Design and Development of Novel Nut-shaped SRR unit cell and analysis of DNG property

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ABSTRACT: This paper presents design and development of a novel Nut-shaped Metamaterial Split Ring Resonator as a unit cell. Metamaterials with negative permittivity and permeability play a crucial role in improving the antenna performance. The unit cell comprises of two Split Ring Resonator with a thin transmission line connecting them. This structure measures a size 12 mm x 12 mm on the FR4 substrate of 16 mm x 16 mm x 1.6 mm. The shape of the unit cell developed in this work has been evolved using nature-inspired fractal geometries on a FR4 substrate. The simulation in the frequency range 2-4 GHz and the retrieval of negative medium properties have been carried out using HFSS 18.2 and MATLAB respectively. The fabrication and experimental verification have also been performed. Using the transmission S_{21} and reflection S_{11} properties the double negative medium properties have been studied using both the Nicholson-Ross-Weir as well as the Transmission-Reflection methods. Comparison of simulation and experimental results of both the methods exhibit the existence of negative medium properties of the unit cell within the selected frequency range. The proposed unit cell exhibits the Effective medium ratio value of 8.16 and 7.45 at 3.06 GHz and 3.35 GHz. This type of DNG SRR unit cell is recommended for Electromagnetic Energy harvesting applications.

INDEX TERMS Double Negative, Effective Medium Ratio, Energy Harvestment, Fractal, Metamaterial, Negative medium property, Nicholson-Ross-Weir, Split Ring Resonator, Transmission-Reflection, Unit cell.

I. INTRODUCTION

A unique idea of fractal shape is imbibed into metamaterial (MTM) to bring novelty to the area of metamaterial research. Catering to wideband applications, Fractal-MTM (F-MTM) [1] plays a crucial role. The Electromagnetic Metamaterial (EM-MTM) shows a dual nature of resonant and non-resonant. The periodicity of the former is equivalent to $\lambda/10$ and later has a period $< \lambda$ and thus have no oscillation or scatter while the former is gifted with atomic resonance. Usually for broadband applications as mentioned by Bin Zheng et.al [2] non-resonant MTMs are preferred as they have a wide field of view, operates in subwavelengths, and are flexible to structural changes with appreciable tolerance. Resonant MTMs are generally Left-Hand MTMs (LHM).

The compromise between gain and bandwidth leads to antenna miniaturization and this is a constraint for RF energy harvesting applications. The primary requirement for this application is high-performance gain and radiation pattern. So, keeping aside miniaturization, adopting a fractal shape in antenna design can be a solution of one kind. In 1983, Mandelbrot [3] introduced a fractal concept and it played a key role in antenna size reduction with gain performance and multi–resonance.

Veselago [4] conceived the MTM concept, wherein he proposed that the materials can be artificially manipulated to create negative permeability and permittivity at specific frequencies which was defined as Double Negative (DNG) material. Lately, in 2000, this concept was again rejuvenated by John Pendry [5]. The MTM structures are a boon to antenna research because of their capability to improve antenna performances in various ways. MTM unit cells can be loaded on a patch, can be used as a DGS (Defected Ground Structures), and arrays of MTM unit cells can be used as a Frequency Selective surface (FSS), Artificial Magnetic Conductor (AMC), or as metasurface depending on the requirement and applications. This author in 2022 worked on an MTM ring [6] acquiring a novel fractal pattern known as Inverse Hilbert. Altaf Hussain et.al studied parallel Double-E square split resonators [7] for multi-band applications having double negative (DNG) properties and their investigation is executed thoroughly.

The future of antenna research will demand wider bandwidths [10]. The proposed MTM unit cell is improving antenna performance in terms of gain and bandwidth and other antenna parameters as well. The usage of MTM in MSA can also be a reason for bandwidth widening too as proposed by Imen Sansa et.al in their novel MTM unit cell [9] for 5G applications in comparison to conventional SRR. In this paper, the performance of the unit cell in the wave port is analyzed. The simulation and measured results are compared. The proposed MTM unit cell characteristics are attained in TEM mode. This Nut-shaped MTM (N-MTM) split ring shows Double Negative characteristics (DNG) (MNG) in 2-4 GHz range and can be exploited for MSA in wideband applications.

II THE UNIT CELL DESIGN

The MTM geometrical changes result in property changes, the proposed novel unit cell design is shown in Fig 1. This Nut-shaped MTM has two hexagonal nut-shaped rings with splits of 0.5mm supported by a metal strip. The resonators are in blue metalized on the FR4 epoxy as a dielectric substrate having a 4.4 dielectric constant. The metal rings attached to the metal bar show inductive properties and the splits in the ring will show capacitive properties.

The outer portion of the ring is a hexagonal shape and the inner one is circular. The proposed MTM pattern is inspired by a fractal shape representing the branching of two metal rings from a single metal bar. The inner radius of the ring is 2.5 mm and the width of the metal bar is 1mm. The hexagonal ring has a split of 0.5 mm. The outer dimensions of rings vary due to their hexagonal shape and its width is 0.3 mm and 0.7 mm as mentioned in Table 1. The overall size of the unit cell is 16 mm x16 mm (length ×width). The substrate used is low-cost FR4 epoxy having 1.6 mm thickness. The metal portion is occupying 12 mm length out of 16 mm substrate. The overall dimension of the unit cell is a multiple of λ /4.

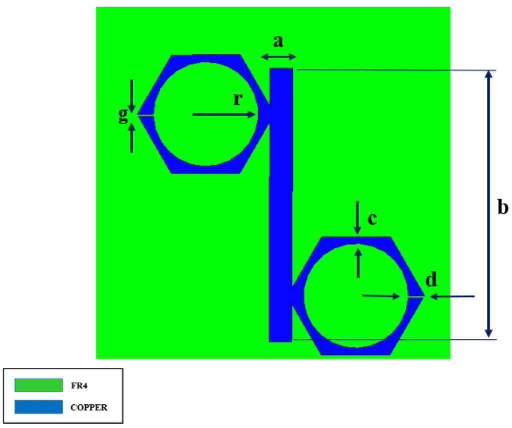


Fig 1 Metamaterial Unit Cell Structure top and bottom view

Table 1 shows dimensions and MTM parameters. The FR4 epoxy used has a dielectric constant of 4.4 and loss tangent tan δ = 0.02.

TABLE I. The MTM parameters specifications

Parameter	Dimension
Substrate (FR4)	16 mm x 16 mm x 1.6mm
a	1 mm
b	12 mm
c	0.3 mm
r	2.5 mm
d	0.7 mm
g	0.5 mm

III THE BOUNDARY CONDITIONS

The simulation is implemented using HFSS 18.2 simulation software. The simulation is done by placing the unit cell in a waveguide and applying boundary conditions–perfect electric on two side walls and perfect magnetic on the top and bottom portion.

The waveguide has two ends along the positive and negative z-axis and the unit cell is placed exactly at the center of the waveguide. The radio wave is passed along the z-axis. The placement of the unit cell and the applications of excitation must have a gap of more than λ /2 to avoid unwanted modes generated from the overlapping of the excited wave and unit cell.

The parameters retrieved in the proposed unit cell structure are S_{11} and S_{21} i.e. Transmission–Reflection coefficient which derives material properties in terms of epsilon (ε), mu (μ), and refractive index (RI). Two parametric retrieval mechanisms are adopted and comparative analysis is executed, one is the NRW method, and the second TR method. The NRW method is an effective parametric retrieval method.

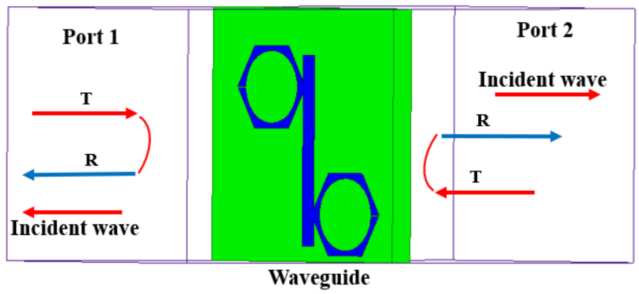


Fig 2. Boundary condition set up for proposed Nut-Shaped MTM unit cell

The detailed demonstration of boundary conditions applied on the unit cell is shown in Fig 2. The unit cell parametric analysis is done between 2-4 GHz. The NRW method [8,16-18] is an effective method to study material properties from the data extracted from simulation and S_{11} (Reflection coefficient) and S_{21} (Transmission coefficient) are represented using V_1 and V_2 and are measured as:

$$V_1 = S_{21} + S_{11} \tag{1}$$

$$V_2 = S_{21} - S_{11} \tag{2}$$

$$\varepsilon_r \approx \frac{C}{\pi jfd}\frac{1-V1}{1+V1} \tag{3}$$

$$\mu_r \approx \frac{C}{\pi jfd}\frac{1-V2}{1+V2} \tag{4}$$

Apart from the NRW method, the TR method can also be used to retrieve and study MTM properties to observe permeability (μ_r), permittivity (ε_r) and RI (n). The S_{11} and S_{21} are measured from the data extracted using the following equations [16-18]:

$$Z = \sqrt{\frac{(1+S_{11})^2 + S_{21}{}^2}{(1-S_{11})^2 + S_{21}{}^2}} \tag{5}$$

$$e^{jnkd} = \frac{S_{21}}{1-S_{11}\frac{z-1}{z+1}} \tag{6}$$

$$n = \frac{1}{kd}\{(\mathrm{Im}\,(\log e^{jnkd}) + 2m\pi) - j\,(\mathrm{Re}\,(\log e^{jnkd}))\} \tag{7}$$

$$\varepsilon_r = n \times z \tag{8}$$

$$\mu_r = n/z \qquad (9)$$

where, k = wave number, d= substrate thickness, z = characteristics impedance

Fig.3 represents the trace over between S_{11} and S_{21} in 2-4 GHz at different dimensions of nuts radii ranging from 2mm to 2.5 mm.

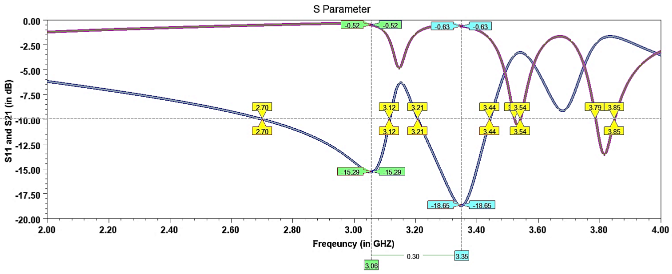


Fig. 3 Optimization of Nut-shaped MTM unit cell at different stages of radius change in the hexagonal ring (a) S_{11} variation as ring radius is changed from 2 mm to 2.5 mm (b) S_{21} variation as ring radius changed from 2 mm to 2.5 mm.

IV THE EQUIVALENT CIRCUIT MODEL FOR THE NUT-SHAPED MTM

The metallization of the proposed unit cell is mounted on a dielectric substrate and the dynamic electromagnetic wave strikes on this pattern of metal are energized to represent and unnatural material property. Fig.4 shows the equivalent circuit model of Nut-shaped MTM, wherein the circular rings with splits have capacitive effect and the metals running in a continuous pattern show inductive nature. The resonance at which the proposed structure operates is measured using:

$f = \frac{1}{2\pi\sqrt{L_{eq}C_{eq}}}$, where L= inductance and C= capacitance

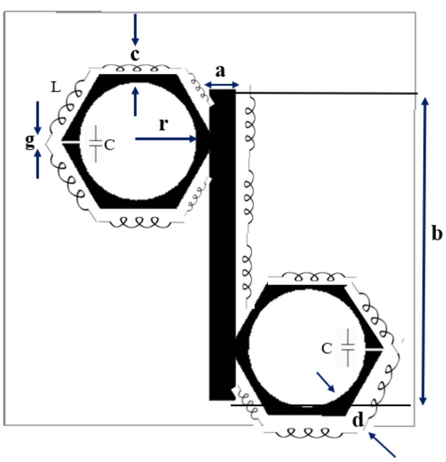


Fig. 4 Equivalent circuit parameters representation in proposed MTM unit cell

Since the split rings are hexagonal in shape and the continuous loop represents the inductance [21] is calculated using the transmission line principle:

$$L_{eq} = 0.01\mu_0\ \{\frac{2(h)^2}{(2w+h)^2}+\frac{\sqrt{(2w+h)^2+l^2}}{h}\}t \qquad (10)$$

The splits in the hexagonal ring exhibit capacitance [21] given by:

$$C = \varepsilon_0[\frac{2w+h}{2\pi(h)^2}\ \ln\{\frac{2(h)}{l}\}t \qquad (11)$$

where, $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m, $\mu_0 = 4\pi \times 10^{-7}$ H/m, a or w = unit cell width (12 mm), h = substrate thickness, t = metallization thickness=0.035 mm, and l = length of unit cell (12mm)

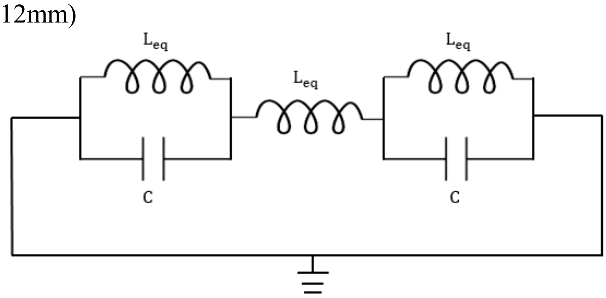


Fig. 5 Equivalent circuit model of proposed Nut-shaped MTM

V SIMULATIONS, EXCITATIONS AND RESULTS

The simulation and measured results underwent the NRW method and TR method to show DNG characteristics. The DNG property is observed between 2-4 GHz. The trace-over characteristics of scattering parameters S_{11} and S_{21} are shown in Fig 6. The excitation applied for this setup is wave-port. The unit cell is resonating at 3.06 GHz and 3.35 GHz as shown in Fig.6 which is a trace over of S_{11} and S_{21} characteristics. The return loss for S_{11} is -15.29 dB at 3.06 GHz and -18.65 dB at 3.35 GHz.

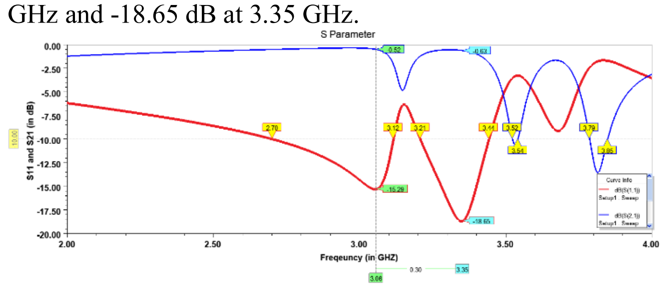


Fig.6 S_{11} and S_{21} characteristics graph showing trace over resonating between 2-4GHz

The simulation is implemented using HFSS 18.2 and MATLAB software. The graphs in Fig. 7 and 8 show material properties in terms of permeability (μ), permittivity (ε), and RI. The simulated graphs are analyzed from 2-4 GHz. The methodology applied is the NRW and the TR method. Fig 7 and 8 show that the proposed MTM unit cell has DNG characteristics.

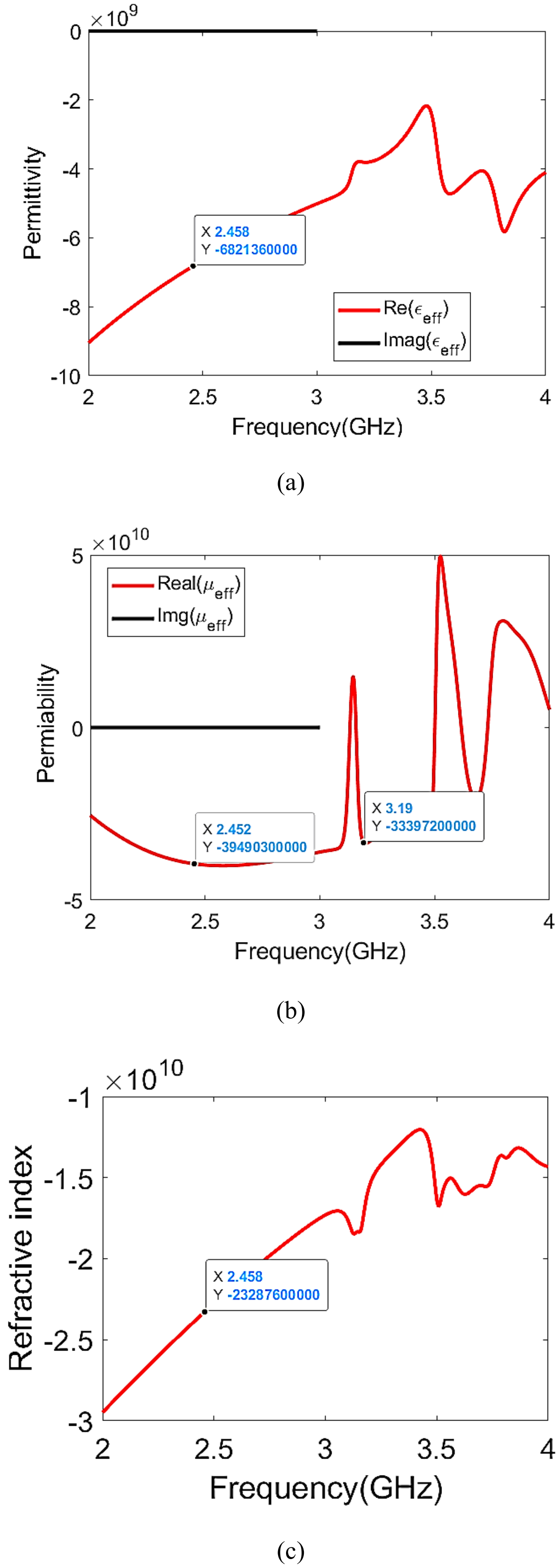


Fig.7 Material property using the NRW method - permeability, permittivity, and Refractive index graph (a) Negative permeability in the range 2-4 GHz (b) Negative permittivity in the range 2-4 GHz (c) Negative RI between 2-4 GHz.

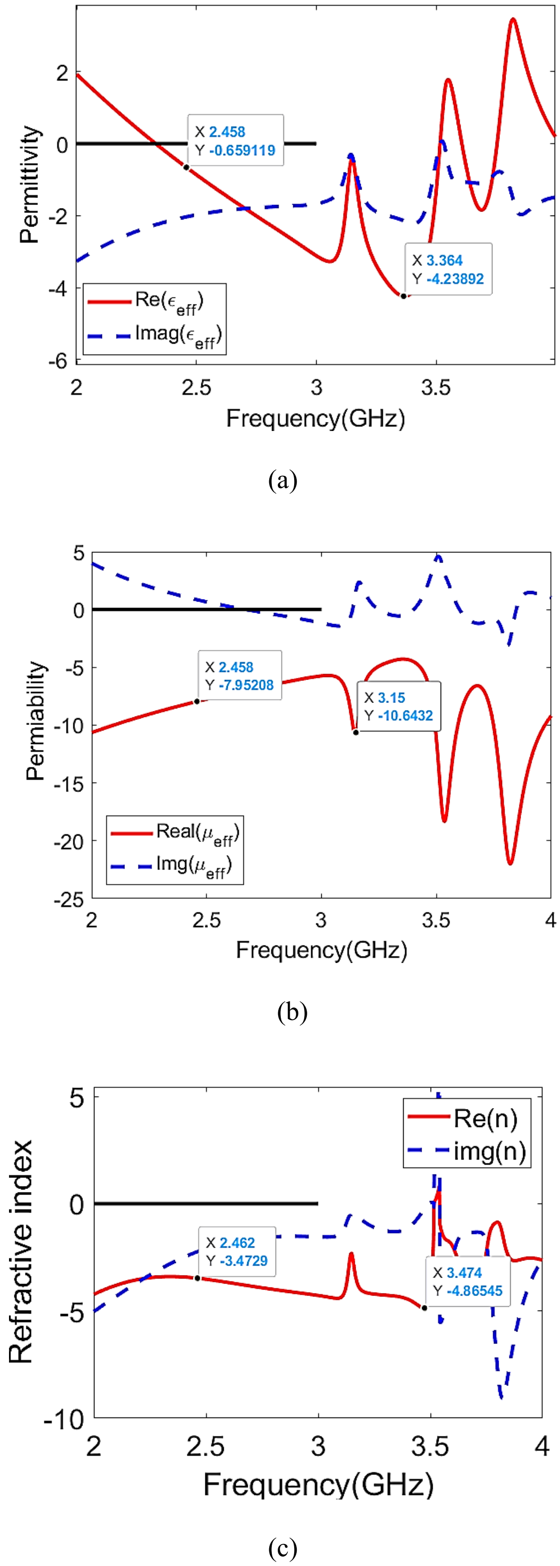
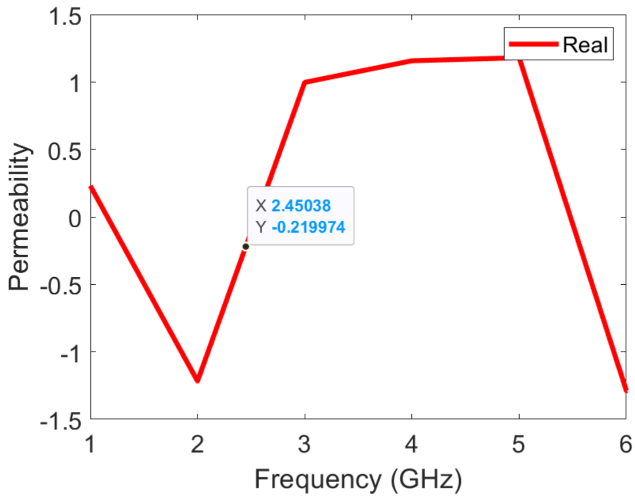


Fig 8 Material property using TR method - permeability, permittivity, and Refractive index graph (a) Negative permeability in the range 2-4 GHz (b) Negative permittivity in the range 2-4 GHz (c) Negative RI between 2-4 GHz.

The measurement results using the NRW method and TR method are shown in Fig.9 and 10. The graph in Fig 9 is the result of the NRW method showing Mu (μ) and Epsilon (ε) negative i.e. Double negative (DNG) medium property and these results are analyzed from measurement values. Similarly, the same measurement results are analyzed using the TR method, and the graphs are shown in Fig.10. The graphs in Fig.9 show mu as -0.2199 at 2.45 GHz and epsilon as -0.19 at 2.45 GHz and proving the DNG nature from the NRW method. In the same scenario, if Fig.10 is observed the value of permeability and permittivity is -21.5 and -21.48 at 2.45 GHz using the TR method, thus validating the MTM nature of the proposed Nut-shaped MTM unit cell with DNG property.



(a)

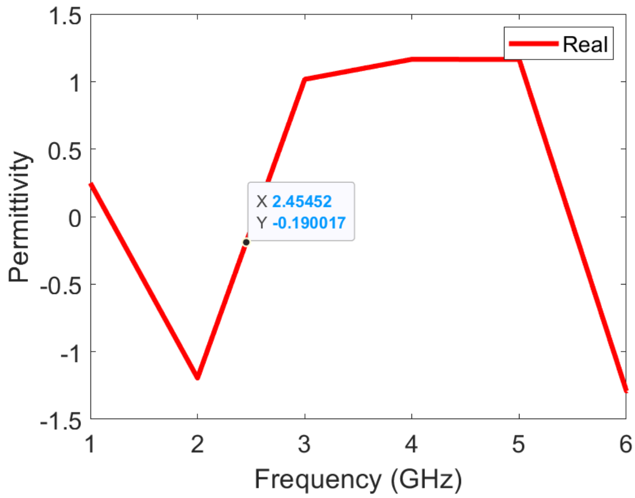


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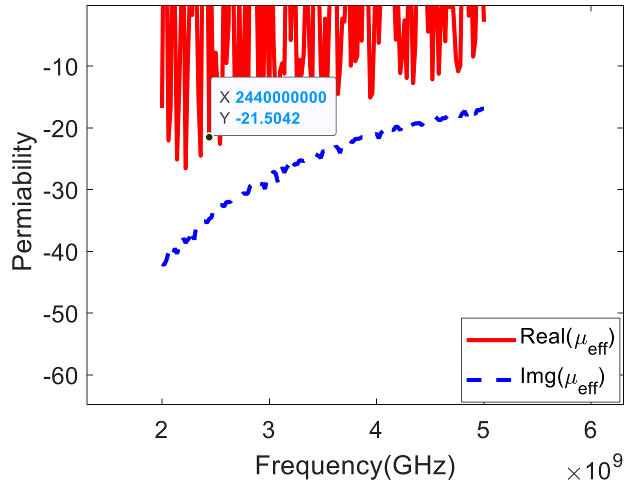
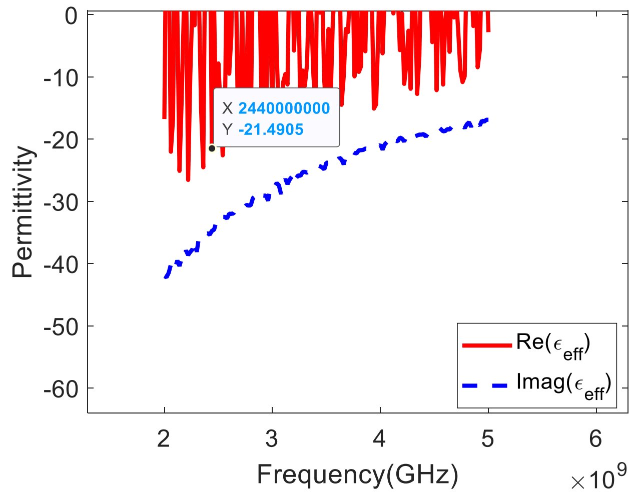
Fig.9 Material property using the NRW method - permeability, permittivity graph (a) Negative permeability in the range 1-6 GHz (b) Negative permittivity in the range 1-6 GHz



(a)



(b)

Fig.10 Material property using TR method - permeability, permittivity graph (a) Negative permeability in the range 2-6 GHz (b) Negative permittivity in the range 2-6 GHz

The reason for the proposed structure to act like MTM or as a resonator is its structure which is in the form of a ring and since metallization is continuous, more inductive property comes up leading to a property bend towards negative RI. The comparative study of different MTM unit cells is demonstrated in Table 2. The MTM with DNG property is widely accepted for various wireless applications. The proposed unit cell pattern satisfies and shows DNG characteristics in the range of 2-4 GHz.

TABLE II. Comparative study of various MTM unit cell

Ref	MTM unit cell structure	Frequency range	Size of MTM	MTM Property
Altaf et.al [7]	Double-E shaped	2.40, 4.50, and 7.24 GHz	8 mm × 8 mm × 1.57 mm	DNG
Imen et.al IEEE, 2019 [9]	Miniaturized MTM	28 GHz	2mm×2mm × 2mm	MNG
Sumanta Bose et.al [13]	Hexagonal SRR	S-band	2.5mm ×2.5 mm	NRIM
Md Siddiky et.al [15]	Double C-shaped square SRR	S-, C-, X-, and K-band	9mm × 9mm	LHM
R Marques et.al [20]	Hexagonal SRR	5 GHz, 6.88 GHz and 8.429 GHz	0.17λ × 0.17λ× 1.6mm	LHM, NMPM
Proposed	**Nut-shaped MTM unit cell**	**2-4 GHz**	**16mm×16 mm x 1.6mm**	**DNG**

VI FABRICATED DESIGN AND MEASUREMENT RESULTS

Fig.11 shows the fabricated unit cell of 12 mm x 12 mm dimension and the measurement of this proposed prototype was analyzed using the Vector Network Analyser (VNA) and S-parameters were studied. The VNA is calibrated using Agilent N5247A: A.09.90.02 unit. The setup consisted of two horn antennas and the MTM unit cell placed in between the transmitter and receiver. The fabricated unit cell parameters are measured between 1-5 GHz.

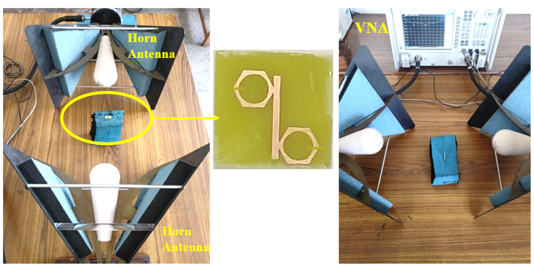


Fig.11 Proposed MTM unit cell after fabrication and measurement setup

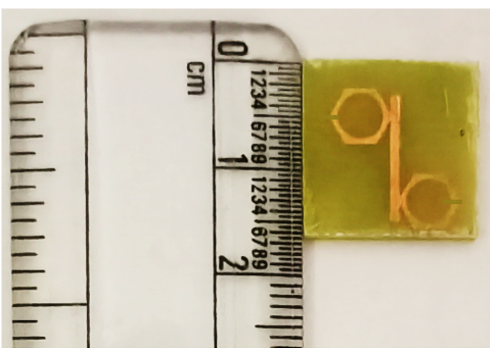


Fig.12 Fabricated prototype of unit cell of size 16mm × 16mm

A. Measurement of EMR

EMR is an effective medium ratio. The significance of EMR is it shows the compact size of MTM and how effective it is. The higher the EMR at low frequency, the better the MTM be. EMR is calculated as, EMR $= \frac{\lambda_{eff}}{L}$, where λ_{eff} = wavelength of the unit cell, L= length of the unit cell. The proposed unit cell has an EMR of 8.16 and 7.45 at 3.06 GHz and 3.35 GHz which is an appreciable value when the various comparisons are done of the differently shaped unit cells as in Table.2. Thus, for a dimension of 12 mm × 12 mm, the proposed novel Nut-shaped MTM unit cell showcase DNG property, improves antenna parameters which can be studied with the antenna with parametric analysis in upcoming works, have effective material properties in terms of scattering parameters, RI, permittivity and permeability and satisfactory value of EMR making this proposed MTM commercially useful.

VII CONCLUSION

In this article, a novel Nut-shaped metamaterial unit cell with splits is proposed. It is a unique structure derived from the fractal concept of branching wherein two Nut-shaped rings are branching at two opposite ends of a conductor strip. The novel structure satisfies the MTM property of negative material parameters in terms of permeability, permittivity, and refractive index. The different design stages are analyzed and their respective material and scattering parameters are studied. The MTM unit cell here under study is scrutinized using the NRW and the TR method and the overall size is 16 mm × 16 mm × 1.635 mm where the metal portion is 12mm × 12 mm. For the S-band the Nut-shaped MTM has an EMR of 8.16 and 7.45 at 3.06 GHz and 3.35 GHz and has the scope in RF energy harvesting applications which can be studied in upcoming works.

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