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Research Article

Design of a Circularly Polarized Broadband Slot Antenna for Base Station Applications

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ABSTRACT

In this paper, a circularly polarized broadband slot antenna is designed for base station applications. The antenna is built on a square-shaped FR4 Epoxy substrate that measures 60 mm in length and 1 mm in height with a relative permittivity of 4.4. The ground plane has a recessed slot, and the feeding mechanism employs an offset microstrip line. The slot enables circular polarization and optimal impedance matching, which are enhanced further by offset feeding and the addition of stubs to create a composite-shaped patch. With an impedance bandwidth of 106% (1.28 GHz-4.16 GHz) and an axial ratio bandwidth of 69% (1.71 GHz-3.51 GHz), the CP broadband slot antenna effectively covers popular mobile communication bands such as GSM 1800, GSM 1900, 3G/LTE 2100, 3G/LTE 2300, 4G/LTE 2500, and 2.4 GHz Wi-Fi bands. The maximum gain is simulated to be 3.5 dB.

Keywords: Circular polarization; Mobile communications; Slot antenna; Base station; Offset feeding

INTRODUCTION

The rapid evolution of wireless communication technologies has enabled ubiquitous connectivity, transforming our lifestyles and work practices [1]. This progress has resulted in a wide range of applications, ranging from mobile networks and IoT devices to smart cities and augmented reality [2]. The base station antenna is a pivotal element in this revolution, ensuring reliable and efficient communication services to handle the exponential growth of data traffic [3-4]. As demand grows, the emphasis shifts to developing high-performance antennas, particularly for mobile networks, in order to meet the requirements of modern applications [4]. Antennas are vital components of wireless communication systems because they enable the transmission and reception of electromagnetic waves [5]. Their design parameters include bandwidth, polarization, impedance, radiation patterns, gain, and efficiency [6]. There are several types of antennas, including patch, slot, monopole, dipole, horn, and Yagi-Uda antennas [7]. Slot antennas, like patch antennas, consist of flat metal plates with slots that allow electromagnetic wave radiation [8]. They are simple and tunable for better performance by adjusting slot size and cavity design. However, slot antennas have low radiation efficiency and higher cross-polarization levels, which can be improved by reducing substrate thickness [9]. Circularly Polarized (CP) antennas are popular for mobile communications because they allow for flexible orientation of the transmitting and reception antennas, improved mobility, and reduced multipath fading caused by reflections and obstructions [10-11]. To generate CP radiation, two orthogonal modes should be excited simultaneously with equal amplitude and 90° phase difference [12-13]. The objective of this paper is to present the design and analysis of a circularly polarized broadband slot antenna specifically customized for base station mobile applications. The proposed antenna aims to address the limitations of traditional narrowband antennas by offering a wide bandwidth while maintaining excellent radiation characteristics. The design incorporates innovative techniques and optimization algorithms to achieve a compact and efficient antenna structure. To achieve the desired performance, the design process involves a comprehensive analysis of the antenna's electromagnetic characteristics, including impedance matching, radiation pattern, and gain. Advanced simulation tools and numerical methods are employed to optimize the antenna's parameters and ensure its compliance with the stringent requirements of base station applications [14].

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MATERIALS AND METHODS

Antenna design

Antenna configuration: The HFSS-designed antenna, which employs an offset microstrip line feeding technique, is a slot antenna with a compositely shaped patch made up of a rectangle with two rectangular and crescent-shaped stubs. The ground plan has a wide slot that has been geometrically modified, and a smaller circular slot is added later to improve the antenna's broadband and circular polarization characteristics.

Antenna geometry: The antenna, simulated using Ansys High-Frequency Structure Simulator (HFSS), utilizes a square-shaped FR4 Epoxy substrate as the ground and a copper-coated patch. The substrate's relative permittivity (εr) is 4.4, and its dielectric loss tangent (δ) is 0.02. With length of 60 mm, and a height of 1 mm, the square substrate measures 60 mm^3 × 60 mm^3 × 1 mm^3 in total size.

Design procedure

Antenna without slot: The antenna without a slot is illustrated in Figure 1. The green colour indicates the patch, while the orange colour represents the ground visible through the 1 mm FR4 Epoxy substrate. The substrate is 60 mm in length, square-shaped, and coated with copper on both sides. The antenna's feeding mechanism consists of a 7.5 mm long, 1.5 mm wide microstrip feedline placed on top of the substrate. A rectangular copper coated patch (20 mm × 16 mm) starts where the feed line ends and is merged with the feedline using the unite function in HFSS. A lumped port is attached at the end of the feedline (Figure 1 and Table 1).

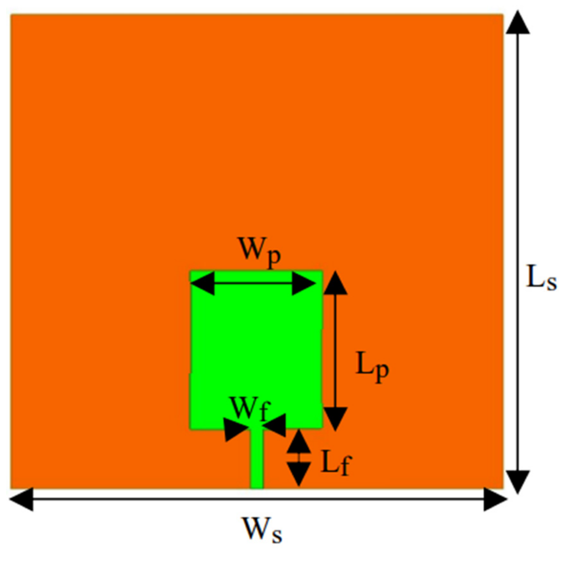


Figure 1: Antenna without slot.

Table 1: Optimized parameters for antenna without slot.

Parameter	L_s	W_s	Lp	W_p	L_f	W_f
Value (mm)	60	60	20	16	7.5	1.5

Slot antenna

The slot antenna illustrated in Figure 2, is based on the antenna without a slot. To create the slot, a portion of the ground plane at the bottom of the substrate is etched. The slot has a total length of 49 mm and a width of 43.7 mm. Additionally two rectangular stubs are added to the ground: One at the upper right corner (37.5 mm × 10 mm) and another at the lower left corner (12 mm × 11.7 mm). These stubs are united to reduce the slot's size, resulting in a recessed shape. The introduction of the slot enables circular polarization and significantly improves impedance matching within the antenna's operating frequency range (Figure 2 and Table 2).

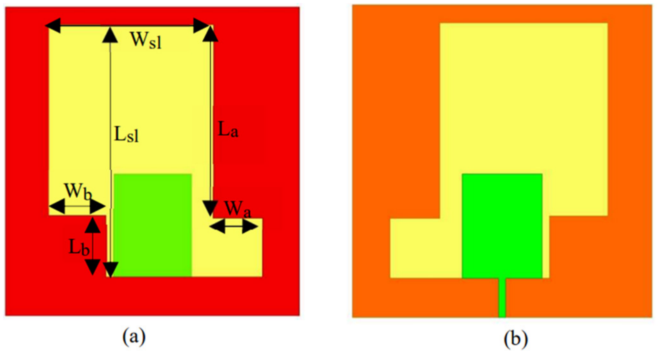


Figure 2: Slot antenna. Note: (a) Bottom view; (b) Top view.

Table 2: Optimized parameters for slot antenna.

Parameter	L_{sl}	W_{sl}	L_a	W_a	L_b	W_b
Value (mm)	49	33.7	37.5	10	12	11.7

Slot antenna with offset feeding

The slot antenna is modified by offsetting the feedline 2 mm from the centre toward the left with respect to the patch. This modification is visualized in Figure 3, offset feeding improved both the impedance bandwidth and the axial ratio bandwidth (Table 3).

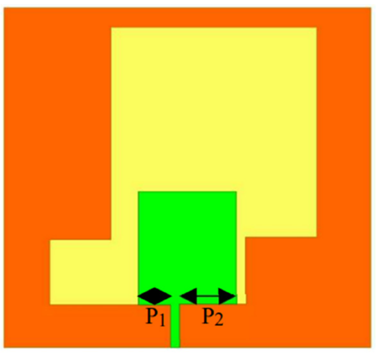


Figure 3: Slot Antenna with offset feeding.

Table 3: Optimized parameters for slot antenna with offset feeding.

Parameter	P_1	P_2
Value (mm)	5.25	9.25

Slot antenna with one stub

The outlook of the slot antenna with one stub is shown in Figure 4. It is obtained by adding a rectangular slab to the top of the patch using the unite function. The stub is positioned so it increases the length of the patch by 3.2 mm to give the patch a T-shape. The stub is 20.5 mm by 5.5 mm. The introduction of this stub increases the Impedance bandwidth of the antenna, allowing for broadband characteristics to be realized (Figure 4 and Table 4).

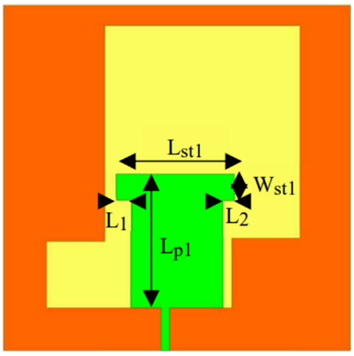


Figure 4: Slot Antenna with one stub.

Table 4: Slot antenna with one stub.

Parameter	L_{pl}	L_{stl}	W_{stl}	L_1	L_2
Value (mm)	23.2	20.5	5.5	2.5	2

Slot antenna with two stubs

The slot antenna with two stubs is shown in Figure 5. Another stub is added to the top of the T-shaped patch using the unite function. This stub has a size of 4.5 mm by 3 mm and is centrally placed on the patch. The introduction of this stub improves the impedance matching and greatly enhances the Axial Ratio bandwidth of the antenna, allowing it to be circularly polarized over a greater range of its operating band (Figure 5 and Table 5).

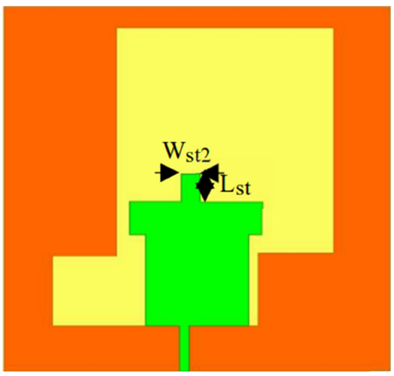


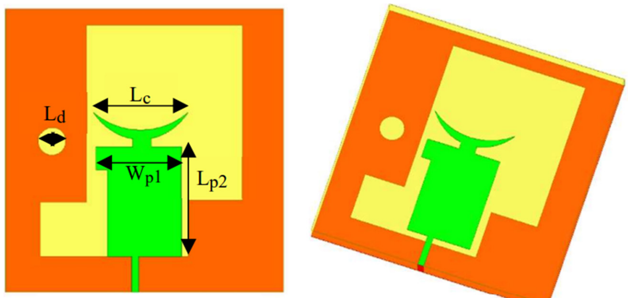
Figure 5: Slot Antenna with two stub.

Table 5: Optimized parameters for slot antenna with two.

Parameter	Lst2	Wst2
Value (mm)	4.5	3

Slot antenna with compositely-shaped patch

The slot antenna with a compositely-shaped patch is created by modifying the slot antenna with two stubs. In Figure 6, a crescent-shaped stub is added to the patch. This crescent shape is achieved by subtracting a circle with a radius of 16 mm from an ellipse with a major radius of 16 mm and a ratio of 0.836. Additionally, a small circular slot with a radius of 3 mm is introduced in the ground plane. To refine the design, the first rectangular stub added to the patch is shortened to 18.5 mm, no longer protruding at the right side of the patch. Its width is reduced to 4.76 mm, and the patch length is increased to 23.25 mm, achieving the desired resonating frequency of 1.8 GHz (Figure 6 and Table 6).



(a) (b)

Figure 6: Slot Antenna with compositely-shaped patch. **Note:** (a) Top view; (b) Trimetric view.

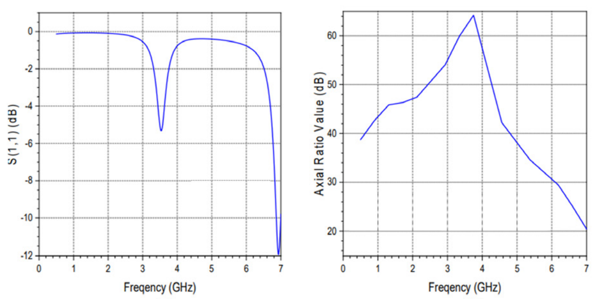
Table 6: Optimized parameters for slot antenna with compositely-shaped patch.

Parameter	Lp2	Wpl	Lc	Ld
Value (mm)	23.25	18.5	20.48	6

RESULTS AND DISCUSSION

Antenna without slot

Figure 7 shows the simulated results of the antenna without a slot. The return loss was less than -10 dB at 6.87 GHz to 7.00 GHz, well outside the desired bandwidth. Furthermore, the axial ratio exceeds 44 dB, indicating a lack of circular polarization characteristics. The antenna at this point is unsuitable for the intended design purpose (Figure 7).



(a) (b)

Figure 7: Results of the antenna without a slot. **Note:** (a) S-parameter (S11) plot (b) Axial ratio plot; (a): (▬): S(1,1) and (b): (▬): Axial ratio value

Slot antenna

Figure 8 shows the slot antenna simulation results. The Return loss is less than -10 dB at 2.07 GHz to 3.46 GHz and 5.80 GHz to 5.93 GHz, indicating good impedance matching in those ranges. The axial ratio value is also less than 3 dB from 1.70 GHz to 2.03 GHz and 2.57 GHz to 3.14 GHz, indicating that the addition of slots introduces circular polarization. The antenna's resonating frequency, however, is around 2.8 GHz, which does not fit the design purpose (Figure 8).

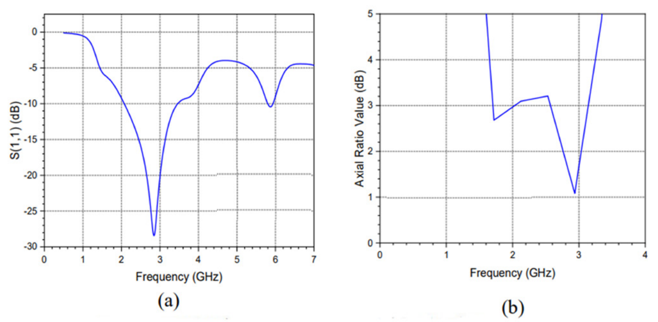


Figure 8: Slot antenna simulation results. **Note:** (a) S-parameter (S11) plot (b) Axial ratio plot; (a): (—): S(1,1) and (b): (—): Axial ratio value

Slot antenna with offset feeding

Figure 9 shows the simulated results of the slot antenna with offset feeding. The return loss bandwidth and the axial ratio bandwidth were both increased by offsetting the antenna's feedline. The return loss bandwidth now spans from 2.07 GHz to 3.97 GHz, while the axial ratio bandwidth is from 1.67 GHz to 3.04 GHz (Figure 9).

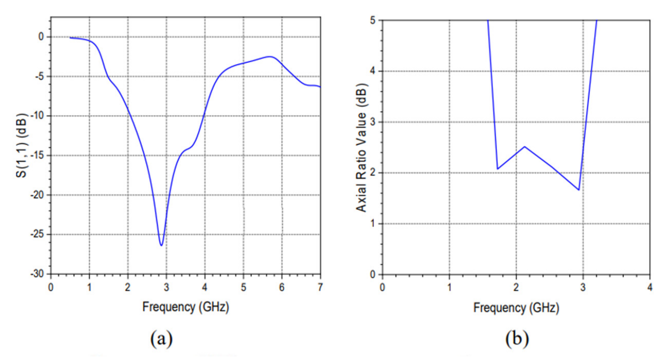


Figure 9: Simulated results of the slot antenna with offset feeding. **Note:** (a) S-parameter (S11) plot (b) Axial ratio plot; (a): (—): S(1,1) and (b): (—): Axial ratio value

Slot antenna with one stub

Figure 10 shows the simulated results of the slot antenna with one stub. Adding a stub to the patch slightly increases the return loss bandwidth, which now spans from 1.31 GHz to 3.37 GHz and 3.64 GHz to 4.03 GHz, but not continuously. The resonating frequency was 2.1 GHz. The axial ratio bandwidth, on the other hand, increased from 1.83 GHz to 2.82 GHz (Figure 10).

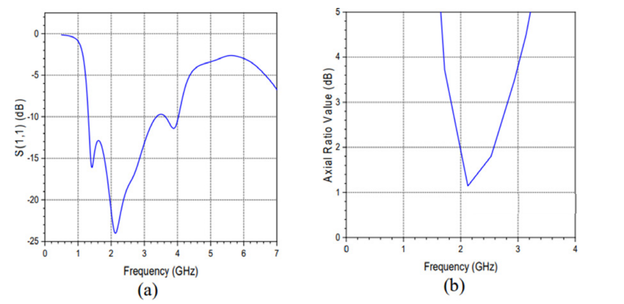


Figure 10: Simulated results of the slot antenna with one stub. **Note:** (a) S-parameter (S11) plot (b) Axial ratio plot; (a): (—): S(1,1) and (b): (—): Axial ratio value

Slot antenna with two stubs

Figure 11 shows the simulated results of the slot antenna with two stubs. The addition of the second stub makes the return loss continuous from 1.39 GHz to 3.96 GHz, but the resonating frequency is shifted away to around 2.65 GHz. The axial ratio bandwidth has been slightly improved and now ranges from 1.70 to 2.90 GHz (Figure 11).

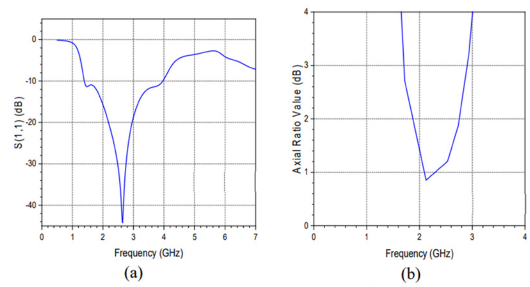


Figure 11: Simulated results of the slot antenna with two stubs. **Note:** (a) S-parameter (S11) plot (b) Axial ratio plot; (a): (—): S(1,1) and (b): (—): Axial ratio value

S-parameter (S11) and axial ratio plot: Figure 12 shows the simulated S-parameter and Axial Ratio results of the slot antenna with compositely-shaped patch. After adding the crescent to the patch and creating a composite shape, the antenna achieves a return loss bandwidth of 1.28 GHz to 4.16 GHz, with the resonating frequency at the desired 1.8 GHz. Additionally, the axial ratio bandwidth significantly increases from 1.71 GHz to 3.51 GHz. This antenna perfectly meets its design requirements (Figure 12).

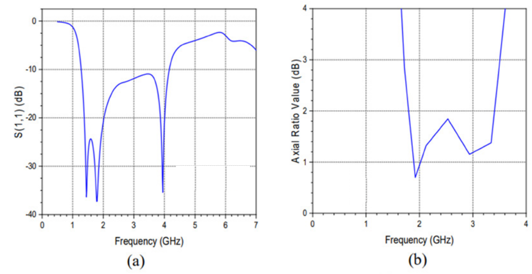


Figure 12: Simulated S-parameter and Axial Ratio results of the slot antenna with compositely-shaped patch. **Note:** (a) S-parameter (S11) plot (b) Axial ratio plot; (a): (—): S(1,1) and (b): (—): Axial ratio value

Gain plot: Figure 13 shows the simulated Gain results of the slot antenna with compositely-shaped patch. The simulated maximum gain is 3.5 dB, remaining above 2 dB across the antenna's frequency range with circular polarization (Figure 13).

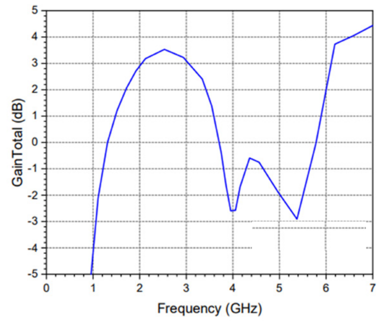


Figure 13: Simulated S-parameter and Axial Ratio results of the slot antenna with compositely-shaped patch. **Note:** (■): Gain total

Radiation pattern in both the E and H planes: Figure 14 shows the simulated Radiation pattern in both E and H plan of the slot antenna with compositely-shaped patch (Figure 14).

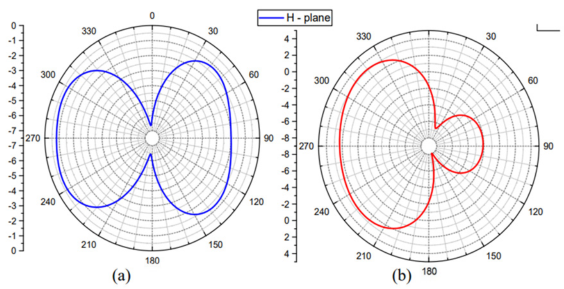


Figure 14: Simulated Radiation pattern in both E and H plan of the slot antenna with compositely-shaped patch. **Note:** (a) Radiation pattern in H-plane (b) Radiation pattern in E-plan; (a) (■): H-plane and (b): (■): Radiation pattern in E-plan

Parametric analysis

Parametric analysis on offset feedline:

Parametric analysis on offset feedline using the simulated S-parameter (S11): Figure 15 shows the result of the parametric analysis on the offset feedline using the S11 plot. Offsetting the feedline improves the impedance bandwidth, and reducing the offset degrades it. An offset length of 2 mm yields the optimal impedance bandwidth (Figure 15).

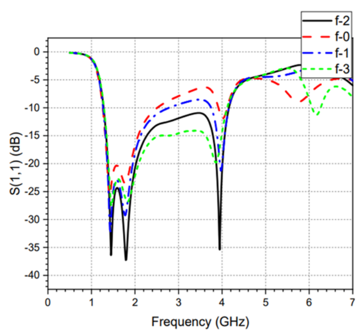


Figure 15: S-parameter (S11) plot for parametric analysis on offset feedline. **Note:** (■) f-2, (■) f-0, (■) f-1, (■) f-3.

Parametric analysis on offset feedline using the simulated axial ratio: Figure 16 shows the result of the parametric analysis on the offset feedline using the AR plot. Increasing the feedline offset improves the axial ratio bandwidth, while decreasing it degrades it (Figure 16).

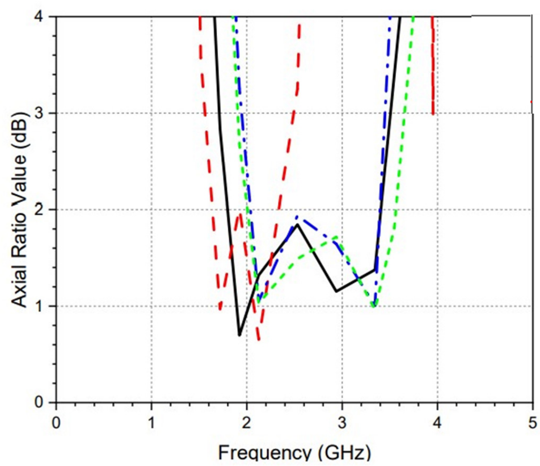


Figure 16: Axial Ratio plot for parametric analysis on offset feedline. **Note:** (■) f-2, (■) f-0, (■) f-1, (■) f-3.

Parametric analysis on crescent stub:

Parametric analysis on the crescent stub using the simulated S-parameter (S11): Figure 17 shows the result of the parametric analysis on the Crescent stub using the S11 plot. Increasing the ratio of the ellipse forming the crescent reduces the impedance bandwidth, causing discontinuity and an increase in reflection coefficient towards the -10 dB mark (Figure 17).

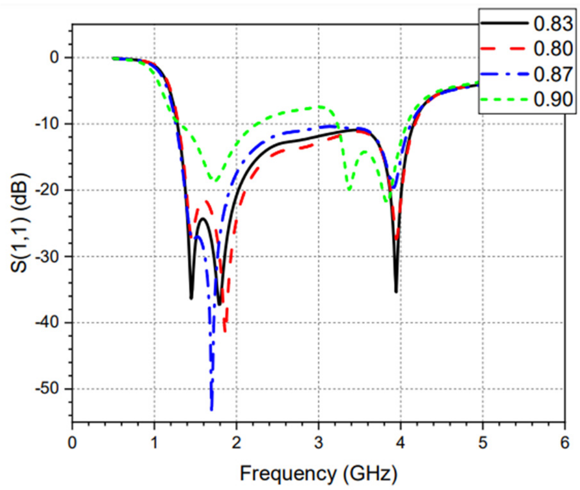


Figure 17: Axial Ratio plot for parametric analysis on offset feedline. **Note:** (■) 0.83, (■) 0.80, (■) 0.87, (■) 0.90.

Parametric analysis on the crescent stub using the simulated axial ratio: Figure 18 shows the result of the parametric analysis on the Crescent stub using the AR plot. Increasing the ratio of the ellipse forming the crescent significantly reduces the axial ratio bandwidth, causing it to decrease until the antenna loses circular polarization (Figure 18).

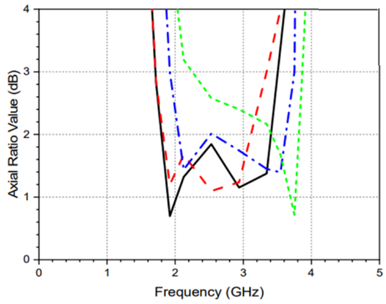


Figure 18: Axial ratio plot for parametric analysis on the crescent stub. **Note:** (■) 0.83, (■) 0.80, (■) 0.87, (■) 0.90.

CONCLUSION

The antenna's optimized operation, achieved through the addition of a crescent-shaped stub forming a compositely shaped patch, resulted in the desired impedance and axial ratio bandwidths, as well as the resonating frequency of 1.8 GHz. The antenna has a wide return loss bandwidth and a lesser axial ratio bandwidth due to the lack of an appropriate phase difference between the excitations. Although the intended design avoids the multiple-feed technique, which can remedy this for simplicity, the axial ratio bandwidth still allows for circular polarization over a wide frequency range. With a simulated maximum gain of 3.5 dB and gain above 2 dB across the frequency range with circular polarization, the antenna proves effective for base station applications. Its compositely-shaped patch ensures optimum performance, providing a 2.9 GHz bandwidth and a 1.8 GHz axial ratio bandwidth for circular polarization. Future plans involve fabrication, measurement, and exploring unidirectional radiation patterns using a reflector. In conclusion, the antenna's performance, including its gain, bandwidths, and circular polarization, makes it well-suited for base station applications.

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