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RESEARCH ARTICLE OPEN ACCESS

A PROPOSED MODEL FOR DESIGNING A METAMATERIAL UNIT CELL 9 - 14GHZ FREQUENCY BAND COMMUNICATIONS

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ABSTRACT

A compact monopole antenna on a printed circuit board incorporating a single negative (SNG) metamaterial targets application in the X and Ku bands at 9.2 and 14.2 GHz. The design utilizes circular split-ring resonator (SRR) unit cells, structured with periodic arrangements smaller than the guided wavelength. Using CST Studio Suite simulation, the antenna demonstrates a wide 750 MHz bandwidth and very low radiation losses. This efficient design enhances performance and coverage, making it well-suited for radar and satellite communications within the targeted frequency bands.

I. INTRODUCTION

Metamaterials are artificially designed composite materials, the electromagnetic characteristics of which differ significantly from those of naturally occurring materials [1]. The peculiar manners of behavior among metamaterials have provoked a rather significant amount of research interest, and it has led to tremendous breakthroughs within a variety of scientific and engineering fields [2]. Conventional classification schemes define the following two main metamaterials assemblies: single-negative (SNG) materials, which exhibit either a negative permittivity or a negative permeability, and double-negative (DNG), and sometimes also left-handed (LH) materials, with simultaneously negative permittivity and negative permeability. Victor Veselago of Russia first theorized about LH metamaterials in 1967, in which

Veselago introduced the possibility of LH materials being able to display various unusual properties in how they guided the propagation of waves in both open space and guided structures [3]. The respective capabilities provided a rationale behind a diverse array of applications, such as holography, data processing, as well as signal multiplexing. The metamaterials (MTMs) have shown usefulness in various areas of engineering, such as antenna designing [4], [5], microwave filtering [6], specific absorption rate (SAR) relief [7], cloaking [8], super-resolution optics [9], electromagnetic (EM) absorption [10], [11], advanced sensors [12], [13], radar applications, and satellite communications [14], [15]. In all these applications, the properties of their optimized electromagnetic responses improve the performance of the devices.

On this note, researchers have implemented new MTM setups that are streamlined in support of certain functions. The framework of Islam et al. proposed a structured MTM on FR-4 substrate on satellite antennas, functioning on 2–4 GHz [16]. A single tri-band microwave use of compact epsilon-negative (ENG) MTM by a crossed-line CSRR structure has been designed by Shahidul et al., based on a unit-cell dimension of 10×10 mm^2 and a low effective medium ratio (EMR) of 4.5 [17]. The authors of [18] developed a meta-atom that could be used at multiband operations, and they had an EMR of 10.55 and a dimension of 12×12×1.6 mm^2. The authors of [19] presented a miniaturized DNG MTM having the modified Z-shape, most appropriate to operate with in X-band, but with an EMR as low as 4.

An SNG MTM was proposed by Islam et al., which aims to calibrate the performance of satellite and radar antennas, with a refractive index of near-zero and an effective magnetic resonance of 14.37 and 8×8 mm^2 unit cell [15]. Cheng et al., in line with imaging, detection, and sensing, developed the scenario of an ultra-slim, recessed, 7-metamaterial-bound absorber that has a single resonator [20], whereas the authors of [21] refined an adjustable, single-resonant broadband MTM absorber utilizing graphene in the terahertz regime, advancing its capacities of filtering, sensing, and modulation. Hossain et al. came up with a multiband application DNG MTM shaped like a double C with moderate EMR [22]. On the other hand, a double-Z shaped DNG-MTM with a footprint size of 8.5×8.5 mm^2 and having an EMR value of 4.80 was provided by Zhou et al. [23], and Hoque et al. provided a dual-band DNG metasurface absorber even though it exhibits a large-size unit cell of 4.80 EMR [24] ,[25]. By presented an H-shaped MTM with a large size DNG absorption structure having EMR = 3.65 [26].

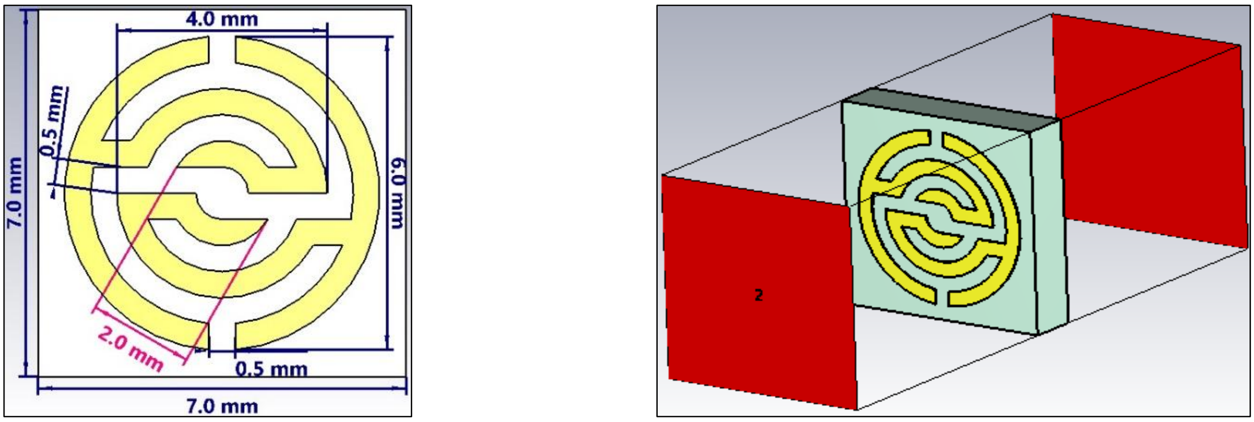
At the same time, demonstrated an asymmetric broadband MTM microwave absorber that can be utilized in the applications related to energy acquisition and stealth [27]. The authors of [28] suggested to work on a polarization-insensitive wideband MTM absorber realized within the C- and X-bands operating range by utilizing a 12.5×12.5 mm^2 unit size, and Zhou et al. are proposed to work on an S-shaped SNG MTM that is designed to operate within the X- and Ku-bands with an EMR below 4 [29]. By. also presented an MTM sensor structured into a meanderline, showing -3 dB/mm sensitivity and EMR of 7.2 [30].other related contributions are the proposed four-fold symmetric MTM absorber in the C-band, distributed by Thummaluru et al. with exceptionally large cell dimensions (28.2×28.2 mm^2) [31], and the DNG MTM structure fabricated in dual-band microwave applications by Faruque et al. (25×20 mm^2) [32]. Islam and his colleagues considered a hexagonal SRR MTM working at S- and X-frequency bands, using a 10×10 mm^2 unit and producing a 8.40 EMR [33].

The team of Rao et al. proposed a CPW-fed MTM-based circularly polarized antenna used in WiMAX and WLAN with a 9×9 mm^2 unit dimension and an EMR of 9.95, with only moderate gain [34]. The authors of [35] suggested a dual-band anisotropic MTM applicable to radar and satellite technologies, while the authors of [36] presented a high-gain, wide-bandwidth patch antenna with a concentrating metasurface, achieving 4.5 dBi gain with 76\% bandwidth [36]. Recently, the authors of [37] presented a left-handed multiband MTM having five absorbing bands, with 11×10 $mm^2compact unit footprint. Kumari et al. developed a principal lay-down ultra-thin polarization-insensitive MTM, in X-band, and made use of a 10×10 mm^2 absorber element with a small effective magnetic-field density (EMR) [38], [39]. According to Almutairi et al., a DNG MTM dual-band absorber in the C-band has a cell unit of 5.5×5.5 mm^2 and an EMR of 7.44 [40]. Thummaluru et al. claimed that a polarization-controllable tunable MTM absorber (POL-TC) in a circular sector structure, as a C-band absorber with dimensions of 9×9 mm^2, can also be tuned over a broad range [41].

Rao et al. have introduced a circular-shaped MTM that has expanded the bandwidth of the antenna fed with CPW, at some cost to the gain [42]. It is possible to benefit from several models of antenna configuration and integration with metamaterial cells to obtain a new generation of antennas with a smaller size, high gain and high efficiency [43-45]. The novel metamaterial single-negative (SNG) presented in this paper is a SSRR -based geometry, and its realization of two resonance peaks at 8.4-9.9 GHz and 14.0-14.2 GHz with a range of negative refractive index (NRI) between 9.26-9.7 GHz. These properties make it suitable in filtering, sensing, and controlling the electromagnetic waves. The findings show that integration of SNG metamaterials into the system can form a strong base in terms of certain application in advanced wireless and communication systems and the proposed design is one way of going about this.

II. ARCHITECTURAL DESIGN OF THE UNIT CELL

Figure 1(a) illustrates the structure of the proposed metamaterial unit cell geometry, which comprises multiple pairs of symmetric C-shaped split-ring resonators (SRRs) structured in an overlapping configuration. Fabricated on an FR-4 substrate, the unit cell possesses a relative dielectric constant of 4.3 and a 1.6 mm thickness, while the metallic conductor layer has a 0.035 mm thickness. To model and analyze the electromagnetic behavior of the structure, simulations utilized CST Microwave Studio (CST MWS), which uses the Finite Integration Technique (FIT). The unit cell was evaluated across the 1-15 GHz frequency range. For simulation purposes, the structure was situated amidst a pair of waveguide ports aligned along z-axis to enable electromagnetic excitation, as depicted in Figure 1b. Boundary conditions were set using a perfect electric conductor (PEC) coincident with x-axis and a perfect magnetic conductor (PMC) along the y-axis. Figure 1(a) shows detailed dimensions and design specifications of the unit cell.



(a) (b)

Figure 1: Unit cell of metamaterial: (a) Unit cell structure in two dimensions and size of a 7 × 7 × 1.6 mm.
(b) three dimensions view simulation setup of two-port.
Source: Authors, (2026).

The unit cell of the proposed metamaterial (MTM) consists of multiple concentric metallic rings, each spaced by a 0.5 mm uniform gap, as illustrated in Figure 2(a). The inner rings feature two splits but are interconnected via a metallic strip of 0.5 mm width, as shown in Figures 2(b) and 2(c). The outer ring includes 2 narrow gaps positioned 180 degrees apart, as depicted in Figure 2d. An enhancement in stopband performance is observed when two thin metallic arms are introduced between the inner and outer rings ,Figure 2(e), leading to the ultimate optimized design of the metamaterial unit cell. From an electromagnetic perspective, the metallic rings function as inductive elements, while the gaps between the rings serve as capacitive elements, forming an LC resonator. Figure 2 provides a step-by-step overview of the design evolution and optimization process of the proposed metamaterial structure.

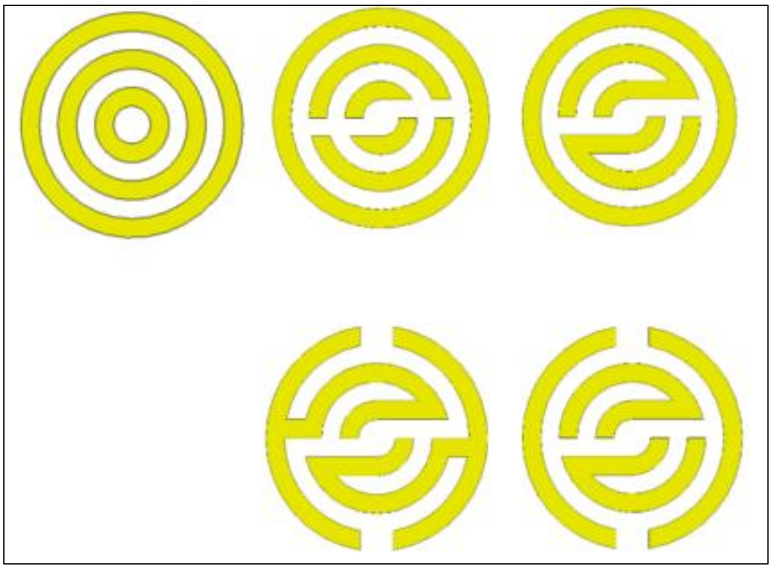


Figure 2: Evaluation schematic of the proposed MTM.
Source: Authors, (2026).

III. SIMULATION OF THE UNIT CELL AND ANALYSIS

The simulation of the MTM unit cell is provided in this section. The suggested SRR operates at 9.2 and 14.2 GHz bands, where X and Ku bands are considered candidates for the applications of radar and satellite. Figure 3 shows the reflection and transmission coefficients of the unit cell are shown. As shown in Figure 3, the unit cell operates with a bandwidth of 750 MHz. at 9.2 and 14.2 GH.

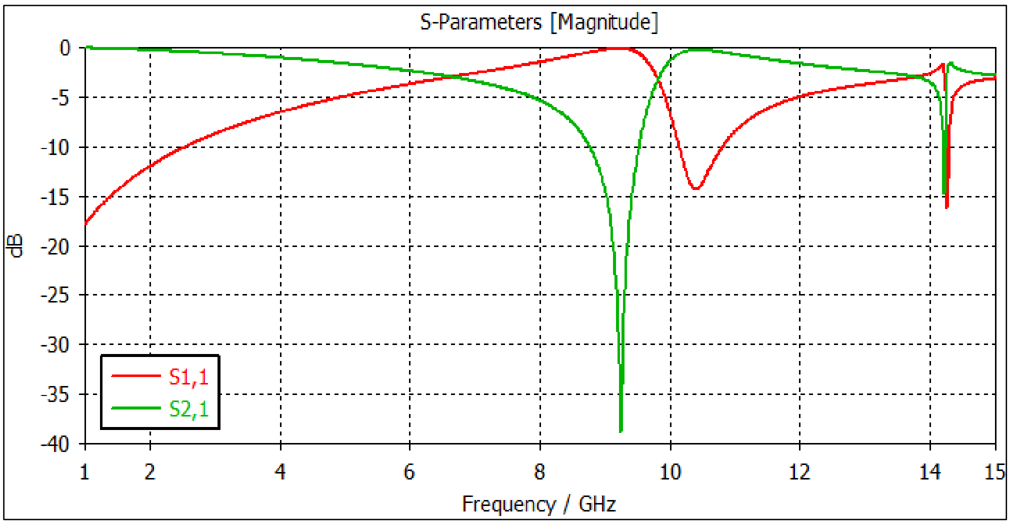


Figure 3: Simulated reflection and transmission coefficients for the SRR metamaterial unit cell.
Source: Authors, (2026).

The simulated relative real components of the effective permittivity, permeability, and refractive index unit cell structure are graphed in Figure 4. The frequency range reveals a negative real permittivity (ϵ) value for the unit cell. Consequently, incorporating SRR with a unit cell yields single epsilon negative (ENG) characteristics from 8.4 to 9.9 GHz and 14 to 14.2 GHz, and negative refractive index (NRI) from 9.26 to 9.7 GHz, as can be seen in Figure 4.

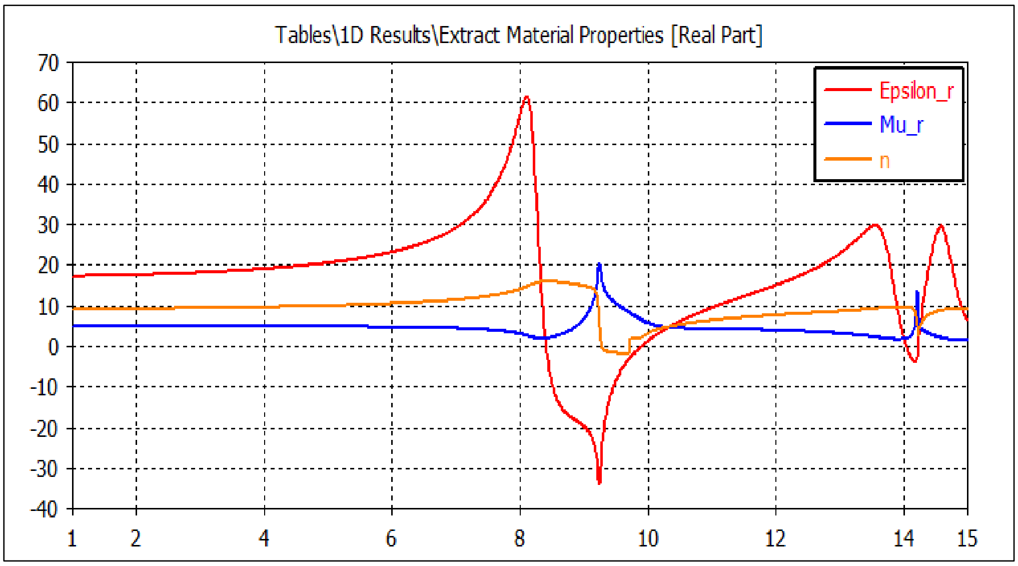


Figure 4: Metamaterial, simulated results of unit cell permittivity, permeability, and refractive index.
Source: Authors, (2026).

III.1 SURFACE CURRENT

Obviously, as is seen in the literature explaining the work of metamaterials, MTM is suffering from radiation losses, since in this paper, a composed metamaterial unit cell is used to overcome the radiation loss by using retrieval and transmission analyses. exposes the induced work of metamaterials, MTM is suffering from losses, since in this paper, a composed metamaterial unit cell is used to overcome the radiation loss by using retrieval and transmission analyses. The technique of radiation loss reduction was done by using the induced surface current and retrieval analysis. Figure 5 exposes the induced surface current on the two circles: the inner and middle circles of the SRR unit cell at the 9.2 band. While in the 14.2 band, expose the induced surface current on the outer circle as demonstrated as shown in Figure 6.

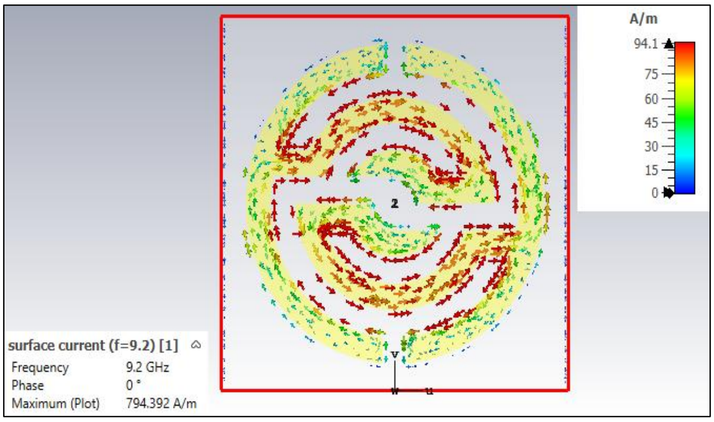


Figure 5: The surface current induced at a frequency of 9.2 GHz.
Source: Authors, (2026).

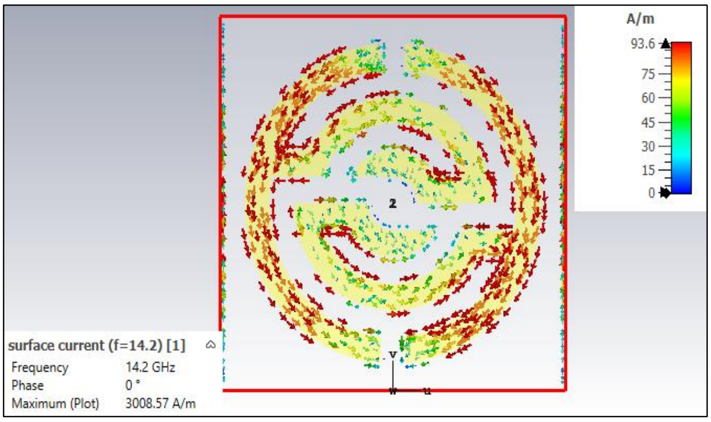


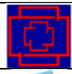
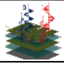
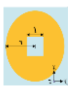
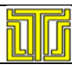
Figure 6: The surface current induced at a frequency of 14.2 GHz.
Source: Authors, (2026).

The dipole response produces large radiation losses. However, by modifying the metamaterial structure to apply opposite currents, the induced currents cancel out each other thus repressing the radiation loss.

III.2 SURFACE CURRENT

Table 1 categorizes the proposed design as "complex" in terms of geometric shape complexity. This is an important consideration for practical implementation. Although circular SRR unit cells are well-established, the overlapping configuration and the introduction of thin metallic arms for optimization (as shown in Figure 2) contribute to this complexity. Designs such as the "simple" circle shape by Almutairi et al. [40] or the square shape by [46] might offer easier fabrication. However, the increased complexity of the proposed design appears to be justified by its dual-band operation and loss-reduction capabilities. A more detailed discussion of the manufacturability and tolerance to fabrication imperfections would further enhance this aspect of the paper., as is seen in the literature explaining the work of metamaterials, MTM is suffering from radiation losses, since in this paper, a composed metamaterial unit cell is used to overcome the radiation loss by using retrieval and transmission analyses. exposes the induced work of metamaterials,

Table 1: Assessment of proposed and current work .

Reference	Year	Substrate	Frequency	Dimension	Design Geometric Layout	Design Shape	Desing Complexity	Application
[47]	2022	FR-4	3.36	10 × 10	Planar Resonator		Intermedia	Sensing Application
[48]	2023	PMMA	5.38	11.2 × 11.2	Multilayer Stack-Up		Intermedia	Wireless Communication
[49]	2023	PDMS	5.11	8 × 8	Multilayered Stack		Intermedia	Stealth Applications
[50]	2023	PDMS	14.3	11 × 11	Circle Shape		Simple	Radar Applications
[46]	2024	PET	18.93	10 × 10	Square Shape		Simple	Wireless Communication
[51]	2024	PVC	5	10.3 × 10.3	Circle Shape		Simple	Object Conformality And RCS
[52]	2024	FR-4	3.8	24 × 24	Maze Pattern		Intermedia	5g Application
Proposed Work	2025	FR-4	9.2,14.2	7 × 7	Symmetric SRR		complex	Radar and Satellite Applications

Source: Authors, (2026).

IV. CONCLUSION

This paper proposed a metamaterial unit cell exhibiting SNG behavior. The proposed design utilizes an SSRR structure, demonstrating operation within the X and Ku bands. It exhibits a NRI in the 9.26 to 9.7 GHz frequency range. Additionally, the unit cell operates at two distinct frequencies that are 9.2 GHz and 14.2 GHz, with a 750 MHz bandwidth. The designed unit cell exhibits SNG characteristics across different frequency bands, indicating its capability to function as a Single Negative metamaterial in specific operational ranges.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Jamal Mohammed Rasool, Ahmed Al Asadi, Ali Kahdum Abd and Omar Alnaseri.
Methodology: Jamal Mohammed Rasool, Ahmed Al Asadi, Ali Kahdum Abd and Omar Alnaseri.
Investigation: Jamal Mohammed Rasool, Ahmed Al Asadi, Ali Kahdum Abd and Omar Alnaseri.
Discussion of results: Jamal Mohammed Rasool, Ahmed Al Asadi, Ali Kahdum Abd and Omar Alnaseri.
Writing – Original Draft: Jamal Mohammed Rasool, Ahmed Al Asadi, Ali Kahdum Abd and Omar Alnaseri.
Writing – Review and Editing: Jamal Mohammed Rasool, Ahmed Al Asadi, Ali Kahdum Abd and Omar Alnaseri.
Resources: Jamal Mohammed Rasool, Ahmed Al Asadi, Ali Kahdum Abd and Omar Alnaseri.
Supervision: Jamal Mohammed Rasool, Ahmed Al Asadi, Ali Kahdum Abd and Omar Alnaseri.
Approval of the final text: Jamal Mohammed Rasool, Ahmed Al Asadi, Ali Kahdum Abd and Omar Alnaseri.

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