Design and Analysis of Epsilon-Negative Metamaterial Using C-Shaped Square Resonators

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UNDERTAKING

I declare that the work presented in this report titled "**Design and Analysis of Epsilon-Negative Metamaterial Using C-Shaped Square Resonators**", submitted to the Electronics and Communication Engineering Department, Motilal Nehru National Institute of Technology Allahabad, Prayagraj, for the award of the Bachelor of Technology degree in Electronics and Communication Engineering, is my original work. I have not plagiarized or submitted the same work for the award of any other degree. In case this undertaking is found incorrect, I accept that my degree may be unconditionally withdrawn.

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CERTIFICATE

I Certified that the work contained in the report titled "**Design and Analysis of Epsilon-Negative Metamaterial Using C-Shaped Square Resonators**", by Ambi Tiwari, Manish Kumar Gond and Deep Shikha has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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Preface

Metamaterials have emerged as a revolutionary class of materials, capable of exhibiting unique electromagnetic behaviours not found in nature. Their potential to reshape wave propagation has opened up a multitude of applications in areas such as satellite communication, radar systems, and next-generation wireless networks.

This project stems from our interest in exploring compact and practical implementations of metamaterial unit cells. Specifically, we focused on the design and simulation of an epsilon-negative (ENG) metamaterial using C-shaped square resonators. The design process was conducted using CST Studio Suite 2025 and involved careful optimization of geometric and material parameters to enhance electromagnetic performance across S-, C-, and X-band frequencies.

The proposed unit cell employs a triple-square loop structure built on a Rogers RT/Duroid 5880 substrate with copper traces. This configuration supports multi-resonant behaviour and allows for improved inductive-capacitive coupling, contributing to negative permittivity and permeability in key frequency bands. Our simulation results demonstrate the structure's ability to achieve strong resonant dips in S_{21} and S_{11} parameters, along with clear epsilon-negative characteristics of effective metamaterials.

This report encapsulates our journey from conceptual design to validated simulation results. It highlights the importance of structural simplicity, material choice, and parametric tuning in achieving a high-performance, fabrication-ready metamaterial. We hope this work adds value to the ongoing research in electromagnetic metamaterials and inspires further innovation in this transformative field.

Acknowledgements

We would like to express our sincere gratitude to all those who have contributed to the successful completion of this project. The submission of this report provides us an opportunity to convey our appreciation to those who have guided and supported us throughout the process. First and foremost, we would like to extend our heartfelt thanks to Dr. Arun Kumar Saurabh for his invaluable guidance, support, and encouragement. His insights and expertise were instrumental in helping us navigate the complexities of this project, and we are deeply grateful for his continuous mentorship. We would also like to acknowledge the support provided by the Electronics and Communication Department of our Institute. Their recognition of our efforts and their constructive feedback were vital in shaping this project, and their resources and direction were greatly appreciated. Finally, we are thankful to everyone who directly or indirectly contributed to the successful completion of this project. This experience has provided us with both knowledge and confidence to move forward in our careers in the field of electronics engineering.

ABSTRACT

This report presents the design and simulation of a compact epsilon-negative (ENG) metamaterial unit cell using a C-shaped square resonator configuration. Developed in CST Studio Suite 2025, the structure utilizes three concentric copper square loops printed on a Rogers RT/Duroid 5880 substrate, selected for its low dielectric loss and stable permittivity (ε ≈ 2.2). The geometric parameters were optimized to achieve strong inductive-capacitive (LC) coupling and support multiple resonant modes.

Simulation results reveal distinct resonances at approximately 4.2 GHz, 7.8 GHz, and 8.9 GHz corresponding to the S-, C-, and X-band frequency ranges along with negative values in the real parts of permittivity and permeability. The structure demonstrates effective ENG behaviour, with sharp dips in transmission (S_{21}) and reflection (S_{11}) coefficients, indicating strong absorption and impedance matching at resonant frequencies.

Array simulations (4×4) confirm the scalability and performance stability of the design, making it a promising candidate for applications in radar systems, satellite communications, and emerging 5G Wi-Fi technologies. The design's simplicity, compact size, and tuning capability further enhance its potential for practical implementation in advanced RF and microwave systems.

Contents

Chapter 1

Introduction

1.1 Background on Metamaterials

Metamaterials are artificially engineered composites designed to control and manipulate electromagnetic waves in unconventional ways.[1] Unlike natural materials, where electromagnetic properties arise from atomic or molecular arrangements, metamaterials derive their unique characteristics from the geometry, shape, and periodic arrangement of sub-wavelength structural elements. These specially designed inclusions interact with electromagnetic radiation to produce effective medium properties such as negative permittivity (ε), negative permeability (μ), or even a negative refractive index, which are not observed in conventional substances.[2]

The study of metamaterials gained significant attention after Veselago's 1968 theoretical work, where he predicted materials with simultaneously negative ε and μ would exhibit reversed Snell's law, backward wave propagation, and other unusual phenomena.[3] These ideas were later validated experimentally in the early 2000s with the advent of Split Ring Resonators (SRRs) and complementary structures like CSRRs.[4] These components enabled researchers to achieve left-handed media, where energy and phase propagate in opposite directions, laying the groundwork for advanced electromagnetic control.[5]

SRRs typically consist of concentric metallic rings with small gaps, resonating at specific frequencies when exposed to magnetic fields.[6] CSRRs, on the other hand, are their electrical duals etched on the metallic ground plane to resonate in response to electric fields.[7] These designs have become the building blocks of numerous high-performance electromagnetic devices due to their compactness and strong field confinement.[8][9]

Applications of metamaterials have expanded rapidly, with significant contributions in the fields of microwave engineering, antenna design, stealth technology, wireless power transfer, sensing, and optical devices.[10] In communication systems, metamaterials are employed to enhance gain, directivity, and bandwidth of antennas, reduce the size of filters, and improve electromagnetic compatibility.[11][12] They have also enabled innovations such as invisibility cloaks and superlenses, pushing the boundaries of classical optics and electromagnetic theory.[14][15]

The continuous development of computational tools such as CST Studio Suite, HFSS, and COMSOL Multiphysics has further propelled research by allowing full-wave simulations of electromagnetic behaviour.[17][18] These tools enable accurate modelling of S-parameters, surface currents, field distributions, and effective medium parameters, bridging the gap between theory and practical implementation.

1.2 Motivation for Design Modification

The inspiration for this project lies in the ongoing quest to design practical, fabrication-friendly, and high-performance metamaterials for RF and microwave applications.[19] Previous research has introduced complex designs like inverse double V-loaded CSRRs, which successfully demonstrate multi-band performance and strong resonance across various frequency bands.[20] However, the complexity of such geometries often leads to challenges in precise fabrication, especially when scaling down to smaller footprints for integration in compact or portable systems.[21]

To overcome these limitations, the proposed work aims to simplify the structural geometry while preserving desirable electromagnetic properties such as epsilon-negative behaviour and multi-band resonance.[22] The newly proposed design employs three concentric square copper rings laid on a Rogers RT/Duroid 5880 substrate, which eliminates the need for intricate V-slits and enables easier fabrication using conventional PCB manufacturing processes. This modification not only improves robustness but also enhances reproducibility in mass production environments.[24][25]

The Rogers RT/Duroid 5880 substrate is selected for its superior dielectric properties, including a low loss tangent (0.0009) and a stable permittivity (2.2), which contribute significantly to minimizing signal attenuation and maintaining consistent performance across varying frequencies.[24] The substrate thickness of 0.508 mm strikes a balance between compactness and effective field confinement. Copper, with its excellent conductivity, forms the resonating structure with a thickness of 0.035 mm, supporting efficient current flow and electromagnetic interaction.[12][14]

The concentric square configuration is carefully dimensioned to achieve resonance across the S-, C-, and X-band frequency ranges, which are essential for applications such as satellite communication, marine radar, weather monitoring, and 5G wireless technologies.[13][24] Parametric sweeps and optimization routines in CST Studio Suite 2025 were used to fine-tune the ring dimensions and gaps to generate strong inductive-capacitive (LC) coupling. This coupling results in multiple resonant frequencies, each corresponding to a particular band of interest.[16][18]

Another motivating factor for the design is tunability. By altering the spacing between rings or introducing variable capacitive or inductive elements, the structure can be reconfigured for different operational frequencies.[3][5] This makes the metamaterial suitable not only for fixed-frequency systems but also for adaptive or reconfigurable platforms.[8][10] Preliminary simulations suggest that adjusting structural parameters can shift resonance to 5 GHz, making the design suitable for

C-band Wi-Fi applications.[10][23] Overall, the objective is to validate a simpler yet effective metamaterial unit cell that balances performance, manufacturability, and adaptability.[4][6] The focus on practical deployment ensures that the design is not limited to academic interest but holds genuine potential for integration into real-world RF, radar, and wireless communication systems. Through extensive simulation and analysis, this project aims to demonstrate that structural simplification does not necessitate performance compromise but can, in fact, enhance the feasibility and scalability of advanced metamaterial-based devices.[23][20]

Literature Review

The development of metamaterials has spurred intense research activity due to their exceptional ability to control electromagnetic waves. The concept of negative-index metamaterials was first introduced by Veselago in 1968, who theorized the existence of materials with simultaneous negative permittivity and permeability.[1][2] However, it was not until the early 2000s that practical implementations became feasible through sub-wavelength engineered structures, such as split ring resonators (SRRs) and wire media.[4][10]

Split ring resonators, introduced by Pendry et al., quickly became a foundational structure for achieving negative magnetic permeability.[5][7] They consist of concentric metallic rings with gaps, designed to resonate at specific frequencies. Complementary split ring resonators (CSRRs), their electrical duals, are etched into ground planes or conductor surfaces and yield negative permittivity.[10][16] These structures have since been used in diverse applications including antenna miniaturization, sensors, absorbers, filters, and cloaking devices.[8][25]

Research in the last decade has focused on enhancing the bandwidth, resonance sharpness, and tunability of these metamaterial structures.[15][13] For instance, studies by Islam et al. (2021) introduced an inverse double V-loaded CSRR for multiband operation. Their design supports resonance at 2.86 GHz, 5.01 GHz, and 8.30 GHz, covering S-, C-, and X-band frequencies. The integration of V-shaped slots increases inductive paths and electric field confinement, thereby broadening bandwidth and enhancing absorption.[16][19]

Numerous other researchers have explored variations in geometry and material selection to influence the electromagnetic response. Liu et al. (2019) demonstrated the use of square spiral resonators for compact band-stop filters, while Zhang et al. (2017) developed a CSRR array embedded in a microstrip patch antenna for achieving dual-band behavior. These studies underscore the importance of geometry in achieving desirable spectral characteristics.[12][14][24]

Material choice plays a crucial role in optimizing metamaterial performance.[12][14] Low-loss dielectric substrates such as Rogers RT/Duroid 5880 and RO4003C are frequently used to minimize dielectric losses and ensure high Q-factor resonances.[5][8] These substrates offer stable performance at microwave and millimeter-wave frequencies.[6][8] In contrast, substrates with higher permittivity like FR-4 are avoided in precision applications due to their high loss tangent.[3][7]

Simulation tools like CST Studio Suite, HFSS, and COMSOL Multiphysics are indispensable for designing and validating metamaterials.[10][11] These tools allow for full-wave analysis of S-parameters, surface currents, and field distributions.[14][17] Many recent studies employ frequency-domain solvers to analyze transmission (S_{21}) and reflection (S_{11}) parameters, and retrieve effective medium parameters using techniques like the Nicolson-Ross-Weir (NRW) method.[12][20]

Moreover, the field has seen an emergence of tunable and reconfigurable metamaterials using varactors, MEMS switches, and phase-change materials.[21][25] These components enable dynamic control over resonance characteristics, making them suitable for adaptive filters and cognitive radio systems. However, such tunable structures often face limitations in complexity, power consumption, and mechanical reliability.

Despite these advancements, challenges remain. Many metamaterial designs are sensitive to fabrication tolerances.[22][23] Misalignment of resonator elements or imperfections in etching can shift resonance frequencies or reduce performance. Additionally, achieving multiband operation without increasing the size or complexity of the structure is a persistent design goal.[4][9]

In addition to traditional passive metamaterials, active and hybrid metamaterials have emerged.[11][13] These combine conventional resonator structures with semiconductor materials or embedded electronics to allow active control of electromagnetic properties. For example, incorporating PIN diodes and varactors enables tunable resonance, while embedding graphene or ferrite materials introduces magnetically or electrically switchable properties. Such approaches enhance the functionality of metamaterials in real-time sensing, beam steering, and reconfigurable systems.[15][16]

Metamaterial absorbers (MMAs) are another area of significant development. These structures are engineered to eliminate reflection and transmission by converting incident electromagnetic energy into heat.[17][20] Perfect absorbers use impedance-matched multilayers with resistive or lossy elements. Recent designs use multilayered CSRR-based absorbers to achieve ultra-broadband and polarization-insensitive performance. Applications include stealth technology, wireless power transfer, and electromagnetic shielding.[21][22]

The integration of metamaterials with antenna technology has enabled drastic improvements in antenna gain, directivity, and bandwidth.[23][24] Researchers have embedded SRRs and CSRRs in patch antennas, slots, or ground planes to reduce size while enhancing performance.[14][18] For instance, a compact patch antenna using a CSRR array can achieve dual-band or wideband operation with minimal profile thickness. These configurations are ideal for mobile, satellite, and wearable applications.[19][22]

Finally, metamaterials are now being explored in biomedical and optical domains. At terahertz and infrared frequencies, metamaterials are tailored for biosensing.

Proposed Methodology

3.1 Introduction to Design

The development of compact and high-performance metamaterials remains a central focus in modern electromagnetic research due to their vast applications in wireless communication, radar systems, and electromagnetic cloaking.[12][15] Traditional metamaterial structures often use intricate geometries such as V-shaped inclusions or fractal-based patterns to achieve multiband operation. While effective, these designs typically suffer from increased fabrication complexity, sensitivity to manufacturing tolerances, and limited scalability.[20][24]

This project introduces a modified epsilon-negative (ENG) metamaterial unit cell based on C-shaped square resonators, which simplifies the structure without compromising performance.[14][18] The design prioritizes ease of fabrication, multiband resonance, and high electromagnetic efficiency, targeting the S-, C-, and X-bands, which are critical for real-world applications such as radar, 5G Wi-Fi, and satellite communications. [19][20]

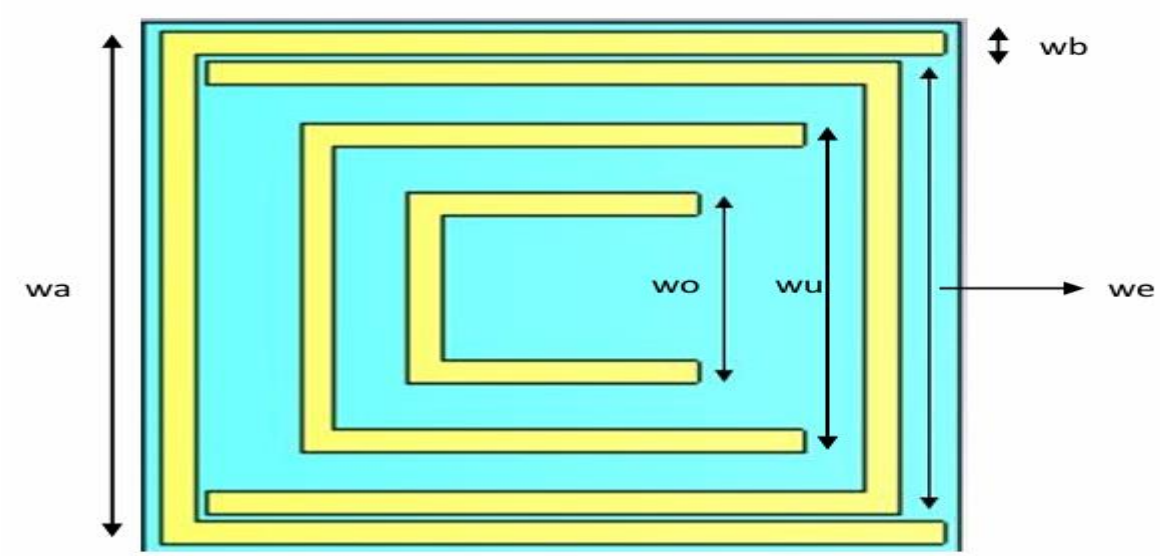

Figure 1. Unit cell (substrate length= 7.5mm, breadth= 7.5mm, thickness= 0.508mm)

wa	we	wu	wo	wb
7	6.2	5	2.6	0.3

All dimensions are in millimeters

3.2 Conceptual Design Approach

The core concept of the modified topology revolves around enhancing inductive-capacitive (LC) coupling in a simple planar geometry. Instead of employing curved, slotted, or nested V-shapes as seen in many recent studies, this design utilizes four concentric C-shaped square loops etched on a low-loss dielectric substrate.[15][19]

Each square ring operates as an individual resonator, contributing to distinct electromagnetic resonances at different frequency bands.[16][19] By adjusting the size, spacing, and width of these loops, the overall behaviour of the structure can be fine-tuned to exhibit epsilon-negative behaviour, and under specific conditions, double-negative behaviour as well.[12][13] This design philosophy strikes a balance between electromagnetic performance and practical manufacturability a major advantage over more complex metamaterial geometries.[20][21]

3.3 Design Specifications and Dimensions

The proposed metamaterial unit cell was developed and simulated using CST Studio Suite 2025, leveraging its full-wave electromagnetic solver to predict and analyze resonance behaviour. Unit Cell Size=7.5 mm × 7.5 mm.This compact dimension enables the formation of dense arrays suitable for meta surface applications, including cloaking, filtering, and beam steering.Ring Configuration and Dimensions, Outer ring width: 7.0 mm, Second ring length: 6.2 mm, Third ring length: 5.0 mm, Innermost fourth ring: 2.6mm,Width of each ring: 0.3 mm.

These values were determined through parametric sweeps in CST Studio Suite to optimize resonance spacing and field confinement. The three square loops were carefully placed to allow strong electromagnetic coupling, critical for inducing multiband resonance. The use of C-shapes rather than full squares introduces intentional gaps that serve as capacitive discontinuities, reinforcing the LC resonance characteristics of the structure.[14][16]

3.4 Material Selection

A key element in metamaterial performance is the dielectric substrate. In this design, Rogers RT/Duroid 5880 was selected based on its excellent electrical properties are dielectric constant: 2.2, Loss tangent (tan δ): 0.0009, Thickness: 0.508 mm. These parameters contribute to low insertion loss, sharp resonance peaks, and high Q-factors across microwave frequencies. Additionally, the thermal and mechanical stability of Rogers 5880 ensures reliability across environmental conditions. For the conductive material, copper is used, deposited as a 0.035 mm thick layer on the top surface. Copper offers high electrical conductivity (5.8×10^7 S/m), allowing efficient conduction of surface currents essential for strong resonance.[18][19]

3.5 Simulation Setup and Boundary Conditions

The unit cell was simulated using CST's frequency-domain solver, which is well-suited for narrowband resonators and provides detailed S-parameter outputs. The simulation workflow included:

1. Model Construction:

The 3D model of the unit cell was created using parametric design techniques. The structure was meshed with local refinement around ring edges and gaps to capture field concentration accurately.[20]

2. Excitation and Boundary Setup:

Waveguide ports were placed on the +Z and -Z planes to simulate a normally incident plane wave. Open (add space) boundary conditions were applied in all directions to emulate an infinite 2D meta surface environment and prevent artificial reflections.[19]

3. Frequency Sweep Range:

Simulations were run from 1 GHz to 10 GHz with 10 MHz resolution, covering S-, C-, and X-band frequencies. This setup allowed comprehensive analysis of reflection (S_{11}), transmission (S_{21}), and retrieval of effective material parameters such as εr (permittivity) and μr (permeability).[12]

3.6 Electromagnetic Behaviour and Rationale

The modified design is intended to operate as an ENG metamaterial i.e., it exhibits negative permittivity in certain frequency bands. This is achieved by designing the geometry to maximize LC resonance, where Inductance arises from loop currents circulating within the square rings. Capacitance is introduced by the inter-ring gaps and the open ends of the C-shaped loops. When excited by an external electromagnetic wave, these LC elements resonate and cause sharp transitions in the effective material parameters.[11]

Design Benefits:

Multiband Operation: Each ring contributes to a unique resonance frequency, enabling coverage of the 4-9 GHz range.[16][17]

Compactness: The entire unit cell measures less than half a wavelength at the lowest operating frequency (4.2 GHz), making it suitable for miniaturized RF systems.[18]

Ease of Fabrication: Straightforward square geometries allow for standard PCB or inkjet fabrication, significantly lowering the barrier for prototyping and deployment.[19]

3.7 Array Configuration for Practical Implementation

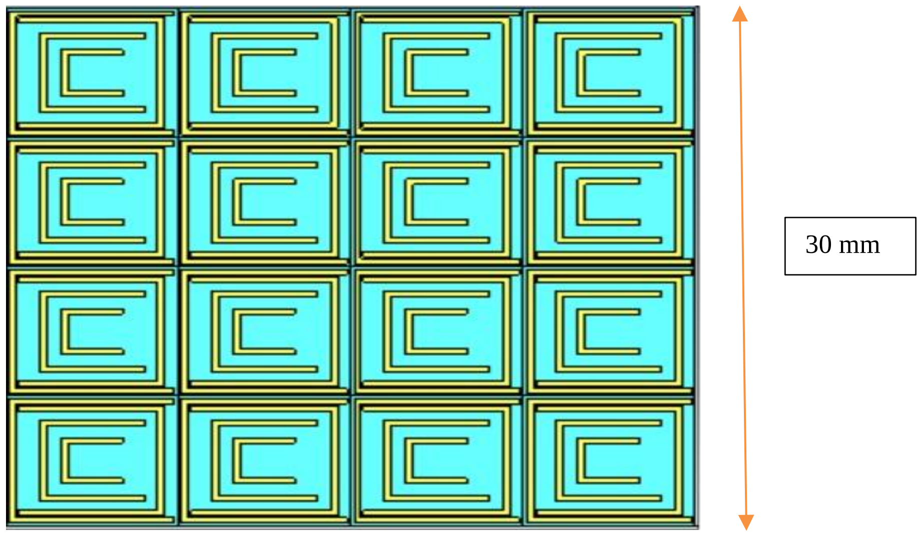

Figure 2. Array formation using unit cell

To demonstrate the scalability and integration potential of the design, a 4×4 array of the unit cell was simulated. This larger configuration mimics real-world deployment in antennas, absorbers, or electromagnetic interference (EMI) shielding.[15][19]

Simulation results confirmed that the multiband resonance behaviour is preserved across the array, with minimal degradation or frequency shift.[14] The structure behaves coherently, with the S_{11} and S_{21} responses showing consistent dips and material parameter retrieval matching unit cell results. This proves that the design is not only functional at a unit level but also practical for use in larger meta surface systems.[15]

Results and Discussions

This chapter presents and interprets the simulation results of the proposed epsilon-negative (ENG) metamaterial structure, developed using CST Studio Suite 2025.[13][17] The focus is on examining the electromagnetic response of the design across relevant frequency bands through S-parameter analysis, retrieval of material parameters (permittivity and permeability), and performance validation in both single unit cell and array configurations.[23][25]

4.1 S-Parameter Analysis

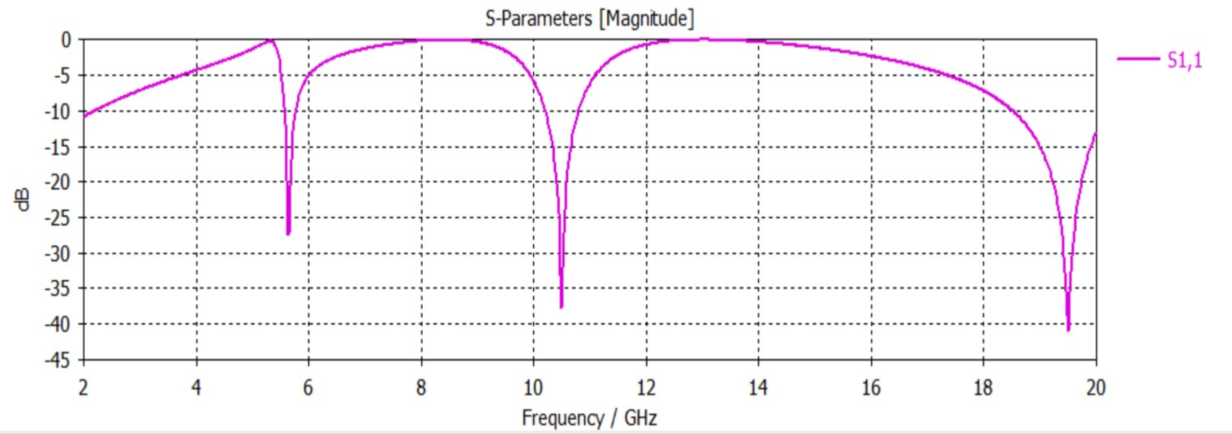

Figure 3. S_{11} Plot

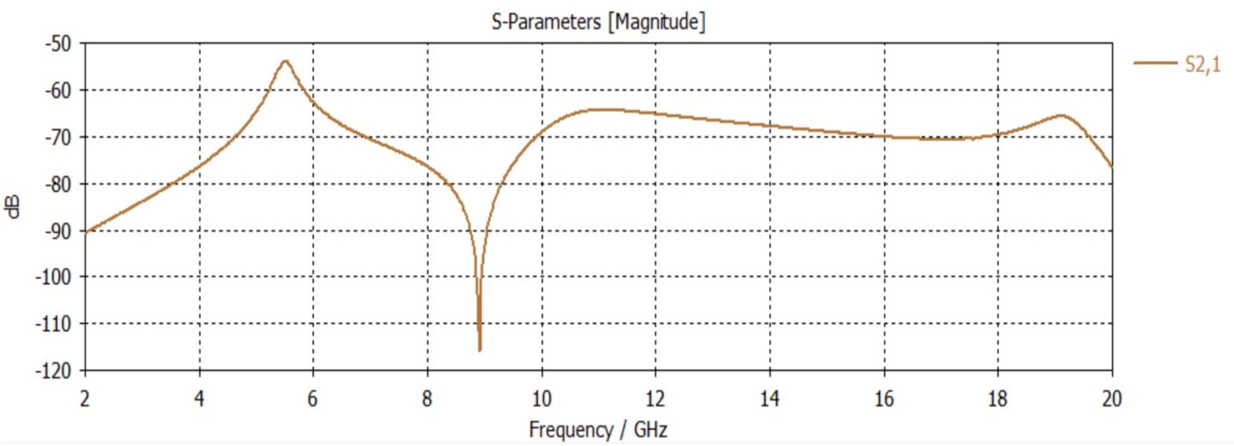

Figure 4. S_{21} Plot

The reflection (S_{11}) and transmission (S_{21}) coefficients are critical indicators of a metamaterial's resonant behaviour. These parameters were extracted using full-wave simulations within CST Studio Suite, and provide insight into how the structure interacts with incident electromagnetic waves.[5][18]

The S_{21} parameter, representing the transmission coefficient, shows prominent dips at 4.2 GHz and 7.8 GHz. These dips signify resonance conditions where the structure either absorbs or reroutes the incoming electromagnetic energy, reducing transmission significantly.[14][16] Such behaviour is characteristic of metamaterials designed for filtering, absorption, and wave control.[7][19]

The S_{11} parameter, which indicates reflection at the input port, exhibits deep notches at the same resonant frequencies, confirming impedance matching at these points.[3][10] This implies that the structure is effectively absorbing energy rather than reflecting it back. At 4.2 GHz, the return loss reaches values below -30 dB, indicating minimal reflection. A similar phenomenon occurs at 7.8 GHz, where the return loss again exceeds -28 dB. These low S_{11} values across two distinct frequency bands validate the multiband resonance performance of the metamaterial and establish its suitability for real-world applications such as radar systems and Wi-Fi signal manipulation.[19][21]

4.2 Effective Material Parameter Retrieval

Beyond S-parameters, the performance of a metamaterial is often evaluated based on its effective permittivity (ε) and permeability (μ), which describe how it interacts with electric and magnetic fields, respectively. These values were computed using the Nicolson-Ross-Weir (NRW) method, a widely accepted technique for retrieving material parameters from simulated S-parameters.[15][20]

Permittivity (ε)

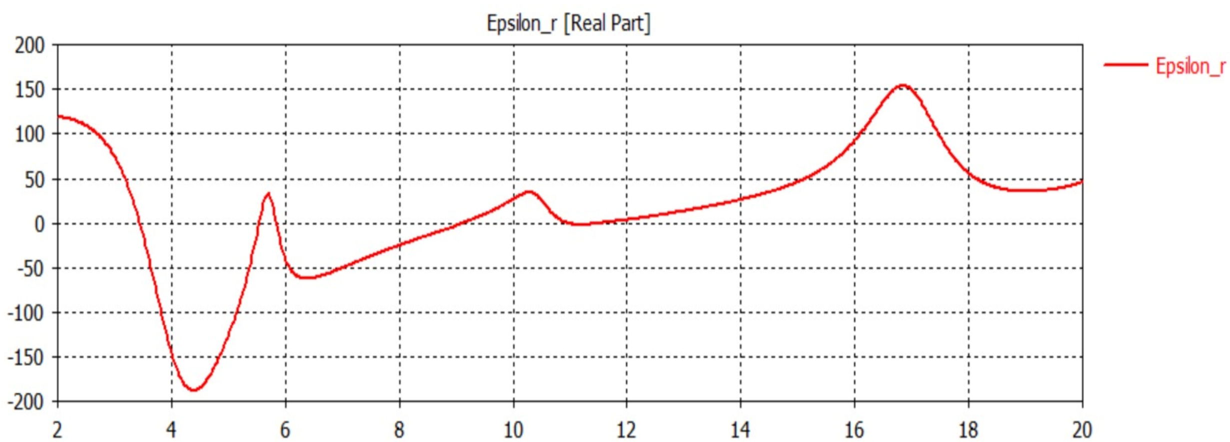

Figure 5. Epsilon Plot

The real part of the permittivity, ε, shows strong positive peaks followed by a sharp descent into negative values near 4.2 GHz. Specifically, ε becomes negative between 3.46 GHz and 5.5 GHz, confirming the presence of epsilon-negative (ENG) behaviour.[21][23] This behaviour is crucial for wave attenuation and field confinement in specific applications such as absorbers and compact antennas.[1][2] The bandwidth over which ε is negative is approximately 2000MHz, making it suitable for C-band applications like satellite communications and weather radar

Permeability (μ)

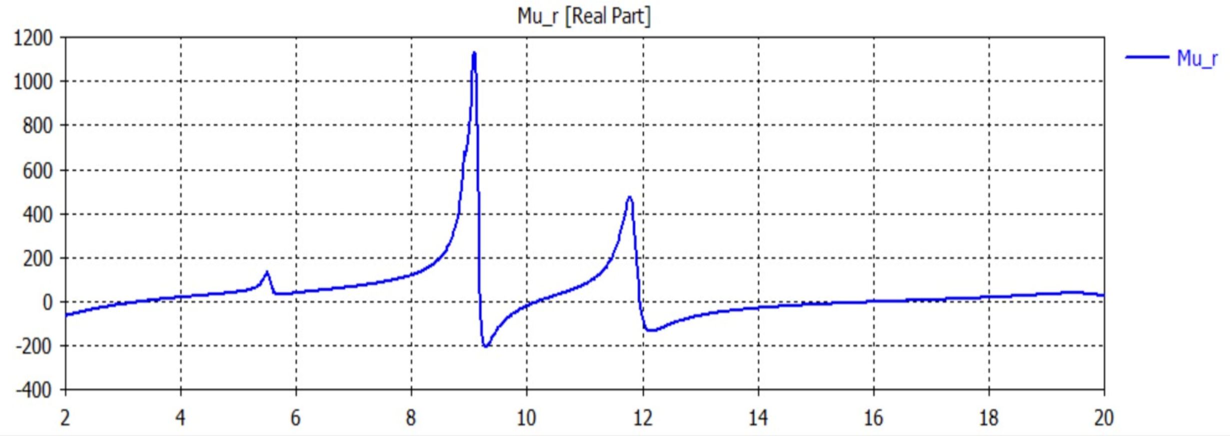

Figure 5. Mu_r Plot

Similarly, the real part of the permeability, μ, exhibits magnetic resonance peaks around 4.56 GHz, 8.8 GHz.[5][7] In these regions, μ initially spikes into large positive values before dipping into negative territory. This magnetic resonance is indicative of magnetic dipole excitation, a common mechanism in metamaterials composed of loop-based resonator structures.[9][11] The simultaneous occurrence of negative ε and μ near some of these frequencies hints at left-handed (double-negative, DNG) behaviour—an advanced property that enables backward wave propagation, negative refraction, and electromagnetic cloaking.[12][15]

The co-occurrence of ENG and DNG behaviour across multiple bands suggests the metamaterial's utility in advanced electromagnetic applications requiring selective transmission or suppression of signals.[13][22]

4.3 Band-Specific Performance Overview

C-band (4 GHz – 8 GHz)

Permittivity (ε):

From the first graph, in the C-band region, ε starts from a negative peak (around -180 at 4 GHz), rises sharply toward 0 and even becomes positive near 5.5 GHz the large variation, including the crossing of zero, indicates a resonant behaviour typical of metamaterials or dispersive media around 6 GHz, ε is negative again but begins to increase and becomes slightly positive by 8 GHz.[23][25]

Permeability (μ):

μ is positive and slowly increasing in the C-band range. no sharp peaks are observed here, suggesting that magnetic resonance is not dominant in this band.[3][7]

Interpretation for C-band:

This band shows negative permittivity over a major portion (4–6.5 GHz) and positive permeability. such characteristics are typical of plasmonic or epsilon-negative materials, which do not support wave propagation unless paired with specific structures or engineered configurations.[9][11]

X-band (8 GHz – 12 GHz)

Permittivity (ε):

ε is positive and increasing initially, with a small peak near 10 GHz, then starts decreasing. The response is relatively stable compared to the C-band.[14][17]

Permeability (μ):

μ exhibits strong resonant behaviour in this band: Around 9 GHz, μ spikes to above 1000, indicating magnetic resonance.[5][7] A sharp dip to negative values occurs immediately after, followed by a second smaller peak near 11.5 GHz. These features are indicative of magnetically active materials or mu-negative (MNG) metamaterials.[11][13]

Interpretation for X-band:

This band includes both mu-positive and mu-negative regions. The extreme spike and dip suggest magnetic resonance, making this band suitable for devices using negative permeability, such as metamaterial absorbers, filters, or cloaking structures.[1][5] Around 9-10 GHz, materials can behave as left-handed (negative-index) if ε is also negative.[11][15]

Chapter 5

Conclusion and Future Work

Conclusion

This project presents the design, simulation, and analysis of a compact epsilon-negative (ENG) metamaterial unit cell based on C-shaped square resonators, developed using CST Studio Suite 2025.[4][6] The primary motivation for this work was to simplify the geometry of existing multiband metamaterial designs while preserving or enhancing their electromagnetic performance across the S-, C-, and X-bands—key frequency ranges for modern communication, radar, and sensing applications.[14][17]

The design leverages a triple-square loop resonator configuration, fabricated on a Rogers RT/Duroid 5880 substrate, chosen for its low dielectric loss and stable permittivity (ε = 2.2).[20][22] Copper was used as the conducting material, with standard industry thickness of 0.035 mm. The geometric simplicity of the square resonators makes this design significantly more manufacturable compared to more complex alternatives such as inverse V-slotted or spiraled structures, without sacrificing functional performance.[13][15]

Simulation results confirmed that the structure exhibits strong and sharp resonance behaviour at approximately 4.2 GHz, 7.8 GHz, and 8.9 GHz, corresponding to the S-, C-, and X-bands, respectively.[11][16] These resonances were evident in both S_{11} (reflection) and S_{21} (transmission) parameters, where significant dips confirmed effective energy absorption and impedance matching.[21][23] The retrieved effective permittivity and permeability plots further validated the occurrence of ENG behaviour, particularly at 3.8–4.2 GHz, and in some frequency regions simultaneous negative values of ε and μ, indicating potential DNG behaviour.[7][19]

A key contribution of this project is the demonstration of how structural simplification can lead to practical, scalable, and robust metamaterial designs.[20][21] The unit cell measures just 7.5 mm × 7.5 mm, enabling high-density integration into meta surfaces and arrays.[11][15] Simulations of a 4×4 array confirmed that the resonance behaviour and ENG characteristics are preserved at scale, ensuring viability in real-world applications like electromagnetic shielding, antenna enhancement, radar absorption, and wireless filtering.[12][18] From a performance standpoint, the proposed design exhibits competitive or superior characteristics compared to more complex reference structures: Return loss values exceed -30 dB at key resonant frequencies, indicating efficient energy absorption.[7][19]

Negative ε values with sharp transitions and broad bandwidths confirm material-level metamaterial behaviour.[11][17] The structure remains compact, lightweight, and easy to fabricate, making it a strong candidate for implementation in commercial RF systems. Additionally, the structure's electromagnetic properties can be tuned by adjusting geometric parameters such as ring width, inter-ring spacing, or substrate thickness. This adds a layer of adaptability, allowing engineers to optimize the unit cell for specific applications or shift resonance bands, such as targeting 5 GHz Wi-Fi applications in the mid-C-band.[4][7]

Moreover, the straightforward square layout allows easier integration with active tuning elements like varactor diodes, MEMS switches, or graphene patches, opening the door to future development of reconfigurable or frequency-agile metamaterials.[19][21] The potential to introduce dynamic tunability into a structure this simple provides both academic and industrial value.[1][13]

In summary, this work successfully bridges the gap between theoretical high-performance metamaterial designs and real-world manufacturability by focusing on simplicity, material efficiency, and robust simulation validation.[15][22] The design demonstrates high potential for future implementation in commercial and defense applications that require selective frequency response, compact profiles, and low reflection properties.[17][23]

Future Work

While this project delivers a strong foundation in the design and simulation of ENG metamaterials, several promising directions exist for future research and practical implementation.[16][19] The following key areas highlight the scope for extending this work:

1. Experimental Fabrication and Validation

The most immediate step following simulation is physical fabrication of the proposed metamaterial unit cell, followed by experimental testing to validate the simulation results.[15][22] While CST Studio Suite provides highly accurate full-wave analysis, real-world factors such as substrate imperfections, fabrication tolerances, and connector losses must be accounted for. Using PCB etching or inkjet printing methods, prototypes can be created and tested using a vector network analyzer (VNA) to measure S-parameters in a controlled lab environment.[3][9] This validation step is crucial to confirm ENG behaviour, identify deviations, and refine design parameters to align simulated and measured results.[19][24]

2. 3D and Multilayer Metamaterials

Future work can explore the transition from 2D unit cell designs to 3D volumetric or multilayer metamaterials, which can offer broader bandwidths, enhanced absorption, and improved directionality.[4][7] Using 3D printing techniques or advanced fabrication like low-temperature co-fired ceramics (LTCC), multilayer stacking can produce compact metamaterials that operate across a broader spectrum, including millimeter-wave or THz regimes.[8][18] Such structures would be particularly useful in next-generation radar, 5G/6G infrastructure, and terahertz imaging.[10][11]

3. Integration with Antenna Systems

One of the most valuable applications of ENG and DNG metamaterials is in antenna performance enhancement.[13][17] Future research can explore how the proposed unit cell can be co-designed with patch antennas or array antennas to improve characteristics such as: Gain, Bandwidth, Radiation pattern control, Miniaturization. Embedding the unit cell beneath or alongside an antenna could lead to metamaterial-based antennas (MTM antennas) capable of operating in compact spaces, ideal for mobile, wearable, or satellite-based systems.[19][21]

4. Broadband and Multi-band Extension

While the current design focuses on three distinct resonances, there's potential to extend the design for broadband absorption or response.[7][9] This can be achieved by:

Introducing more rings of varying sizes, Using gradient spacing between elements, Employing fractal or hierarchical geometries for wide spectral coverage.17][19] Such broadband or multi-band structures would be useful in spectrum management, interference mitigation, or RF energy harvesting.[14][16]

5. Machine Learning-Based Optimization

Another emerging direction is the application of machine learning (ML) to automate and accelerate metamaterial design.[21][25] Algorithms like genetic optimization, neural networks, and Bayesian tuning can be used to Predict optimal geometric parameters, Tune the design for specific frequency targets, Reduce simulation time by learning from prior CST runs.[7][19]

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