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A Novel Evolution of a Rectangular-Shaped Single-Band (47 GHz) Patch Antenna with Elongated Rectangular Slots for V-Band Uses

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Abstract

An extended rectangular slotted modified single-banded antenna patch for V-band uses is described within this research study. With a loss of return of -40.88 dB, the rectangular antenna effectively transmits and receives signals at 47 GHz. The recently designed MIMO antenna design comprises a single banded antenna patch with an elongated rectangular slot. It is constructed on a Rogers RT/Duroid 5880 substrate with a thickness of 0.0254mm. The antenna is 6 mm x 7 mm x 0.254 mm and features a minimal design. It uses frequencies between 46.04 and 48.07 GHz to function. The High Frequency Structure Simulator (HFSS) program was used to create the recommended antenna. Software is crucial in the design, enabling powerful directional signal transfer and reception over long distances. This makes the antenna ideal for 5G, mobile networks, and wireless technologies, offering excellent diversity performance. The study examines reflection coefficients, Z parameters, radiation efficiency, VSWR, and 2-D E and H plane radiation patterns.

1. Introduction

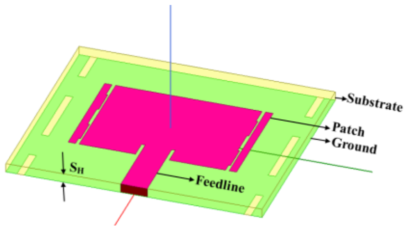
Fifth-generation (5G) technology is rapidly advancing, enhancing wireless communications by reducing latency, improving spectral efficiency, and increasing data rates. 5G systems, ten times faster than 4G, offer stable connectivity and reliable IoT applications. The FCC allocated 25-70 GHz frequencies for 5G [1]. 5G antennas can be set up as SISO, SIMO, MISO, or MIMO. SISO uses one antenna for transmission and reception, common in radio, satellite, GSM, and CDMA. SIMO and MISO have multiple antennas, while MIMO uses multiple channels for spatial multiplexing, reducing losses and fading but increasing complexity and size [13]. Mm Wave frequencies reduce antenna size, enabling User Equipment (UE) to provide beamforming and spatial multiplexing [3]. MIMO allows 5G to achieve up to 100 times greater bandwidth than 4G [5] by enhancing spectrum efficiency without increasing transmission or bandwidth capacities [6]. Microstrip Patch Antennas, used in 5G, consist of a dielectric material (e.g., FR4 or Rogers) between a copper patch and a ground plane. These antennas, etched or printed onto the substrate using photolithography, are favoured for their small size, low profile, and easy PCB integration [10].

Article [1] discusses an antenna for the Ka-band at 28 GHz and 38 GHz using a Rogers RO4003 substrate, measuring $27.65 \times 12 \times 0.273$ mm³, with bandwidths of 26–30 GHz and 36–41.5 GHz, and a peak/average gain of 5.2/5.3 dB. Article [2] describes a smaller Ka-band antenna at 28 GHz and 37 GHz using a FR4 substrate ($3.205 \times 3.2 \times 1.6$ mm³) with peak/average gains of 17.26/22.08 dB and bandwidths of 1.485 GHz and 0.2213 GHz. Paper [4] presents a V-band antenna using the Rogers RT5880 substrate, measuring 2.9×3.5 mm², operating at 60 GHz with a peak gain of 8.84 dB and bandwidth of 50-73 GHz. Article [6] proposes a MIMO antenna with good impedance bandwidth (43.5-47 GHz) using four laminated angled dipoles and four reflectors. Article [7] introduces a four-element MIMO patch antenna for 60 GHz communications (1.3 mm x 1.8 mm × 0.1 mm), using EBG structures to improve gain and far-field patterns. Article [8] suggests a low-profile planar MIMO antenna for 5G mm Wave in the 24–40 GHz band with partial ground planes and a tilted spade-shaped microstrip-fed radiator resonating at 35 GHz. Article [9] analyses a multiband antenna for Ka & V bands using slits and slots. Paper [10] presents a dual-band microstrip antenna for V and Ka bands, using a Rogers RT/Duroid 5880 substrate, achieving dual peaks at 29.84 GHz and 60.27 GHz with peak return losses of -39.47 dB and -37.90 dB. Paper [11] describes a dual-Port Super Wide Band MIMO antenna for 4G and 5G, with max return losses of -44.56 dB at 66.88 GHz and -52.43 dB at 55.68 GHz, and 94% efficiency. Paper [12] proposes an improved planar slot antenna with CPW-fed slots and parasitic dipoles. Article [14] suggests a dual-frequency microstrip antenna for 5G at 38 GHz and 60 GHz, using capacitive and inductive coupling, achieving impedance matching bandwidths of 2 GHz at 38 GHz and 3.2 GHz at 60 GHz.

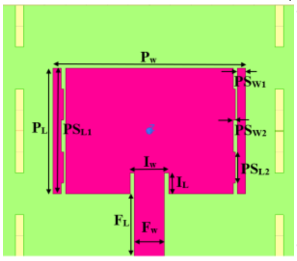
2. Proposed Design of the Antenna

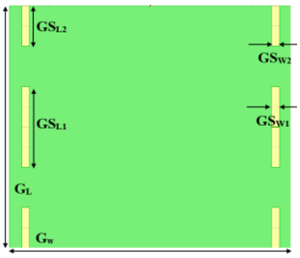
A dedicated antenna patch for specific mm Wave bands is proposed, comprising the ground plane, radiating patch, feedline, port, and dielectric substrate. Rogers RT/Duroid 5880 separates the ground and patch, affecting electrical characteristics. The rectangular patch, typically printed or engraved by photolithography, creates a thin copper film on the dielectric material.

The 50-ohm impedance feedline connects to the patch, transforming energy into an electromagnetic wave. Performance characteristics like return loss and bandwidth are improved through shape optimization and slot addition. The antenna structure (Figure 01(a)) uses a Rogers RT/Duroid 5880 dielectric substrate with a permittivity of 2.2, enhancing gains and efficiency. The design measures 6 x 7 x 0.254 mm³ or G_W x G_L x S_H mm³. The patch design includes extended rectangular slots for improved performance. Initial design features two long slots (PS_{L1} x PS_{W1} mm²) at the ends and four thin rectangular flaps (PS_{L2} x PS_{W2} mm²) to enhance resonance (Figure 1(b)). Shorter rectangular slots were added to the ground to improve return loss.A microstrip feedline (F_W x F_L mm²) stimulates the patch. Additional slots (GS_{L1} x GS_{W1} mm²) were carved into the ground for optimal frequency function. Two elongated slots (1 mm x 0.2 mm) were added to the upper ground plane (GS_{L2} x GS_{W2} mm²), with similar slots parallel to the Y-axis in the lower half (Figure 1(c)). The final design excels in advanced 5G applications, achieving a narrow band centred at 47 GHz with a return loss of -40.88 dB.

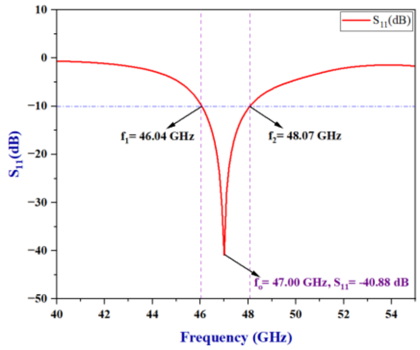


(a)





(b) (c)



(d)

Figure 1. (a), (b), (c) Proposed 47 GHz single-band antenna design, (d) Coefficient of reflection for the proposed antenna.

The width and length of a rectangular microstrip can be determined using the following formulas.

$$P_{W47} = \frac{C_o}{2f_{47}\sqrt{\frac{\varepsilon_s + 1}{2}}} \quad (1).$$

$$\varepsilon_{eff.} = \frac{\varepsilon_s + 1}{2} + \frac{\varepsilon_s - 1}{2}\left[\frac{1}{\sqrt{1 + 12\frac{h_{47}}{\mathrm{W}}}}\right] \quad (2)$$

$$P_{L47} = \frac{C_o}{2f_{47}\sqrt{\varepsilon_{eff.}}} - 0.824h_{47}\left(\frac{(\varepsilon_{eff.}+0.30)\left(\frac{Wm}{h_{47}}+0.264\right)}{(\varepsilon_{eff.}-0.258)\left(\frac{Wm}{h_{47}}+0.80\right)}\right) \quad (3)$$

Where, c_o= light speed in vacuum, f_{47}= resonant frequency i.e., 47GHz, ε_s= permittivity of dielectric substrate i.e., 2.2 and ε_{eff} = effective permittivity calculated using: $\varepsilon_{reff.} \cong \frac{\varepsilon_r+1}{2}$, where ε_r represents effective permittivity.

3. The Evolution of Design

The microstrip patch antenna development involves six steps. Initially, Antenna 01, Step-01, with a conventional rectangular patch and undisturbed ground (Figure 2), achieves a return loss of -30.1842 dB at 48.1 GHz. Various modifications were made to further improve the return loss.

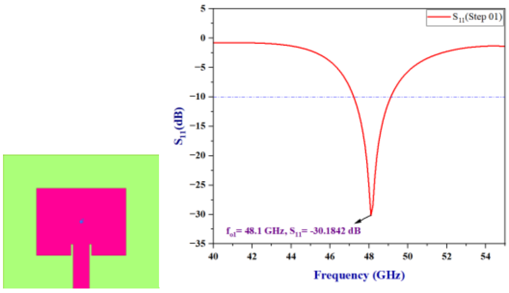


Figure 2. Antenna 01, Step-01 with Coefficient of Reflection of Step-01.

Antenna 01 was improved by adding two elongated rectangular slots at the patch's extremities, resulting in Antenna 02, Step-02, as shown in Figure 3. The reflection coefficient graph shifts towards the intended frequency, achieving resonance at 47.4 GHz with a return loss of -24.34 dB.

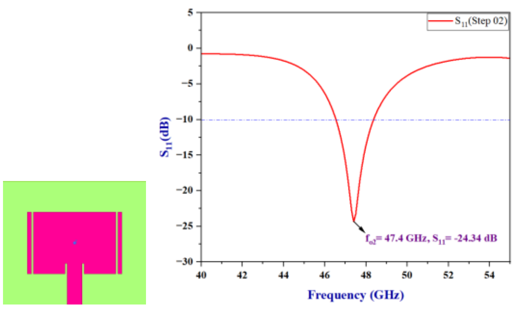


Figure 3. Antenna 02, Step-02 with Coefficient of Reflection of Step-02.

The third phase, Antenna 03, Step-03, shown in Figure 4, includes elongated slots and four thin rectangular flaps (0.74mm by 0.05mm) to maintain symmetry. A third peak at 47.2 GHz appears with a return loss of -19.76 dB. The goal is to achieve optimal return loss as the design evolves.

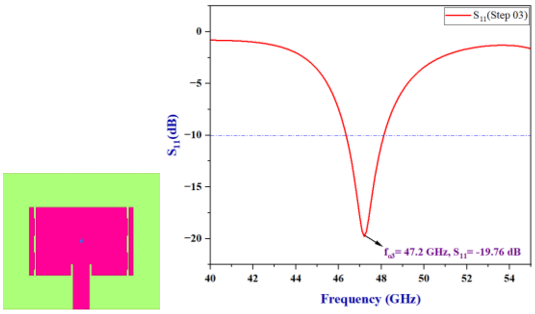


Figure 4. Antenna 03, Step-3 with Coefficient of Reflection of Step-03.

The ground plane was modified to increase return loss by adding two elongated rectangular slots, as shown in Figure 5, while leaving the patch undisturbed. This revised design, Antenna 04, Step-04, aims to prevent further deterioration of return loss. Figure 5 shows twin peaks at 35.40 GHz and 47.1 GHz, with return losses improving to -28.63 dB and -20.32 dB, respectively.

In Step-5, final refinements are made to optimize antenna performance. Two shortened rectangular slots (1mm by 0.2mm) are added to the upper half of the ground plane, as shown in Figure 6. This design, Antenna 05, Step-05, resonates at 47.3 GHz with an improved return loss of -24.53 dB.

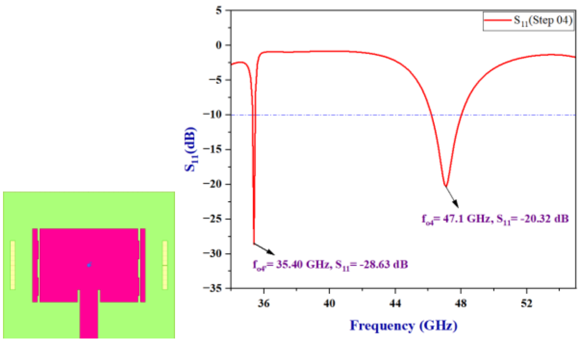


Figure 5. Antenna 04, Step-04 with Coefficient of Reflection of Step-04.

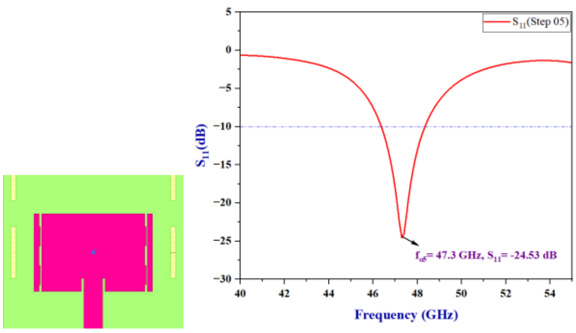


Figure 6. Antenna 05, Step-05 with Coefficient of Reflection of Step-05.

To maximize return loss, all ground adjustments were completed. The final layout, shown in Figure 1, includes two additional rectangular slots (1 mm by 0.2 mm) in the bottom half of the ground plane, parallel to the Y-axis. These changes make the antenna resonant at 47.00 GHz, significantly improving return loss to -40.88 dB, making it suitable for V-band applications.

Figure 7 compares the reflection coefficients for steps 1 to 6 with the final design, showing improved performance in the V-band. Through iterative design and enhancements, the microstrip patch antenna meets the demanding requirements of V-band applications, achieving a return loss of -40.88 dB by optimizing both the patch and ground plane.

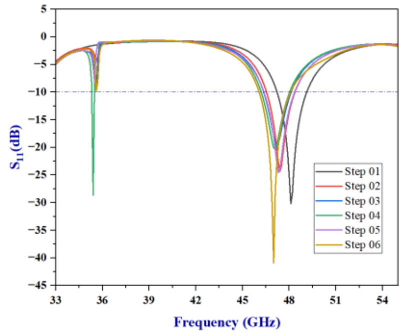


Figure 7. A contrast of the coefficients of reflection for steps 1, 2, 3, 4, 5, and 6 and final proposed Antenna design.

4. Z Parameter and Far-Field Results

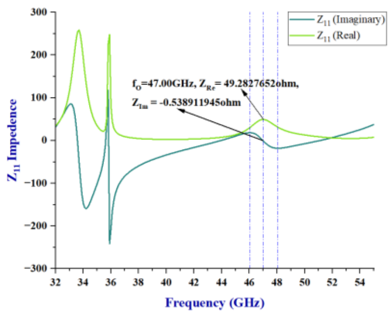


Figure 8. Z parameter plot

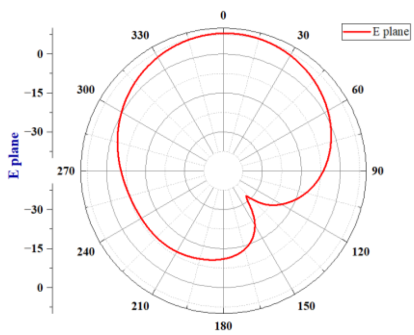


Figure 9. E-plane radiation pattern at 47GHz

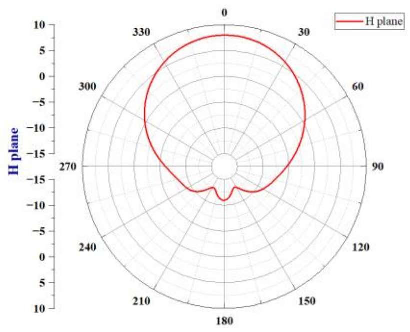


Figure 10. E-plane radiation pattern at 47GHz

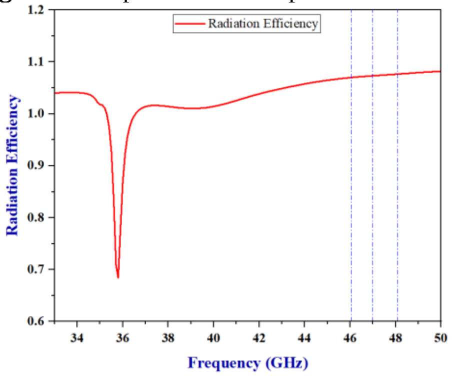


Figure 11. Radiation Efficiency at 47GHz

5. Conclusion

This study investigates a microstrip-based miniature antenna with exceptional V-band performance and a unique radiating element design, making it ideal for upcoming 5G networks. Its compact rectangular design measures 6 mm $\times$ 7 mm $\times$ 0.254 mm on a Rogers 5880 substrate. It resonates at 47 GHz with a return loss of -40.88 dB. The performance characteristics, analyzed through S-parameter and VSWR patterns, nearly match ideal values, making it well-suited for 5G applications.

6. References

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