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DESIGN AND ANALYSIS OF METAMATERIAL UNIT CELLS FOR ANTENNA ENGINEERING

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Abstract: In this research paper, we present a comprehensive analysis of metamaterial unit cells for antenna engineering. The analysis includes the examination of unit cells with both single and double substrates through a waveguide medium. The first unit cell comprises a split ring resonator (SRR) with two splits placed within the perpendicular sides. Inside the SRR, a circular splitted ring resonator (C-SRR) is printed on a copper-backed FR4 dielectric substrate. This configuration exhibits a stop-band phenomenon at 5.5 GHz. The second unit cell also consists of an SRR with two splits within the perpendicular sides. Inside this structure, a circular splitted ring resonator (C-SRR) is designed using two different substrates (FR4 and Rogers RT5880) backed by a metallic ground plane. This unit cell demonstrates a stop-band phenomenon at 10.7 GHz. Furthermore, we conduct a detailed analysis of the extraction of medium parameters such as permittivity and permeability for both metamaterial unit cells. The extraction methodology and results are discussed extensively. To validate our findings, simulations are performed using the CST Microwave Studio, a widely-used commercial software in the field. Through these simulations, we obtain reliable and significant results.

***Index Terms* – Metamaterials, Antenna, Permittivity, Permeability, Split Ring Resonators**

I. INTRODUCTION

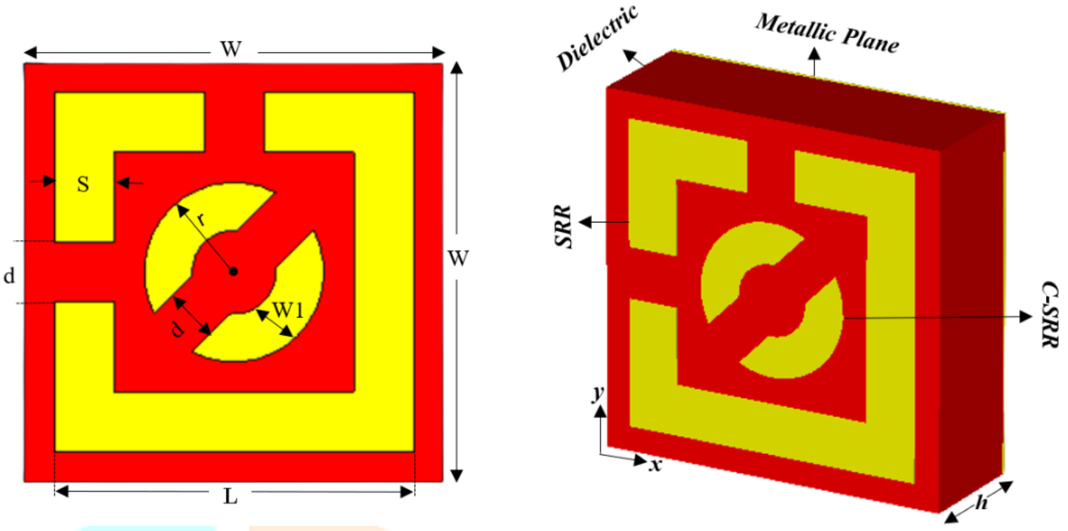
In recent years, metamaterials have garnered significant attention from researchers due to their exceptional properties, enabling the design of highly efficient antennas for future wireless communication [1]. Unlike naturally occurring materials, metamaterials possess unique characteristics [2]. The ability to manipulate the values of permittivity, permeability, and refractive index in metamaterials has revolutionized antenna design technology. These artificial structures, known as metamaterials, were first proposed by Veselago [3]. The classification of metamaterials is based on the permittivity and permeability of the material, such as double negative (DNG), negative permittivity (ENG), and negative permeability (MNG). Metamaterials are composed of periodically arranged unit cells [4]. Various shapes can be employed for the unit cells, including split ring resonators (SRR) [5], complementary split ring resonators (C-SRR) [6] [7], rectangular complementary split ring resonators (RC-SRR) [2], and more.

Metamaterial structures offer various advantages in multi-band antenna design, including the creation of additional resonances, improved gain, enhanced bandwidth, and potential miniaturization. These unique properties of metamaterials can be harnessed to achieve desired antenna characteristics. In this research, we propose two novel metamaterial unit cells designed to achieve resonances at 5.5 and 10.7 GHz. The first unit cell consists of a single substrate (FR4), which exhibits resonance at 5.5 GHz. The second unit cell is constructed using two different substrates (FR4 and Rogers RT5880) and demonstrates resonance at 10.7 GHz. The obtained results align well with our expectations, as we successfully achieve negative permittivity and negative permeability in the designed metamaterial unit cells.

II. ANALYSIS OF THE PROPOSED METAMATERIAL UNIT CELL

A. THE PROPOSED FIRST UNIT CELL

The proposed metasurface consists of specific geometrical structures as described below. The first unit cell is comprised of a split ring resonator (SRR) with two splits placed on perpendicular sides. Within the SRR, a circular splitted ring resonator (C-SRR) is printed on a copper-backed FR4 dielectric substrate, as illustrated in Fig. 1(a). The dimensions of the proposed unit cell are provided in millimeters: W = 7, L = 6, d = 1, S = 1, r = 1.5, W1 = 0.8, and h = 2.4. For the unit cell, the relative permittivity is set to 4.4, and the loss tangent is 0.02. The material used for both the SRRs and the ground plane is copper, which has a conductivity of 5.8×10^7 S/m. The thickness of the copper layer is 0.035 mm. while the Fig. 1(b) shows the 3D view of the single substrate unit cell. The observed stop band phenomenon occurs at 5.5 GHz, as depicted in Fig. 2. At this frequency, it is evident that the reflection coefficient (S_{11}) approaches zero, and the transmission coefficient remains below -10 dB. These medium parameters are calculated by placing the unit cell within a waveguide medium [8] [9]. The unit cell is subject to two boundary conditions: (i) Perfect Electric Conductor (PEC) above and below the unit cell and (ii) Perfect Magnetic Conductor (PMC) in front and behind the unit cell. The corresponding real and imaginary reflection and transmission coefficients are obtained and illustrated in Fig. 3. By employing this concept, the magnitude (in dB) of the transmission and reflection coefficients is computed, as demonstrated in Fig. 2. It is evident that the unit cell exhibits a stop-band behavior around 5.5 GHz.



(a) (b)

Fig 1: (a) top view of the unit cell (b) 3D schematic diagram of the unit cell with single substrate.

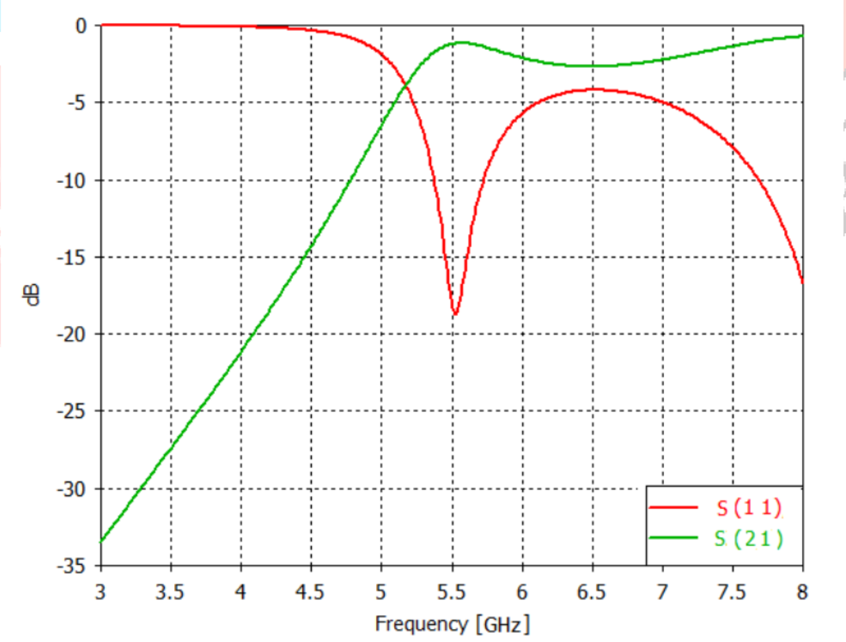


Fig 2: S-parameter of the proposed design

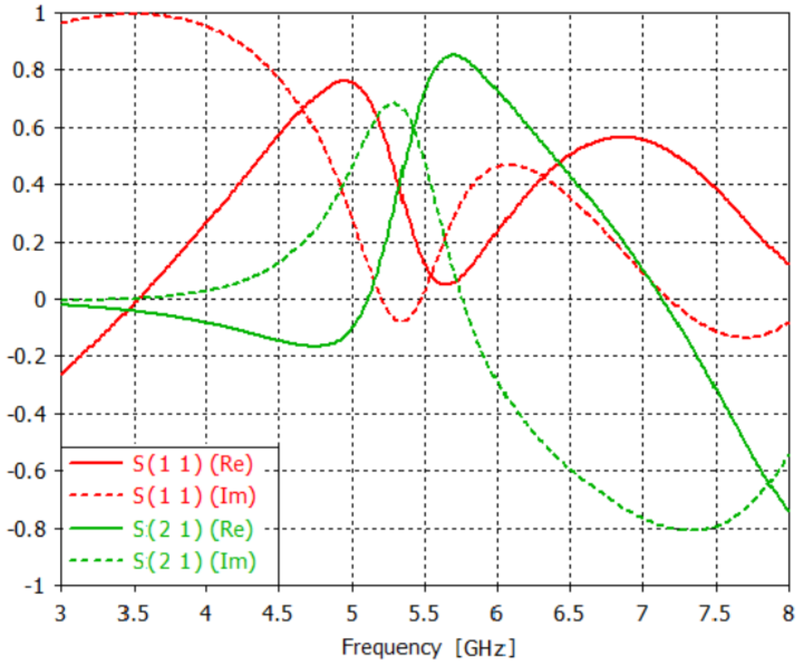


Fig 3: Real and imaginary reflection and transmission coefficient of first unit cell

B. THE PROPOSED SECOND UNIT CELL

The second unit cell, similar to the first unit cell, was analyzed using CST Microwave Studio software. This unit cell is composed of two different substrates, namely FR4 and Rogers RT5880. The design, dimensions, and frequency of this unit cell are identical to those of the first unit cell. A 3D schematic diagram of the unit cell with the double substrate configuration is depicted in Fig. 4. The extracted values of the transmission and reflection coefficients are illustrated in Fig. 5. By analyzing the corresponding real and imaginary reflection and transmission coefficients, as shown in Fig. 6, it is evident that the unit cell exhibits a stop band behavior around 10.7 GHz.

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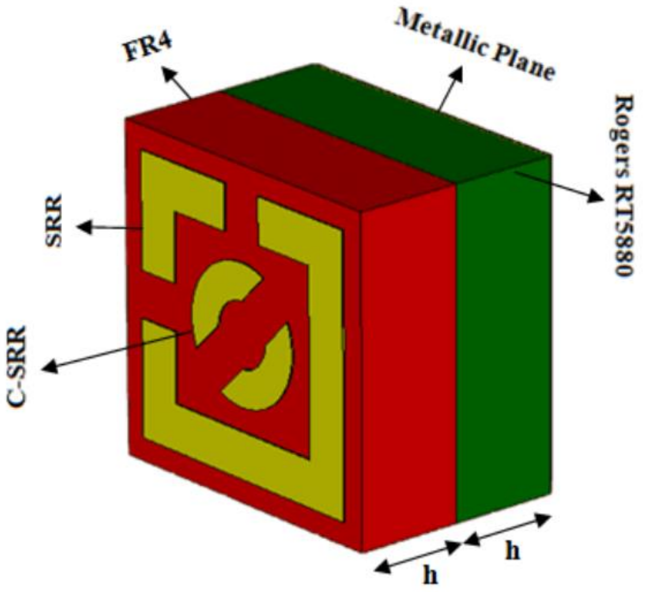

Fig 4: 3D schematic diagram of the unit cell with double substrate

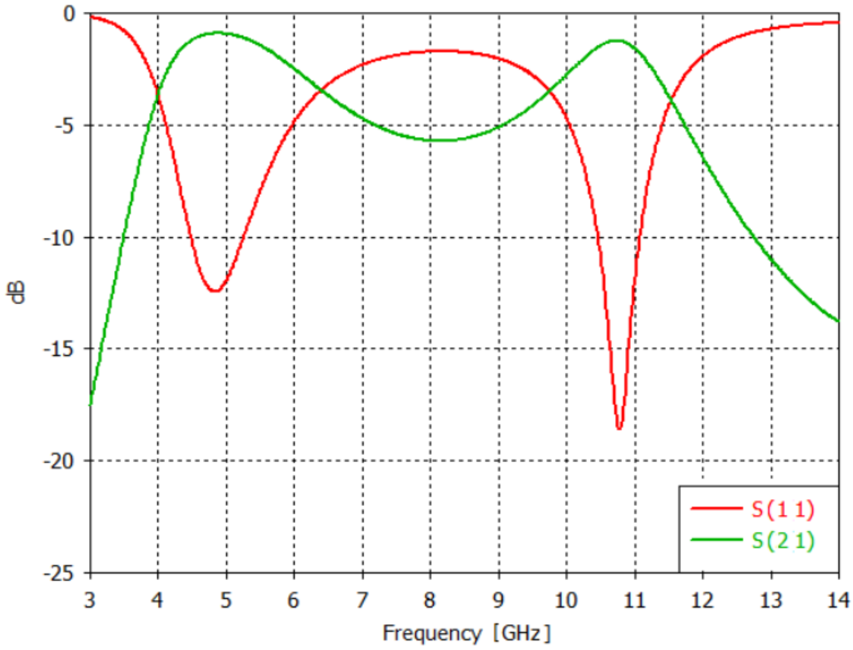

Fig 5: S-parameter of proposed design

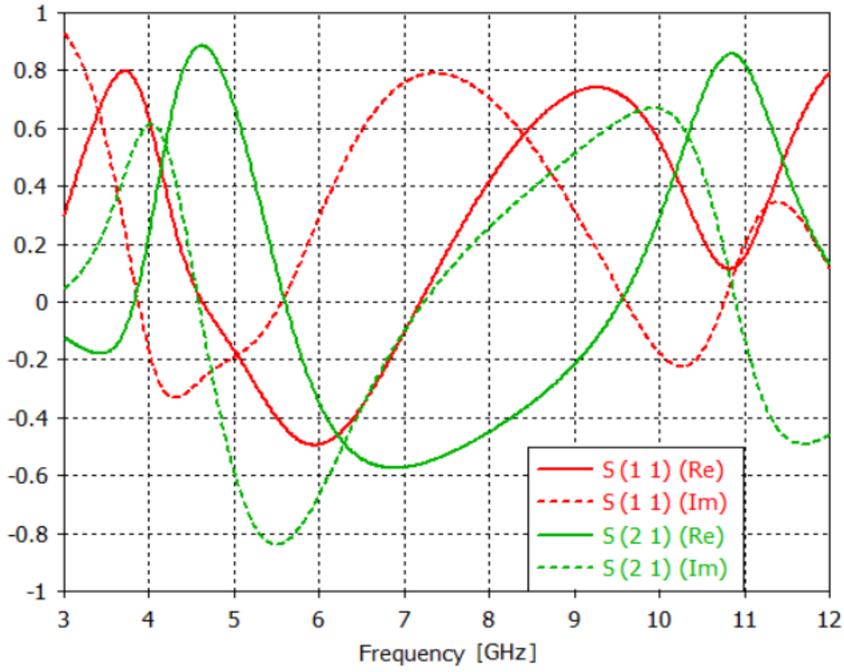

Fig 6: Real and imaginary reflection and transmission coefficient of second unit cell.

III. EXTRACTION OF NEGATIVE PERMITTIVITY AND NEGATIVE PERMEABILITY

A. PERMITTIVITY AND PERMEABILITY FOR FIRST UNIT CELL

From the values obtained from the waveguide medium, we first calculate effective impedance (Z_{eff}) as

$$Z_{eff} = \sqrt{\frac{(1+S_{11})^2 - S_{21}{}^2}{(1-S_{11})^2 - s_{21}{}^2}} \qquad (1)$$

From the values of Z_{eff}, Permittivity (ϵ_{eff}) and effective permeability $\left(\mu_{eff}\right)$are calculated [9]

$$_{eff} = \frac{n_{eff}}{z_{eff}} \qquad (2)$$

$$\mu_{eff} = n_{eff\times}Z_{eff} \qquad (3)$$

The entire value of ϵ_{eff} and μ_{eff} is calculated using MATLAB Code and Plot is illustrated in Fig. 7 and Fig 8.

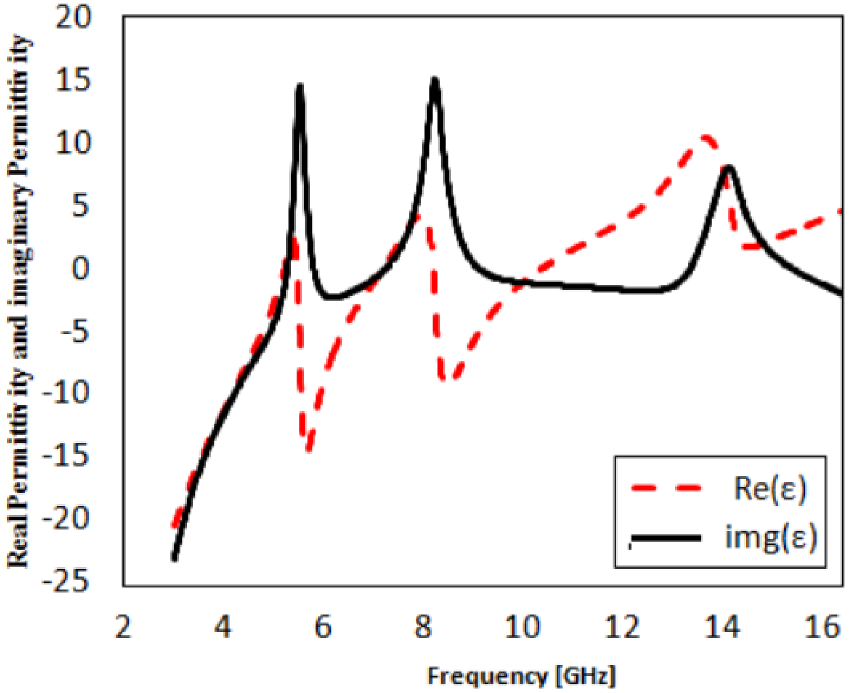

Fig 7: Retrieved permittivity for first unit cell

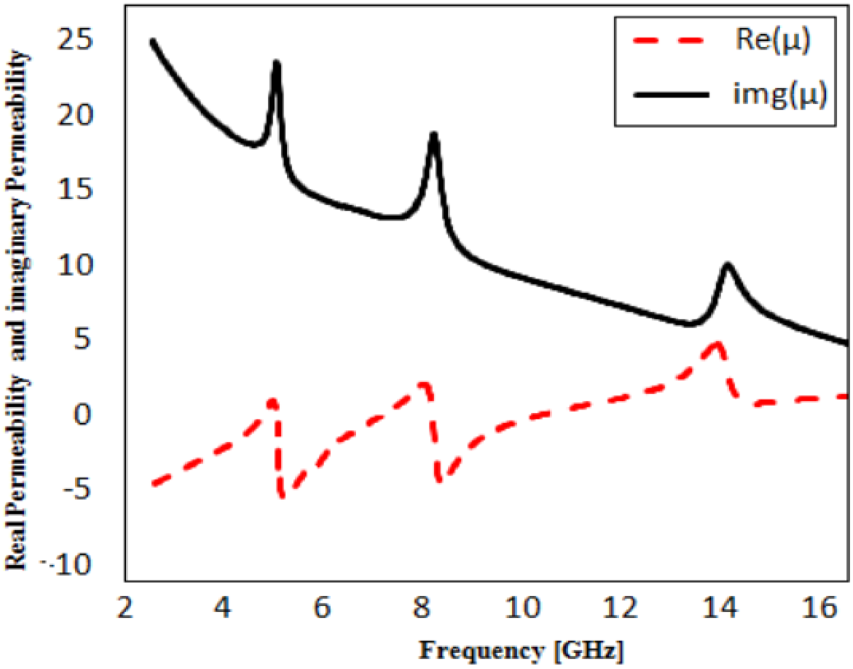

Fig 8: Retrieved permeability for first unit cell

B. PERMITTIVITY AND PERMEABILITY FOR SECOND UNIT CELL

Similar to the calculation procedure described for the previous unit cell, the effective permittivity ϵ_{eff} and effective permeability μ_{eff} of the second unit cell were computed. The results are presented in Fig. 9 and Fig. 10. It is evident that this unit cell exhibits a stop band phenomenon at 10.7 GHz. This observation is supported by the negative permeability observed within this frequency range, as indicated in the S-parameter graph where the stop band is observed exclusively at 10.7 GHz.

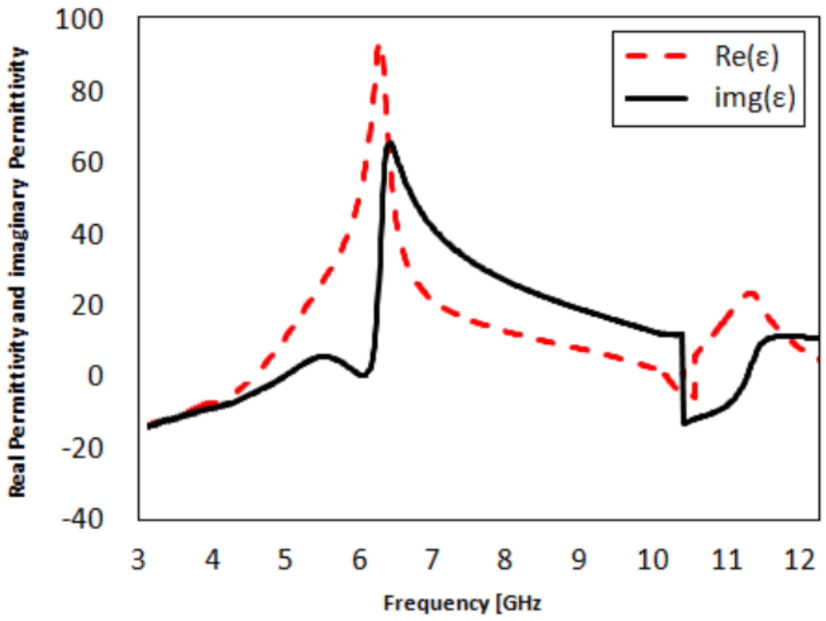

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Fig. 9. Retrieved permittivity for second unit cell.

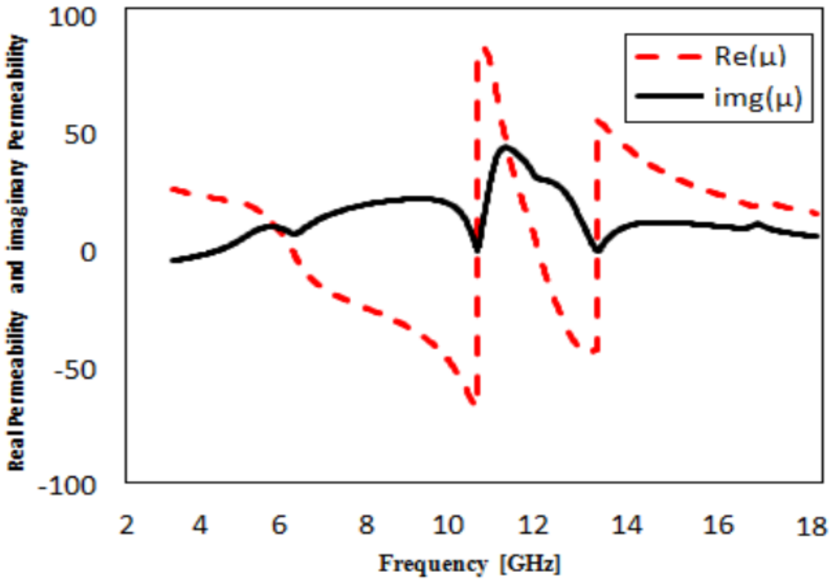

Fig 10: Retrieved permeability for second unit cell

IV. CONCLUSION

In this research paper a novel metamaterial unit cells have been analyzed by using simulation software CST Microwave studio for single substrate and double substrate with stop-band at 5.5 and 10.7 GHz band respectively. The studied unit cell exhibits good stop-band phenomenon at the respective resonance. These unit cells can be integrated with microstrip patch antenna to get desired multiband operations by utilizing these metamaterial unit cells as substrate. Overall, this research contributes to the understanding and exploration of metamaterial unit cells in antenna engineering, providing valuable insights for the design and analysis of advanced antenna systems.

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