International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 08 August 2026
Page No: 5238 - 5243
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0685

Design and Performance Analysis of Metamaterial Loaded House-Shaped Microstrip Antenna with OLR Superstrate for 3.5 GHz 5G Applications

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Abstract
A 3.5 GHz microstrip patch antenna is developed in this study with a metamaterial-based enhancement of sub-6 GHz 5G communication. The suggested design uses Rogers Reinforced Teflon /duroid 5880, having a relative electric permittivity of 2.2 and a dissipation factor of 0.0009, with a house-shaped copper patch as the radiating element. A metamaterial superstrate consisting of 15 Open-Loop Resonator (OLR) cells in a 3 × 5 arrangement is positioned above the patch to modify the electromagnetic behavior of the antenna. A coaxial-probe is used for excitation, and the complete structure is modeled and analyzed using High Frequency Structure Simulator (HFSS) in ANSYS. The antenna characteristics are evaluated in terms of S11, VSWR, bandwidth, gain, directivity, radiation efficiency, and far field patterns. Three antenna configurations are investigated to determine the individual influence of the superstrate and OLR loading. The final configuration demonstrates improved impedance and radiation characteristics relative to the basic antenna, indicating its suitability for 3.5 GHz sub-6 GHz 5G applications.
Keywords: *5G Sub-6 GHz, Microstrip Patch Antenna, Metamaterial, Open-Loop Resonator (OLR), Pentagonal Patch Antenna, Rogers REINFORCED TEFLON/duroid 5880, Coaxial Feeding, ANSYS HFSS, Radiation Efficiency, Antenna Gain.*

1. Introduction
The continuous evolution of 5G wireless technology has created a need for antennas with improved impedance matching, sufficient gain, good radiation efficiency, and a compact configuration. Within the 5G spectrum, sub-6 GHz bands are important because they offer a suitable trade-off between transmission coverage and achievable data rates, with 3.5 GHz being one of the significant frequency regions for 5G deployment. Microstrip patch antennas are widely considered for such applications due to their low-profile nature, straightforward construction, fabrication simplicity, and convenient integration with planar circuits [1][2]. Nevertheless, conventional patch antennas may exhibit restricted bandwidth, gain, and radiation characteristics. To overcome these limitations, researchers have explored approaches such as altering the patch shape, selecting suitable dielectric materials, and introducing electromagnetic loading techniques [3][4].The use of metamaterial structures offers an effective method for controlling the electromagnetic behavior of microstrip antennas [5]. Resonant elements, including Open-Loop Resonators (OLRs), can couple with the fields generated by the radiating patch and consequently alter its overall radiation response [2]. Earlier investigations have demonstrated the benefits of OLR-loaded antennas; however, many of these designs employ different operating frequencies and patch geometries. The present study develops a house-shaped microstrip patch antenna near 3.5 GHz using low-loss Rogers REINFORCED TEFLON/duroid 5880 as the dielectric material [6]. A superstrate is introduced above the radiating patch, carrying 15 identical OLR elements arranged in a 3 × 5 array [7][8]. The complete antenna is modeled in ANSYS HFSS and assessed using S11, VSWR, impedance bandwidth, gain, directivity, radiation efficiency, and radiation patterns [9][10]. To determine the contribution of the metamaterial structure, the results of the basic antenna, superstrate-loaded antenna, and final antenna containing 15 OLR cells are compared.

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2. Literature Survey

Previous research has explored pentagonal microstrip patch antennas for multiband wireless communication because of their simple geometry and favorable radiation properties. Modifying the patch with slots or slits can alter its resonant behavior and support operation at multiple frequencies. The incorporation of metamaterial-based Open-Loop Resonators (OLRs) has also been reported as a method for improving gain and reducing cross-polarization. The position and arrangement of these resonators above the patch can influence the impedance and radiation characteristics of the antenna. Such studies provide a useful basis for developing metamaterial-loaded patch antennas with enhanced performance [11].

3. Methodology

3.1.Intended Antenna Design

The Intended antenna is modeled in ANSYS HFSS for operation near 3.5 GHz [4]. The structure consists of a house-shaped copper patch, copper ground plane, coaxial probe feed, lower substrate, and superstrate, as illustrated in Fig. 1 [12]. Rogers REINFORCED TEFLON/duroid 5880, with a relative electric permittivity of 2.2 and dissipation factor of 0.0009, is used for both dielectric layers. Each layer has a thickness of 1.27 mm, while an airgap of 21.65 mm separates the patch and superstrate. The overall antenna dimensions are 60 × 60 mm². As shown in Figure 1 Intended Antenna design.

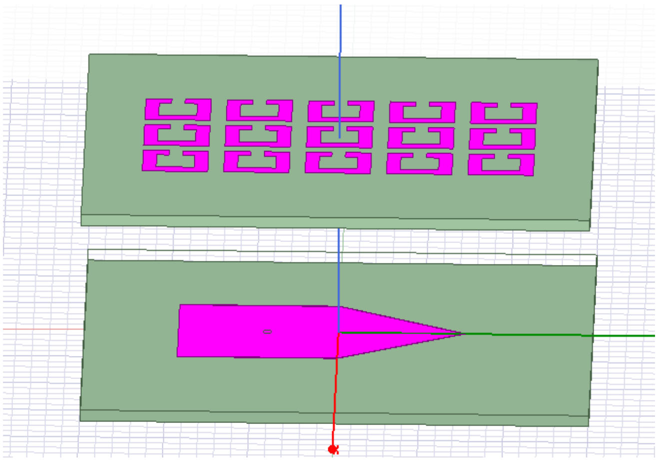

Figure 1 Intended Antenna design

To evaluate the effect of the Intended loading technique, three antenna configurations are investigated. The first configuration is the basic house-shaped patch with the lower substrate and coaxial probe feed [13]. The second configuration adds the superstrate above the basic antenna without OLR elements, as shown in Fig. 2 [14]. The third configuration, representing the Intended antenna, incorporates 15 identical copper OLR cells arranged in a 3 × 5 array on the superstrate above the radiating patch, as shown in Fig. 3 [15]. In all configurations, the coaxial probe is used to excite the patch and provide the input signal. As shown in Figure 2 Geometry of House-shaped Antenna, Figure 3 Geometry of OLR Superstrate Antenna.

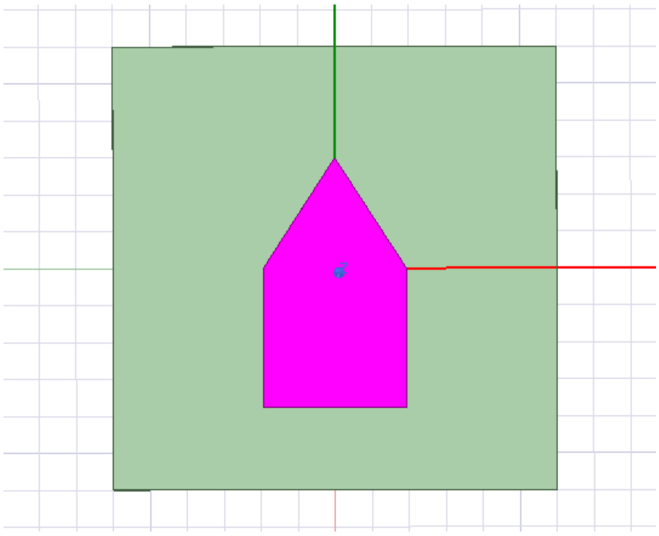

Figure 2 Geometry of House-shaped Antenna

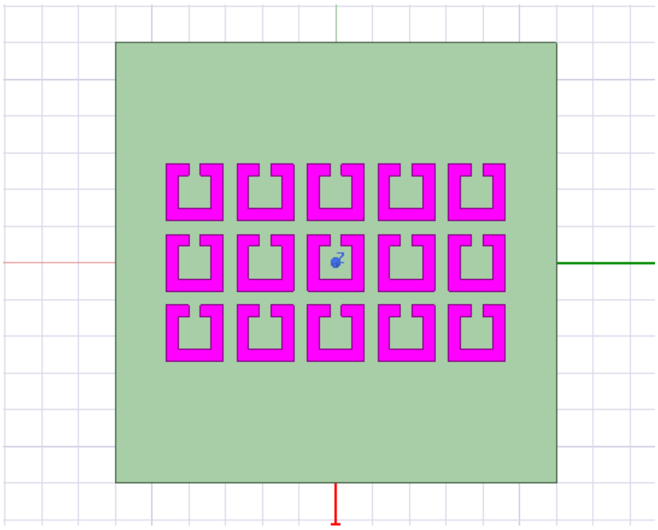

Figure 3 Geometry of OLR Superstrate Antenna

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3.2.Simulation Setup

The antenna is simulated in ANSYS HFSS using the Driven Modal solution at 3.5 GHz. A maximum of 20 adaptive passes is specified with a convergence criterion of ΔS = 0.02, and convergence is achieved after 10 passes with a final ΔS of 0.015569. A radiation region is included for far-field evaluation, while a frequency sweep is used to obtain S11, VSWR, and −10 dB bandwidth [16]. The far-field results provide gain, directivity, radiation efficiency, and radiation patterns. Finally, the three antenna configurations are compared to determine the influence of the superstrate and 15-OLR metamaterial loading on the overall performance.

3.3.Design Equations

1. **Effective dielectric constant**

$$\mathcal{E}eff = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12h}{W}\right)^{-1/2}$$

2. **Effective patch dimension**

$$a_{eff} = \frac{c}{2fr\sqrt{\mathcal{E}eff}}$$

3. **Fringing-field correction**

$$\Delta a = 0.412h\frac{(\mathcal{E}eff+0.33)\left(\frac{a}{h}+0.264\right)}{(\mathcal{E}eff-0.258)\left(\frac{a}{h}+0.8\right)}$$

4. Results And Discussion

The antenna performance is analyzed in terms of S11, VSWR, −10 dB impedance bandwidth, gain, directivity, radiation efficiency, and radiation patterns. The basic antenna is used as the reference, followed by the superstrate-loaded and Intended 15-OLR configurations. The comparison is performed to assess the contribution of each added structure to the overall antenna performance.

4.1.Reflection Coefficient and Bandwidth

The simulated S11 response used to determine the resonant frequency and impedance matching characteristics of the antenna. For the basic configuration exhibits resonance at approximately 3.4775 GHz, with S11 parameter of −20.23 dB. With the introduction of the superstrate and 15 OLR cells, the Intended antenna operates close to 3.5 GHz and achieves a lower S11 of approximately −36.41 dB, as shown in Fig. 4. This improvement indicates enhanced impedance matching between the coaxial feed and the Intended antenna structure as shown in Figure 4 S-Parameter & Bandwidth.

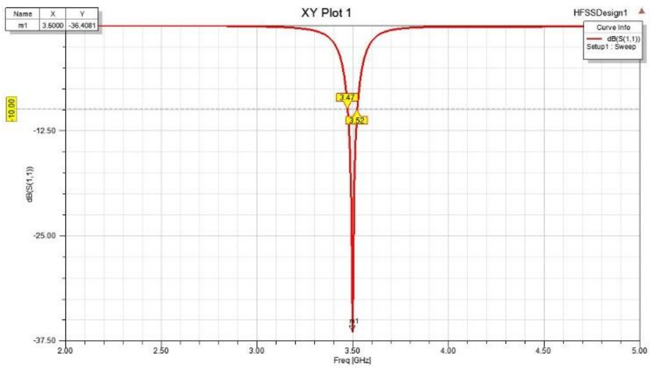

Figure 4 S-Parameter & Bandwidth

The VSWR response is used to measure the impedance matching and maximum power transfer of the antenna. A value close to 1 represents better impedance matching. The basic antenna shows a VSWR of approximately 1.22, while the Intended antenna reaches about 1.03 at its resonant frequency, as shown in Fig. 5. This reduction in VSWR indicates improved impedance matching with the addition of the superstrate and 15-OLR metamaterial structure. As shown in Figure 5 VSWR.

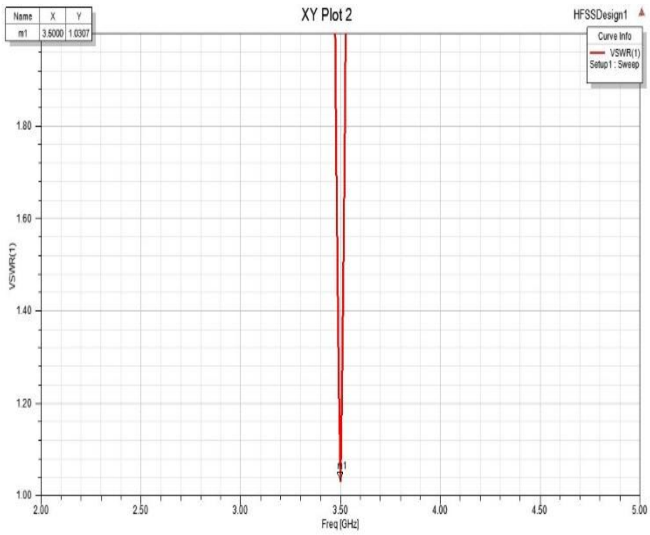

Figure 5 VSWR

4.2.Gain and Directivity

The radiation characteristics are evaluated from the HFSS far-field results using peak gain and directivity.

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The basic antenna provides a peak gain of approximately 7.54 dBi, whereas the Intended metamaterial-loaded configuration reaches about 8.31 dBi, indicating improved radiation performance. The Intended antenna also accomplishes a peak directivity of 8.34 dBi, as shown in Fig. 6, demonstrating a more concentrated radiation pattern. Gain and directivity indicates that the suggested antenna has low radiation losses and good radiation efficiency. As shown in Figure 6 Gain.

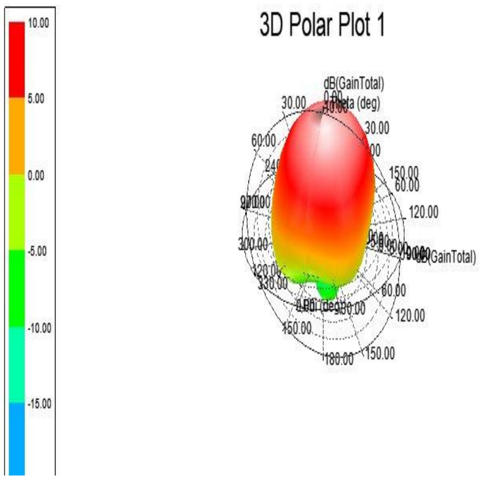

Figure 6 **Gain**

4.3.Radiation Pattern

The far-field performance of the suggested antenna is studied using Electric Plane, Magnetic Plane far field patterns at the operating frequency. The Electric Plane shows the radiation in the plane of the electric field, while the Magnetic Plane shows the radiation in the plane of the magnetic field. These patterns are used to study the radiation direction and distribution of the Intended antenna. As shown in Figure 7 Far Field Pattern of both Electric Plane& Magnetic Plane.

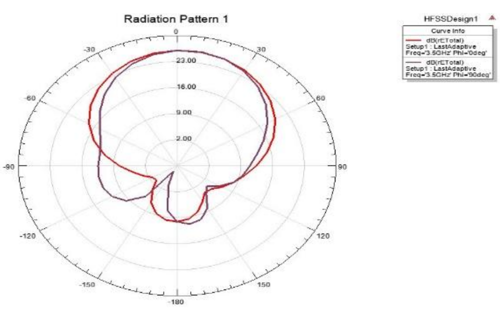

Figure 7 **Far Field Pattern of both Electric Plane& Magnetic Plane**

The Electric Plane and Magnetic Plane radiation patterns show the radiation behaviour of the Intended antenna at the selected operating frequency, as shown in Fig. 7. These patterns help to understand the main radiation direction and beam shape of the antenna.

4.4.Performance Comparison

The simulated results for the basic, superstrate-loaded, and Intended antennas are presented in Table 1. The Intended configuration demonstrates improved impedance matching and gain, while maintaining operation near the desired 3.5 GHz frequency. As shown in Table 1 Comparison of different parameters.

Table 1 **Comparison of different parameters**

Parameter	**Basic Antenna**	**Superstrate Loaded Antenna**	**Intended Antenna (15 OLRs)**
Resonant Frequency (GHz)	3.4775	3.4775	3.5
Minimum S11 (dB)	−20.2267	-23.5043	-36.4081
VSWR	1.2159	1.1432	1.0307
Peak Gain(dBi)	7.54	7.60	8.31

4.5.Discussion

The simulation results presented in Table 2 demonstrate that the Intended metamaterial-loaded antenna offers improved overall characteristics compared with the basic house-shaped patch. The superstrate alters the electromagnetic environment of the patch, while the 15 OLR cells further influence the interaction of the radiated fields with the upper structure. These modifications affect the resonant frequency, impedance matching, gain, bandwidth and directivity. Hence, the Intended antenna is suitable for operation near the 3.5 GHz 5G sub-6 GHz band. As shown in Table 2 Summary of the Suggested Antenna.

Table 2 Summary of the Suggested Antenna

Parameter	Intended Antenna
Resonant frequency	3.50 GHz
Minimum S11	−36.4081 dB
−10 dB Bandwidth	≈ 50 MHz
VSWR	1.0307
Peak Gain	8.30978 dBi
Peak Directivity	≈ 8.34 dBi
OLR Configuration	3 × 5 (15 cells)
Substrate & Superstrate Thickness	1.27 mm
Air Gap	21.65 mm
Overall Antenna Size	60 × 60 mm²
Substrate Material	Rogers REINFORCED TEFLON/duroid 5880
Feeding Technique	Coaxial Probe Feed

Conclusion

A house-shaped microstrip patch antenna with metamaterial loading was designed and simulated near 3.5 GHz for potential sub-6 GHz 5G applications. The structure employs Rogers REINFORCED TEFLON/duroid 5880, coaxial probe feeding, and a 3 × 5 array of 15 Open-Loop Resonator (OLR) cells on the superstrate. Three configurations were evaluated to examine the effects of the superstrate and OLR loading. The Intended antenna achieves approximately −36.41 dB S11, 1.03 VSWR, 8.31 dBi peak gain, and 8.34 dBi directivity near the target frequency. The results demonstrate improved impedance matching and radiation characteristics compared with the basic configuration. These results indicate that the Intended superstrate-loaded OLR structure is a promising candidate for 3.5 GHz 5G sub-6 GHz wireless communication applications.

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