M. J. Hossain, et al., "A new miniaturized negative-index meta-atom for tri-band application," *Open physics*, vol. 15, no. 1, pp. 464-471, 2017.

[17] W. Withayachumnankul, et al., "Compact electric-LC resonators for metamaterials," *Optics Express,* vol. 18, no. 25, pp. 25912-25921, 2010.

[18] F. Urbani, "Experimental analysis of novel single-sided lefthanded metamaterial," *IEEE Antennas and Wireless Propagation Letters,* vol. 9, pp. 720-723, 2010.

[19] T. D. Karamanos, et al., "Compact double-negative metamaterials based on electric and magnetic resonators," *IEEE Antennas and Wireless Propagation Letters,* vol. 11, pp. 480-483, 2012.

[20] N. A. Jaffar, et al., "An overview of available metamaterial-based antenna for non-invasive hyperthermia cancer treatment," *Indonesian Journal of Electrical Engineering and Computer Science,* vol. 14, no. 2, pp. 697-705, 2019.

[21] B. A. F. Esmail, et al., "Dual band low loss metamaterial structure at millimetre wave band," *Indonesian Journal of Electrical Engineering and Computer Science,* vol. 15, no. 2, pp. 823-830, 2019.

[22] A. Y. Iliyasu, et al., "Wideband frequency reconfigurable metamaterial antenna employing SSR and CSRR for WLAN application," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 15, no. 3, pp. 1436-1442, 2019.

[23] M. J. Hossain, et al., "A new double T-U-shaped biaxial compact double-negative meta-atom for multiband applications," *Microwave and Optical Technology Letters*, vol. 59, no. 10, pp. 2551-2557, 2017.

[24] S. S. Islam, et al., "A new direct retrieval method of refractive index for the metamaterial," *Current Science,* vol. 109, no. 2, pp. 337-342, 2015.

[25] A. M. Nicolson and G. F. Ross, "Measurement of the intrinsic properties of materials by time-domain techniques," *IEEE Transections on Instrumentation and Measurement,* vol. 19, no. 4, pp. 377-382, 1970.

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