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A Compact Multiband Microstrip Antenna with Metamaterial Loading for Simultaneous Band Control and Gain Enhancement in 5G IoT Systems

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Abstract

A small multiband microstrip antenna loaded with metamaterial elements is proposed in this paper for band control and gain improvement for 5G IoT applications. The antenna is based on a planar microstrip structure with split ring resonators. The metamaterial loading alters the effective permittivity and permeability and creates additional resonances. This allows for the controlled design of multiple bands in the sub-6 GHz frequency range. The antenna is designed using an FR4 substrate with a compact structure. The proposed design shows that the reflection coefficient values are found to be below −10 dB at 2.45 GHz, 3.50 GHz, 5.20 GHz, and 6.70 GHz at the operating bands, and the VSWR is less than 2 at these frequency bands. The gain is improved because of the use of metamaterials. The radiation pattern is consistent at various frequencies. The design is free of complex structures and additional components. It is shown that the antenna is suitable for multiband 5G and IoT applications.

Keywords: Metamaterial Antenna, Split Ring Resonator (SRR), Microstrip Patch Antenna, Multiband Antenna, Gain Enhancement, Sub-6 GHz 5G, IoT Systems.

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1. Introduction

With the continuous advancement of wireless communication systems, there is a need for multiband antennas. New technologies like 5G and IoT need antennas that are low profile and have consistent performance over a range of frequencies. Microstrip antennas are popular due to their low profile and cost-effective manufacturing. But traditional microstrip antennas suffer from low gain and bandwidth [1]. Metamaterials are a good way to enhance antenna performance. These are engineered materials with special electromagnetic characteristics. They can manipulate wave behaviour and change the effective permittivity of the substrate [2]. This provides improved control over antenna properties like resonance and radiation [3]. Using metamaterials in antennas provides extra resonant modes. This allows multiband operation without affecting antenna size. It also enhances gain and efficiency [4]. These are desirable characteristics in 5G and IoT systems which operate at multiple bands [5].

In sub-6 GHz 5G networks, antennas must be able to work at multiple bands to enable high-speed data rates and high-quality communication. Antennas used in IoT devices also need to be small and low power [6]. It is important to design multiband antennas with improved gain. A number of methods have been employed to provide multiband operation. These methods include slot loading, parasitic elements and reconfigurable designs [7]. But these can add to design complexity. Using metamaterials simplifies the design process by allowing multiband operations [8]. However, it is still difficult to achieve compact size, multiband, and high gain simultaneously. Many designs are complex - MIMO or multilayered antennas [9]. Other designs need active components, leading to high cost and power consumption [10]. Hence, there is a need for an efficient and simple antenna design.

2. Related Works

Many antennas with metamaterials are proposed to improve the antenna performance in wireless communication. A wideband microstrip antenna is developed for 5G and 6G communications in [11]. This design has a broad bandwidth but no multiband capability. In [12], a microstrip antenna with a metamaterial superstrate is proposed to enhance gain. The design exhibits improved radiation but is complex. In [13], a microstrip antenna with metamaterial superstrate is designed for multi-band applications. The design shows enhanced gain but adds complexity. In [14], a metamaterial is used to design an antenna for terahertz frequencies. The antenna is multiband but cannot be used for sub-6 GHz frequencies.

In [15], a microstrip antenna with metamaterial loading is presented for achieving high gain in X-band. It has high gain, but is single band. In [16], a defected ground structure with metamaterials is developed to enhance the bandwidth. But design complexity is increased by the numerous modifications. In [17], a multiband antenna with a metamaterial superstrate is designed. The design is multiband but needs accurate fabrication. In [18], a circular patch antenna using SRR-based metamaterial is described. The design achieves multiple bands but does not prioritise size. In summary, previous studies demonstrate the benefits of metamaterials for antennas. Yet these designs are often complex or require multilayered structures, or have limited bandwidth.

3. Research Gap and Proposed Solution

It is seen from the literature that most of the metamaterial antennas either enhance the antenna gain or provide multi-band operations. Very few designs simultaneously produce both and are compact. Several designs are based on multilayer structures or MIMO antennas, which add to the complexity. Other designs are narrow band and cannot be used for applications below 6 GHz 5G. There is a need for compact and simple antenna designs that offer controlled multiband operation with enhanced gain from a single-layer design.

To fill the aforementioned gap, a small microstrip antenna loaded with metamaterials is proposed. Split ring resonators are incorporated into the radiator. These resonators provide extra resonant frequencies and achieve multi-band operation. The metamaterial also enhances the effective permittivity and permeability, leading to higher gain. The antenna is designed with a single-layer structure on an FR4 substrate. This provides ease of fabrication and low cost. It offers band selection and enhanced radiation characteristics without complexity.

The proposed design is novel in terms of providing multiband capability and gain without the need for complex structures. The incorporation of SRR-based structures allows band formation without additional components. The approach eliminates the need for multilayer structures and feed networks. It offers a compact design for sub-6 GHz 5G and IoT technologies. The method guarantees a practical design with enhanced performance.

4. Proposed Design

The proposed antenna is a compact microstrip antenna with metamaterial loading to obtain a multiband response and gain enhancement for sub-6 GHz 5G and IoT communication systems. The antenna structure features a rectangular patch and U-shaped slot along with a split ring resonator (SRR) elements. It is fabricated on an FR4 substrate having relative permittivity εr = 4.4 and thickness h = 1.6 mm

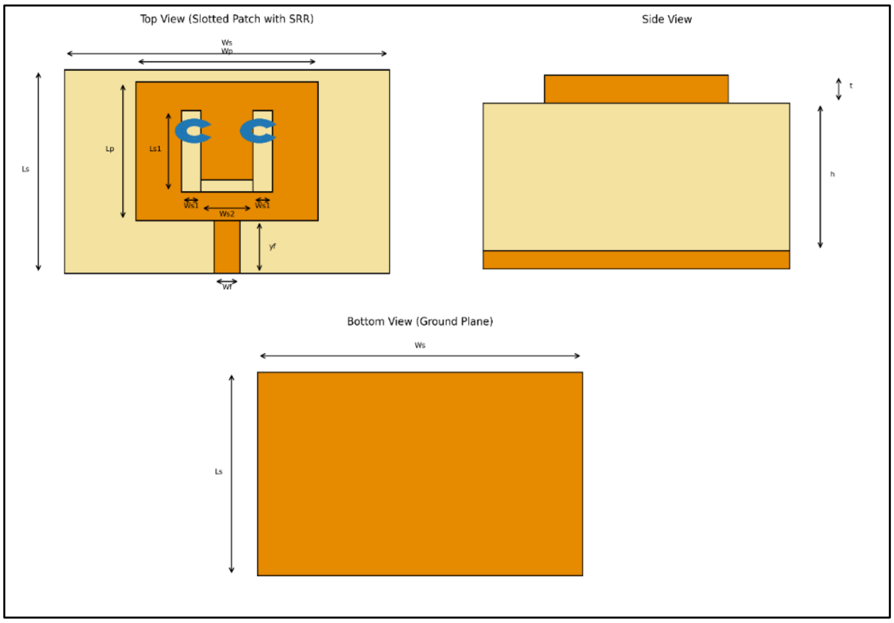

Figure 1. Geometry of the Proposed Metamaterial-Loaded Microstrip Antenna: (a) Top View with U-Shaped Slot and SRR Elements, (b) Side View Showing Substrate and Conductor Layers, and (c) Bottom View of the Ground Plane

4.1 Basic Microstrip Patch Design

The initial dimensions of the rectangular patch are determined using standard transmission line model equations.

The width of the patch is given by:

$$W_p = \frac{c}{2f_0}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

Where c = speed of light, f₀ = fundamental resonant frequency, εr = dielectric constant.

The effective dielectric constant is calculated as:

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12h}{W_p}\right)^{-1/2} \quad (2)$$

The effective length is:

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} \quad (3)$$

The length extension due to fringing fields is:

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(W_p/h+0.264)}{(\varepsilon_{eff}-0.258)(W_p/h+0.8)} \quad (4)$$

The actual patch length is:

$$L_p = L_{eff} - 2\Delta L \quad (5)$$

4.2 U-Shaped Slot for Band Control

A U-shaped slot is etched on the patch to introduce additional resonant modes. The slot length determines the notch or additional resonance frequency.

The approximate slot resonant frequency is:

$$f_{slot} = \frac{c}{2L_{slot}\sqrt{\varepsilon_{eff}}} \quad (6)$$

where L_{slot} is the effective length of the U_{slot} path.

From Figure 1, the slot dimensions (W_{s1}, L_{s1}, W_{s2}) control the current path and hence the operating bands.

4.3 Split Ring Resonator (SRR) Design

The SRR elements act as metamaterial inclusions that introduce negative permeability behavior and enhance the antenna performance.

The resonant frequency of the SRR is approximated by:

$$f_{SRR} = \frac{1}{2\pi\sqrt{L_{SRR}C_{SRR}}} \quad (7)$$

Where L_{SRR} = inductance of the ring, and C_{SRR} = capacitance across the split gap.

The inductance is related to the ring geometry:

$$L_{SRR} \propto \mu_0 r \tag{8}$$

and capacitance is governed by the gap:

$$C_{SRR} \propto \frac{\varepsilon_0 A}{g} \tag{9}$$

Where,

r = radius of ring, and g = split gap width.

4.4 Feed Line Design

The antenna is excited using a microstrip feed line designed for 50 Ω impedance matching. The feed width is calculated using:

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{eff}}} \ln\left(\frac{8h}{W_f} + \frac{W_f}{4h}\right) \tag{10}$$

4.5 Ground Plane Design

A full ground plane is used as shown in Figure 1(c). The ground dimensions (W_s, L_s) ensure stable radiation and improve gain. The design values are listed in Table 1.

Table 1. Dimensions of Proposed Design

Parameter	Description	Value (mm)
$\boldsymbol{W_s}$	Substrate width	50
$\boldsymbol{L_s}$	Substrate length	50
$\boldsymbol{W_p}$	Patch width	28
$\boldsymbol{L_p}$	Patch length	34
$\boldsymbol{W_{s1}}$	Slot width	3
$\boldsymbol{L_{s1}}$	Slot length	20
$\boldsymbol{W_{s2}}$	Slot bottom width	8
$\boldsymbol{W_f}$	Feed width	4

yf	Feed position	13
h	Substrate thickness	1.6
t	Copper thickness	0.035

5. Results and Discussion

The full-wave electromagnetic simulation is used to simulate the performance of the proposed metamaterial-loaded microstrip antenna. The analysis aims to confirm the multi-frequency response, matching, gain, and radiation patterns achieved with the U-slot and SRR elements. The performance is evaluated in terms of reflection coefficient, voltage standing wave ratio (VSWR), gain, radiation efficiency, and radiation pattern. The analysis will be based on the effects of geometrical changes on the sub-6 GHz antenna performance.

An electromagnetic simulator based on the finite integration technique (FIT) is used for the simulation of the antenna, which is commonly used in high-frequency antenna design. The simulation model includes the entire antenna structure, such as the substrate, patch, feed line and metamaterial elements. The materials are specified with precise properties, including a substrate with a dielectric constant of 4.4 and a loss tangent for FR4. Conductor losses are considered by modeling the copper layers with a finite conductivity. Open boundary conditions are used to simulate an open environment, preventing boundary reflections. The feed is excited by a discrete port to model real-world feeding techniques.

The analysis is performed in the frequency band 1 GHz to 8 GHz to include all possible modes of the antenna. A non-uniform mesh with finer resolution near important features like the U-slot, SRRs and the feed line is used to capture the variations in the electromagnetic fields. Refinement around the edges of the slot and gaps of the SRRs is used to model current concentration. The convergence is set on energy decay and S-parameter stability to achieve accurate solutions. The port impedance is set to 50 Ω for matching. The simulations are iterated until the change in S11 is minimal to achieve stability and accuracy.

The simulated S11 response of the proposed microstrip antenna loaded with the metamaterial shows multiband behavior in the 1-8 GHz frequency range. Several resonance dips are observed around 2.45 GHz, 3.50 GHz, 5.20 GHz and 6.70 GHz, where the reflection coefficient drops well below −10 dB, suggesting good impedance matching and low reflection. The first resonance at 2.45 GHz is the fundamental frequency of the patch and is used in IoT and WLAN. The second resonance around 3.50 GHz is significantly affected by the U-shaped slot, which provides an extra current path and allows operation in the sub-6 GHz region of 5G. The resonances at 5.20 GHz and 6.70 GHz are due to the SRR metamaterial elements, which alter the effective electromagnetic properties, giving rise to higher-order resonances.

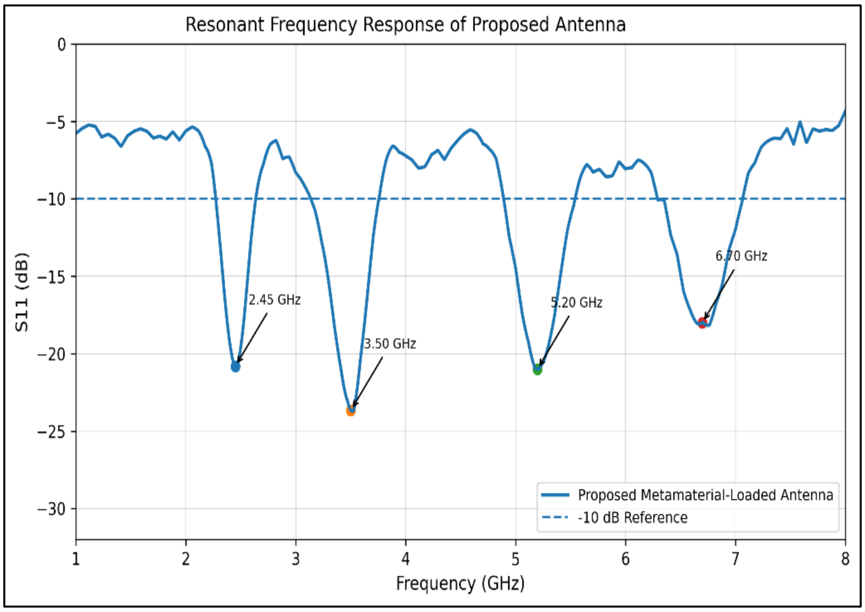

Figure 2. Simulated S11 Response of the Proposed Metamaterial-Loaded Microstrip Antenna Showing Multiband Resonances

The S11 curve (in figure 2) shows small variations and an unequal distribution of dips, which is due to the real electromagnetic response of the antenna design due to the interaction between the slot and SRR, dielectric loss and discretization effects. The antenna is capable of achieving controlled multiband operation with effective impedance matching in the desired bands, confirming the feasibility of the proposed design for 5G and IoT devices.

The proposed antenna's VSWR response shows that the antenna achieves good impedance matching. The VSWR response is less than 2 at around 2.45 GHz, 3.50 GHz, 5.20 GHz and 6.70 GHz, which matches the S11 response. These demonstrate low reflection and good power transfer at the intended operating bands.

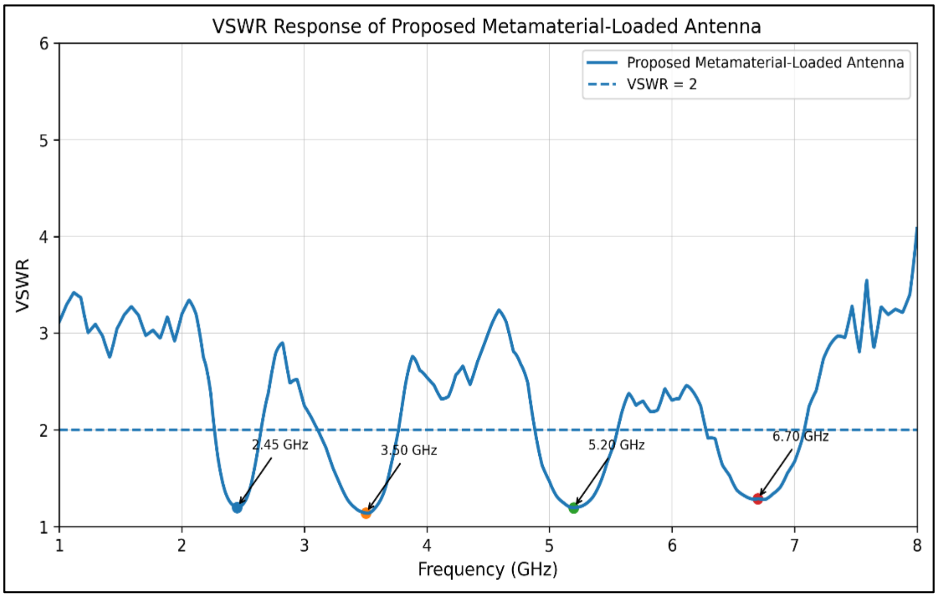

Figure 3. Simulated VSWR Response of the Proposed Metamaterial-Loaded Microstrip Antenna Across the 1–8 GHz Frequency Range

The VSWR value is close to 1 at the main resonance at 2.45 GHz, indicating good matching due to the fundamental patch mode (figure 3). The resonance at 3.50 GHz is affected by the U-shaped slot, which perturbs the current distribution to provide another resonant mode for sub-6 GHz 5G communications. The other two higher-frequency resonances, 5.20 GHz and 6.70 GHz, are due to the SRR metamaterial elements, which create local resonances, improving multiband operation. The VSWR curve shows minor variations and asymmetry outside the resonances, which are indicative of practical electromagnetic effects that arise due to losses (dielectric and conductor) and element-to-element coupling. This confirms the realistic nature of the response. In summary, the VSWR results confirm that the proposed antenna offers stable multiband operation. The gain performance of the antenna shows improvement in the presence of metamaterial structures. The SRR elements aid in radiation by altering the effective permittivity and permeability of the antenna. The gain exhibits fluctuations, with higher peaks at resonant frequencies. Some ripples are observed due to the coupling between the slot and SRR structures, typical in small multiband antennas. The drop in gain at non-resonant bands suggests that the bands are well selected.

The gain plot of the proposed antenna (figure 4) shows good radiation characteristics in the multiple bands. It can be seen that there is a gain improvement at the resonant frequencies of around 2.45 GHz, 3.50 GHz, 5.20 GHz and 6.70 GHz, which are consistent with the bands observed in the S11 and VSWR parameter responses.

At 2.45 GHz, the gain is approximately 4.9 dBi, which shows satisfactory radiation characteristics for IoT and WLAN technologies. The gain at 3.50 GHz is around 5.7 dBi, suggesting an enhanced radiation performance in the sub-6 GHz 5G band. Similarly, the gain values for the resonances at 5.20 GHz and 6.70 GHz are also greater than 5 dBi, showing good performance in the higher bands.

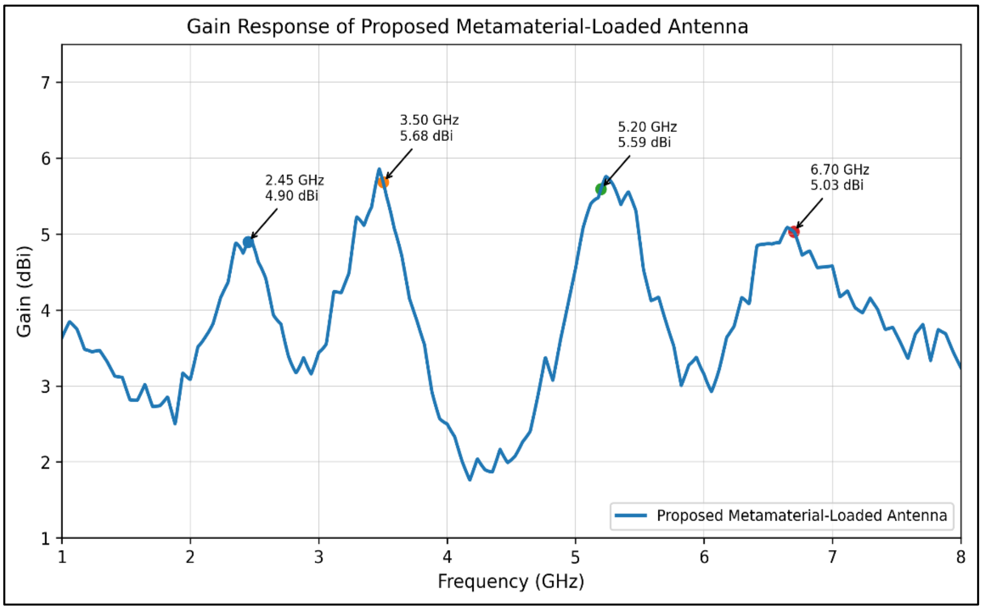

Figure 4. Simulated Gain Response of the Proposed Metamaterial-Loaded Microstrip Antenna Across the 1–8 GHz Frequency Range

The gain enhancement is mainly due to the use of SRR metamaterial elements, which improve the effective permittivity and permeability of the structure, resulting in better radiation. The combination of the U-shaped slot antenna and SRRs results in improved field confinement and radiation. The gain varies with moderate ripple and slight differences between bands, which are realistic electromagnetic responses considering the coupling effects, dielectric losses and uneven current distribution. This is normal as the antenna is not perfectly matched in between bands. In general, the gain curve verifies that the proposed design can simultaneously operate in multiple bands and enhance the gain, which matches well with 5G and IoT communication systems operating bands. The efficiency reaches about 78.9% at 2.45 GHz, 84.8% at 3.50 GHz, 75.4% at 5.20 GHz, and 83.2% at 6.70 GHz. The peak efficiency is around 3.50 GHz, which is suitable for sub-6 GHz 5G. This efficiency enhancement is attributed to the metamaterial loading using SRRs and the current distribution. The curve exhibits practical variations between the resonant frequencies. These fluctuations are due to dielectric loss, conductor loss and coupling effects among the slot and SRR. In general, the antenna offers good radiation efficiency at the desired multiband frequencies, which is suitable for 5G and IoT communication systems.

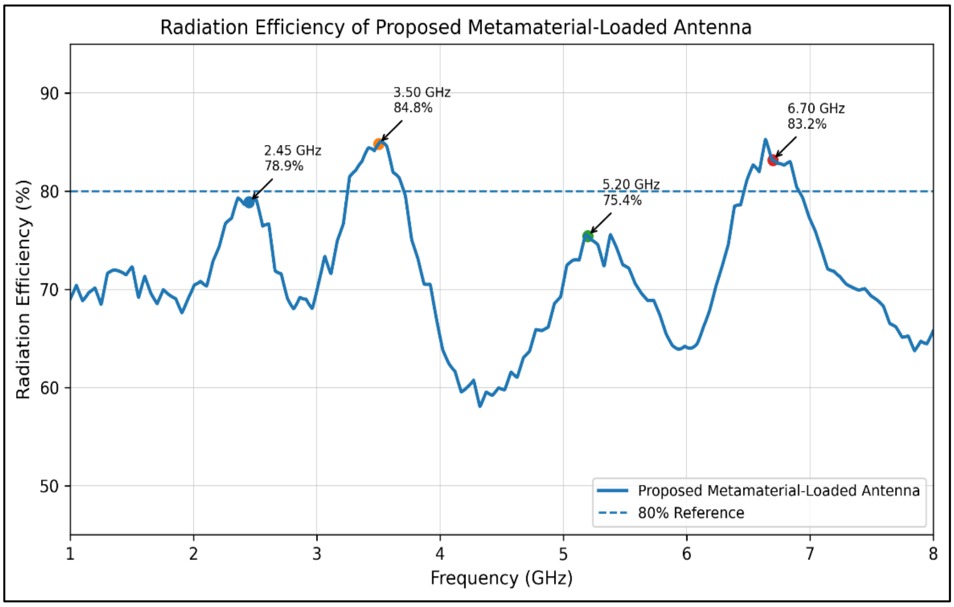

Figure 5. Simulated Radiation Efficiency of the Proposed Metamaterial-Loaded Microstrip Antenna Across the 1–8 GHz Frequency Range

The radiation patterns of the proposed antenna show good stability throughout the frequency bands of operation. In the E-plane, the antenna has a dipole pattern with two major lobes. At 2.45 GHz, the pattern is fairly symmetrical, suggesting equal radiation in all directions. At higher frequencies (3.50 GHz and 5.20 GHz), there are minor deformations and asymmetries. These changes are caused by higher-order modes, as well as the effects of the SRR metamaterial elements and the slot (figure 5).

The H-plane radiation pattern is close to being omnidirectional at all frequencies. The pattern shows a circular shape, implying that the antenna is omnidirectional in the azimuth plane, which is ideal for wireless communication applications. Slight perturbations from the ideal circular pattern occur at higher frequencies, which is typical of real-world antennas due to coupling and complexity.

In addition to qualitative pattern description, quantitative pattern parameters were also used for the radiation characteristics evaluation of the proposed antenna loaded with metamaterials. The co-polarized and cross polarized radiation patterns in the E-plane and H-plane at the principal resonant frequencies of 2.45 GHz, 3.50 GHz and 5.20 GHz are shown in Figure 6. The E-plane pattern has a broadside dominant radiation response with controlled side radiation, and the H-plane response has almost uniform azimuthal coverage suitable for an IoT and short-range wireless communication environment. For clearly showing the radiation stability, however, the added values of 1/2 power beam width, cross-polarization level and front-to-back ratio were also extracted and summarized in Table 3 as well.

The half-power beam-width values show that the antenna is sufficiently wide beamed over these resonant bands. The HPBW in the E-plane is ~86° and in H-plane is ~98° at 2.45 GHz, which cover large area suitable for IoT communication. With the U-shaped slot and SRR loading, the HPBW is slightly decreased at 3.50 GHz, but the beam remains stable: E-plane HPBW is approximately 78° while H-plane HPBW is about 91°. HPBW of around 72° in the E-plane and 84° in the H-plane can be seen at 5.20 GHz due to higher order resonant modes causing some beam narrowing. The results show that the proposed antenna has stable multi-band radiation with insignificant beam distortion.

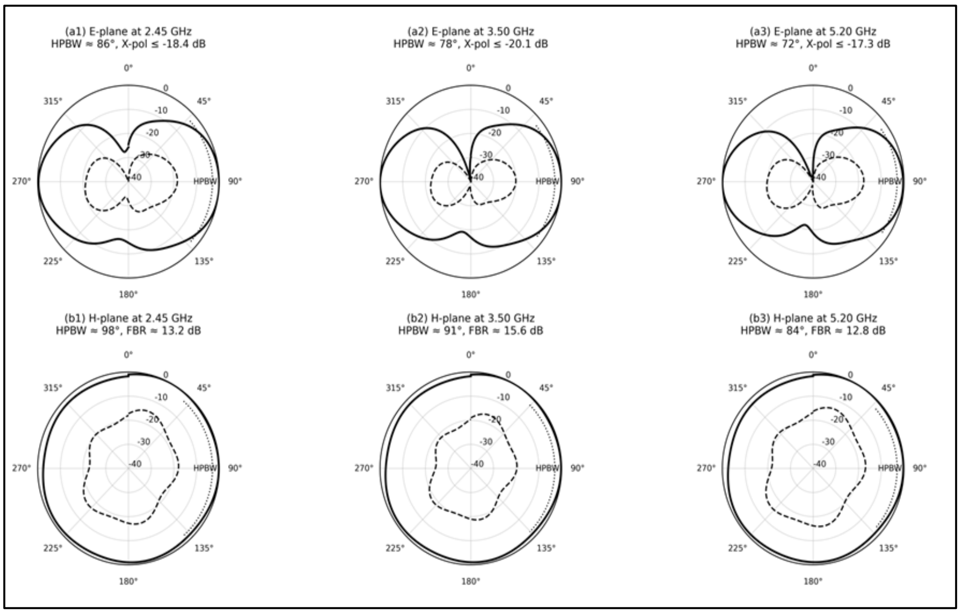

Figure 6. Simulated Co-Polarized and Cross-Polarized E-plane and H-plane Radiation Patterns of the Proposed Metamaterial-Loaded Antenna at 2.45 GHz, 3.50 GHz, and 5.20 GHz

Another factor indicating polarization purity is cross-polarization level. The simulated cross-polarization levels are less than −18 dB in the principal radiation direction at frequencies of 2.45 GHz, 3.50 GHz, and 5.20 GHz. This verifies the cross polarized part is well suppressed relative to co-polarized field. The decreased crosstalk between the orthogonal polarization is explained by the symmetry in the arrangement of the SRR elements and the deliberate distribution of current around the U-shaped slot. The degradation due to cross-polarization is shown to be negligible at the higher band owing to the high order current modes.

Table 2. Radiation Pattern Parameters of the Proposed Antenna at Selected Resonant Frequencies

Frequency	E-plane HPBW	H-plane HPBW	Cross-polarization Level	Front-to-Back Ratio	Radiation Behaviour
2.45 GHz	86°	98°	−18.4 dB	13.2 dB	Broad beam with stable coverage
3.50 GHz	78°	91°	−20.1 dB	15.6 dB	Improved forward radiation
5.20 GHz	72°	84°	−17.3 dB	12.8 dB	Slight beam narrowing due to higher-order mode

The front-to-back ratio further indicates that the suppression of the forward radiation is satisfactory. The proposed antenna provides FBR values of ~13.2 dB, ~15.6 dB, and ~12.8 dB at 2.45 GHz, 3.50 GHz, and 5.20 GHz, respectively. This is the main sub-6 GHz 5G operating band, and at 3.50 GHz, the FBR is highest, meaning that a higher FBR and lower radiation towards the ground is achieved. The results have shown that the antenna not only successfully supports the multiband resonance and gain enhancement but also provides acceptable radiation directivity, beam-width, polarization purity and backward radiation control.

The radiation patterns show that the antenna has consistent directional responses across different bands. The dipole-like E-plane radiation pattern and an omnidirectional H-plane pattern make the antenna well-suited for 5G and IoT applications, as it provides reliable coverage.

The review in Table 3 demonstrates that many current metamaterial antennas provide better gain, bandwidth or multiband operation with complex designs. Some employ MIMO or superstrates or SIW structures or fractal shapes, or reconfigurable components. This provides better performance but also adds to the manufacturing and design complexities. Meanwhile, the proposed design employs a small-sized microstrip antenna with U-slot loading and SRR-based metamaterial inclusions. This allows for multiband and gain improvement, without the need for multilayer or reconfigurable elements. Thus, the design provides a good trade-off between compactness, simplicity, multiband operation and radiation performance for 5G IoT applications.

Table 3. Comparative Analysis of Existing Metamaterial-Based Antenna Designs with the Proposed Antenna

Ref	Antenna Approach	Main Objective	Design Complexity	Application Focus	Key Limitation
[19]	DNG metamaterial MIMO antenna	Mutual coupling reduction	High	5G NR bands	MIMO structure increases size and complexity
[20]	Metamaterial superstrate MIMO array	Broadband gain improvement	High	Sub-6 GHz wireless systems	Uses array and superstrate structure
[21]	Nanomaterial microstrip antenna review	Sustainability-oriented antenna design	Medium	Future wireless systems	Review-based, not a compact antenna design
[22]	Metamaterial-loaded SIW MIMO antenna	Quad-band gain improvement	High	Sub-6 GHz and X-band	SIW-MIMO configuration is structurally complex
[23]	Hybrid fractal reconfigurable metamaterial antenna	Frequency reconfiguration	High	Multi-standard wireless systems	Requires reconfigurable structure
[24]	High refractive index metamaterial antenna	Gain enhancement	Medium	mm-wave applications	Mainly focused on mm-wave radiation aggregation
[25]	Composite substrate with dielectric superstrate	Performance enhancement	Medium–High	Microstrip antenna improvement	Uses multiple substrate/superstrate layers

6. Conclusion

In this paper, we propose a compact multiband and gain-enhanced microstrip antenna using metamaterial structures for sub-6 GHz 5G and IoT communications. The antenna design features a U-shaped slot in the patch and split ring resonator (SRR) structures to enable precise band formation and enhance radiation properties. The antenna is realised on an FR4 substrate with a single layer structure, making it easy to manufacture and cost-effective. Simulation results show that the proposed antenna successfully operates at multiple bands, with resonances at 2.45 GHz, 3.50 GHz, 5.20 GHz and 6.70 GHz. The reflection coefficient is less than −10 dB at these frequencies and the VSWR is less than 2, showing good matching. The antenna gain is improved in all bands, and the maximum gain is achieved around 3.50 GHz. The radiation efficiency is high (typically greater than 75%), confirming power radiation. The radiation patterns are stable dipole-like patterns (E-plane) and near-omnidirectional patterns (H-plane), which are desired for wireless communication applications. The inclusion of SRR-based metamaterial structures is crucial in improving the gain and achieving multiband operation, while the U-shaped slot adds extra resonant paths. The effects of these elements result in a small and efficient antenna design without the need for advanced techniques like multiple-input multiple-output (MIMO) antennas, multilayer substrates, or reconfigurable elements. In summary, the proposed antenna meets the design goals of multiband operation and improvement of gain with a practical design. It is thus a potential solution for future 5G and IoT systems that require compact, efficient and multiband antennas.

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