Design and Analysis of Compact Multiband Concentric Spiral Patch Antenna for S-Band and C-Band Wireless Applications

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Abstract — This paper presents the design and analysis of a compact multiband concentric spiral microstrip patch antenna for S-Band and C-Band wireless communication applications. The proposed antenna consists of a circular disc radiating patch with three concentric ring-shaped slots etched on its surface to enable multiband operation. The antenna is designed on an FR-4 dielectric substrate with a relative permittivity of 4.4 and thickness of 1.6 mm. The design and performance evaluation are carried out using CST Studio Suite 2024. Simulation results demonstrate that the antenna achieves triple-band resonance at 2.7 GHz in the S-Band and at 5.145 GHz and 5.685 GHz in the C-Band, with a minimum return loss (S11) of −41.81 dB and VSWR values of 1.016, 1.515, and 1.152 at the respective resonant frequencies. The compact structure, low VSWR, and satisfactory radiation performance confirm that the proposed antenna is suitable for satellite communication, WLAN, and radar sensing applications in the S-Band and C-Band frequency ranges.

Index Terms — Multiband antenna, concentric ring slots, spiral patch, S-Band, C-Band, CST Studio Suite 2024, FR-4 substrate, return loss, VSWR.

I. INTRODUCTION

The rapid growth of wireless communication technologies over the past few decades has significantly transformed the way information is transmitted and received across the globe. From satellite communication and radar systems to wireless local area networks and mobile communication, antennas play a crucial role in enabling seamless connectivity. An antenna serves as a vital interface between guided electrical signals and electromagnetic waves propagating in free space. It performs the essential function of converting electrical energy into radiated electromagnetic waves during transmission and, conversely, capturing incoming electromagnetic waves and converting them back into electrical signals during reception [1]. Due to this fundamental capability, the performance of any wireless communication system is highly dependent on the design and efficiency of the antenna employed [3]. With the increasing demand for high-speed data communication, multifunctional devices, and compact wireless systems, there is a growing need for antennas that are not only efficient but also capable of operating across multiple frequency bands. Modern communication devices are expected to support various standards and services simultaneously, which often operate at different frequency ranges. As a result, the development of multiband antennas has become an important area of research [5]. A multiband antenna can operate at more than one frequency band, thereby eliminating the need for multiple antennas within a single device. This not only reduces hardware complexity but also minimizes size, weight, and overall system cost [8].

Among the various types of antennas available, microstrip patch antennas have gained widespread attention due to their attractive features. These antennas are characterized by their low-profile structure, lightweight design, ease of fabrication, and compatibility with printed circuit board (PCB) technology. They can be easily integrated with other microwave circuits, making them highly suitable for modern compact wireless devices. Furthermore, microstrip antennas offer flexibility in terms of shape and size, allowing designers to explore different geometries to achieve desired performance characteristics. Despite these advantages, conventional microstrip patch antennas suffer from certain limitations, such as narrow bandwidth, relatively low gain, and limited efficiency. These drawbacks become more prominent when the antenna size is reduced to meet compact design requirements.

Frequency bands such as the S-Band (2–4 GHz) and C-Band (4–8 GHz) are of great importance in modern wireless communication systems. The S-Band is widely used in applications such as weather radar, satellite communication, remote sensing, and wireless communication systems operating near 2.4 GHz, including widely used Wi-Fi standards. On the other hand, the C-Band is extensively utilized for satellite communication links, radar systems, and high-speed wireless local area networks operating at frequencies such as 5.2 GHz and 5.8 GHz. The ability to design a single antenna that can effectively operate in both S-Band and C-Band frequencies is highly desirable, as it reduces the need for multiple antennas and simplifies system integration.

In recent years, there has been increasing interest in developing compact multiband antennas that can support both communication and sensing applications [6]. For instance, antennas operating in the 5 GHz range are widely used in wireless networking and vehicular communication systems, while higher microwave frequencies are often utilized in radar-based sensing applications. Integrating these functionalities into a single antenna structure can significantly enhance system efficiency and reduce implementation complexity. However, achieving such integration requires careful design to ensure stable radiation characteristics, efficient impedance matching, and minimal interference between operating bands [5].

One of the promising approaches for achieving multiband operation in microstrip antennas is the use of concentric ring-shaped slots. These slots are etched onto the radiating patch in a circular pattern, creating multiple current paths that correspond to different resonant frequencies [7]. Each ring slot introduces a specific resonance, allowing the antenna to operate at multiple frequencies. This approach is particularly effective in maintaining compact dimensions while providing distinct and well-defined resonant bands [8]. Furthermore, the arrangement of these concentric rings in a spiral configuration further enhances the antenna performance by increasing the effective current path length and improving the distribution of surface currents [5].

The spiral arrangement of concentric ring slots offers additional advantages in terms of radiation characteristics[8]. It enables a more uniform current distribution across the patch, which contributes to improved radiation efficiency and stable performance across multiple frequency bands. Additionally, this configuration helps in achieving better impedance matching, which is essential for minimizing signal reflection and maximizing power transfer between the antenna and the transmission line. As a result, antennas based on concentric spiral slot designs are well-suited for modern multiband communication systems [5],[7],[8].

In this work, a compact multiband concentric spiral microstrip patch antenna is proposed for applications in S-Band and C-Band frequency ranges. The antenna design consists of a circular radiating patch integrated with three concentric ring slots, forming a spiral-like structure. This design approach enables the antenna to achieve multiple resonant frequencies while maintaining a compact size. The antenna is fabricated on an FR-4 dielectric substrate with a relative permittivity of 4.4 and a thickness of 1.6 mm. The use of FR-4 material ensures a cost-effective and mechanically robust design, making it suitable for practical implementation.The design and analysis of the proposed antenna are carried out using CST Studio Suite 2024, a widely used electromagnetic simulation tool that provides accurate modeling of antenna characteristics. The simulation process involves evaluating key performance parameters such as return loss (S11), Voltage Standing Wave Ratio (VSWR), radiation pattern, and gain. These parameters are essential for determining the efficiency and suitability of the antenna for real-world applications.

The simulation results demonstrate that the proposed antenna successfully achieves triple-band operation at 2.7 GHz, 5.145 GHz, and 5.685 GHz. The resonance at 2.7 GHz falls within the S-Band, while the resonances at 5.145 GHz and 5.685 GHz lie within the C-Band. The antenna exhibits excellent impedance matching at all operating frequencies, with a minimum return loss of −41.81 dB and VSWR values close to unity. These results indicate that the antenna is capable of efficient radiation with minimal signal reflection.

Overall, the proposed compact multiband concentric spiral microstrip patch antenna demonstrates strong potential for use in various wireless communication applications, including satellite communication, WLAN systems, and radar sensing. Its compact size, multiband capability, and reliable performance make it a suitable candidate for integration into modern communication devices. The design approach presented in this work contributes to the ongoing research efforts in developing efficient and compact multiband antennas for next-generation wireless systems.

II. ANTENNA DESIGN METHODOLOGY

Microstrip patch antennas are widely recognized for their simplicity, compactness, and compatibility with modern planar fabrication techniques. A typical microstrip antenna consists of a metallic radiating patch printed on a dielectric substrate, backed by a conductive ground plane. The radiation mechanism is primarily governed by fringing electromagnetic fields generated at the edges of the patch. These fields allow energy to radiate into free space, enabling wireless communication. The resonant frequency of such antennas is determined by several factors, including the geometry of the patch, the dielectric constant of the substrate, and the feeding mechanism. In this work, a circular patch geometry is selected as the primary radiating element because it offers symmetrical radiation patterns and supports efficient implementation of concentric slot structures for multiband operation.

The proposed antenna is fabricated on an FR-4 dielectric substrate, which is widely used in microwave circuit design due to its low cost and ease of availability. The substrate has a relative permittivity (εr) of 4.4, a loss tangent of 0.02, and a thickness of 1.6 mm. These properties provide a balance between performance and manufacturability. The overall dimensions of the substrate are maintained at 55 × 55 mm², resulting in a compact footprint suitable for integration into modern wireless systems. A full ground plane is placed on the bottom side of the substrate, constructed using annealed copper with a thickness of 0.035 mm. This ground plane ensures proper reflection of electromagnetic waves and supports stable radiation characteristics.

To excite the antenna, a microstrip line feeding technique is employed. This method is preferred due to its simplicity and its ability to provide good impedance matching with standard 50 Ω transmission lines. The feed line is designed with a width of 3 mm and extends along the X-direction from 26 mm to 29 mm. It has a length of 20 mm along the Y-direction, ranging from 0 mm to 20 mm. The feed line is directly connected to the circular patch, ensuring efficient transfer of power from the transmission line to the radiating structure. The main radiating element of the antenna is a circular copper patch with an outer radius of 17 mm. The patch is positioned at the center coordinates (27.5 mm, 34 mm) on the top surface of the substrate. The circular geometry is particularly advantageous because it provides uniform current distribution and facilitates the implementation of concentric slot configurations. To achieve multiband operation, three concentric ring-shaped slots are etched into the circular patch. These slots play a crucial role in modifying the surface current paths, thereby introducing multiple resonant frequencies.

The innermost slot is defined by an outer radius of 5.0 mm and an inner radius of 3.5 mm, resulting in a slot width of 1.5 mm. The second slot, located at the middle region of the patch, has an outer radius of 11 mm and an inner radius of 9.5 mm. The outermost slot is designed with an outer radius of 14.5 mm and an inner radius of 13.0 mm. All three slots maintain a uniform width of 1.5 mm to ensure consistent perturbation of the current distribution across the patch surface. These concentric ring slots effectively increase the electrical path length without increasing the physical size of the antenna. As a result, multiple resonant modes are generated, enabling the antenna to operate at different frequency bands.

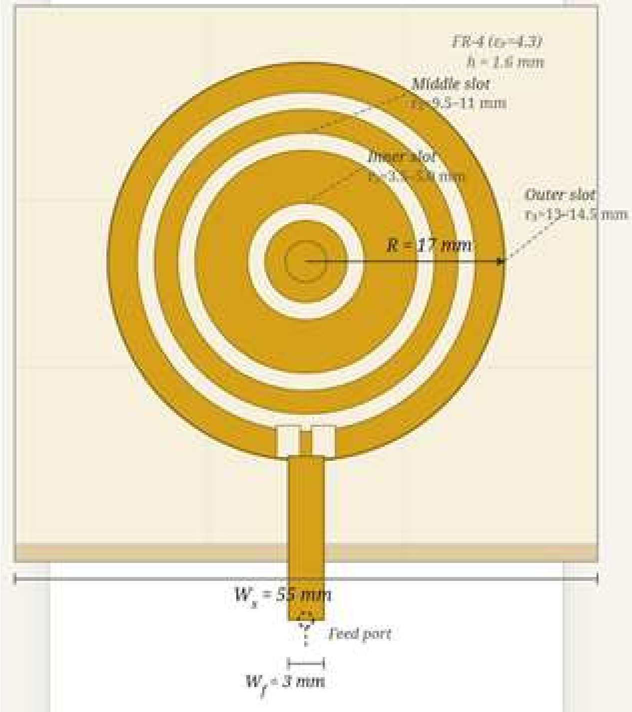


Fig. 1. Microstrip antenna geometry

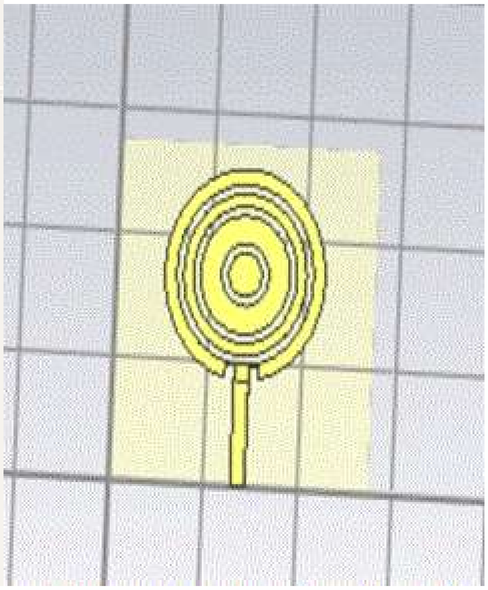


Fig. 2. Microstrip antenna in CST

In addition to the ring slots, two rectangular slots are incorporated near the feed region to enhance impedance matching. These slots are symmetrically placed on either side of the feed line at the lower portion of the circular patch. The left rectangular slot extends from X = 24 mm to 26 mm and Y = 17 mm to 19.5 mm, while the right slot spans from X = 29 mm to 31 mm within the same Y range. These slots help in controlling the current distribution around the feed junction, which reduces impedance mismatch and improves return loss performance. The symmetric placement of these slots ensures balanced current flow and contributes to stable antenna operation.

All metallic parts of the antenna, including the patch and ground plane, are modeled using annealed copper to ensure high conductivity and minimal losses. The complete antenna structure is designed and analyzed using CST Studio Suite 2024, a powerful electromagnetic simulation tool widely used in antenna design. The simulation process allows for accurate evaluation of key performance parameters such as return loss (S11), Voltage Standing Wave Ratio (VSWR), radiation pattern, and gain.

The chosen design approach, which combines a circular patch with concentric ring slots and additional rectangular slots, provides an effective solution for achieving multiband operation within a compact structure. The concentric slots introduce multiple resonances by altering the current paths, while the rectangular slots near the feed improve impedance matching. Together, these design elements enhance the overall performance of the antenna without significantly increasing its complexity or size.

The detailed dimensions and parameters of the antenna are summarized in Table I. These parameters serve as a reference for fabrication and further optimization. The combination of compact size, simple geometry, and effective multiband characteristics makes the proposed antenna suitable for modern wireless communication systems.

TABLE I: ANTENNA DESIGN PARAMETERS

Parameter	Description	Value
Substrate material	FR-4 (lossy), εr = 4.4	—
Substrate size	Length × Width	55 × 55 mm²
Substrate thickness	Z: 0 to 1.6 mm	1.6 mm
Ground plane	Copper, Z: −0.035 to 0 mm	0.035 mm
Patch radius	Circular disc outer radius	17 mm
Patch centre	(Xcenter, Ycenter)	(27.5, 34) mm
Inner ring slot	Outer / Inner radius	5.0 / 3.5 mm
Middle ring slot	Outer / Inner radius	11 / 9.5 mm
Outer ring slot	Outer / Inner radius	14.5 / 13.0 mm
Feed line width	X: 26 to 29 mm	3 mm
Feed line length	Y: 0 to 20 mm	20 mm
Copper thickness	Patch and ground	

IV. RESULTS

The performance of the proposed compact multiband concentric spiral microstrip patch antenna designed for S-Band and C-Band wireless applications is evaluated using full-wave electromagnetic simulations in CST Studio Suite 2024. The antenna is modeled on an FR-4 dielectric substrate and analyzed over a frequency range of 1 GHz to 6 GHz to examine its multiband characteristics and impedance behavior. Key parameters such as return loss (S11), Voltage Standing Wave Ratio (VSWR), and resonant frequencies are studied to determine the effectiveness of the proposed design.

The simulated return loss (S11) response of the antenna is shown in Fig. 2. The S11 parameter represents the amount of power reflected back toward the source due to impedance mismatch. For efficient antenna performance, the return loss should be below −10 dB, which indicates that the majority of the input power is radiated. From the simulation results, the proposed antenna exhibits three distinct resonant frequencies, confirming successful multiband operation.

The first resonance is observed at 2.7 GHz in the S-Band region. At this frequency, the antenna achieves a return loss of −41.81 dB, indicating excellent impedance matching and minimal reflection loss. This result suggests that nearly all the input power is effectively radiated, making the antenna highly efficient at this frequency. The strong resonance at 2.7 GHz is primarily due to the optimized circular patch geometry and proper feed line design, which together ensure effective power transfer.

The second resonant frequency occurs at 5.145 GHz within the C-Band. The return loss at this frequency is −13.76 dB, which satisfies the standard condition for acceptable antenna operation. Although the matching is not as strong as at the S-Band resonance, it still indicates efficient radiation and reliable performance for practical wireless applications.The third resonance is obtained at 5.685 GHz, also in the C-Band region. At this frequency, the antenna achieves a return loss of −23.00 dB, indicating good impedance matching and efficient radiation characteristics. The presence of two resonances within the C-Band demonstrates the capability of the antenna to support multiple applications within the same frequency range.

In addition to return loss, the Voltage Standing Wave Ratio (VSWR) is analyzed to further evaluate impedance matching. The VSWR indicates how effectively power is transmitted from the feed line to the antenna, with values less than 2 considered acceptable. The simulated VSWR response is illustrated in Fig. 3. At the first resonance of 2.7 GHz, the VSWR is found to be 1.016, which is very close to unity and indicates nearly perfect matching. At 5.145 GHz, the VSWR is 1.515, which remains within the acceptable range. Similarly, at 5.685 GHz, the VSWR is 1.152, confirming good matching at the second C-Band resonance. These values demonstrate that the antenna maintains stable impedance characteristics across all operating frequencies.

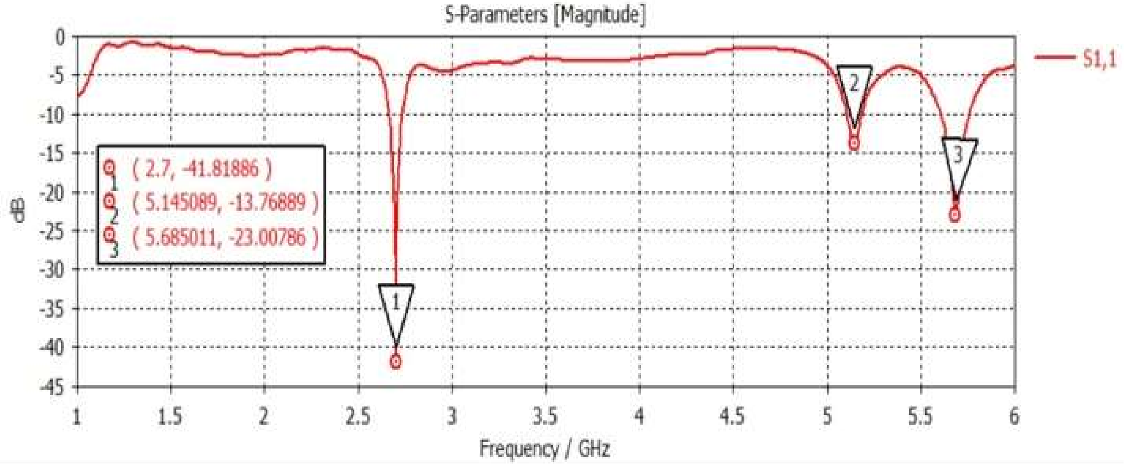


Fig. 3. Simulated return loss (S11) of the proposed antenna.

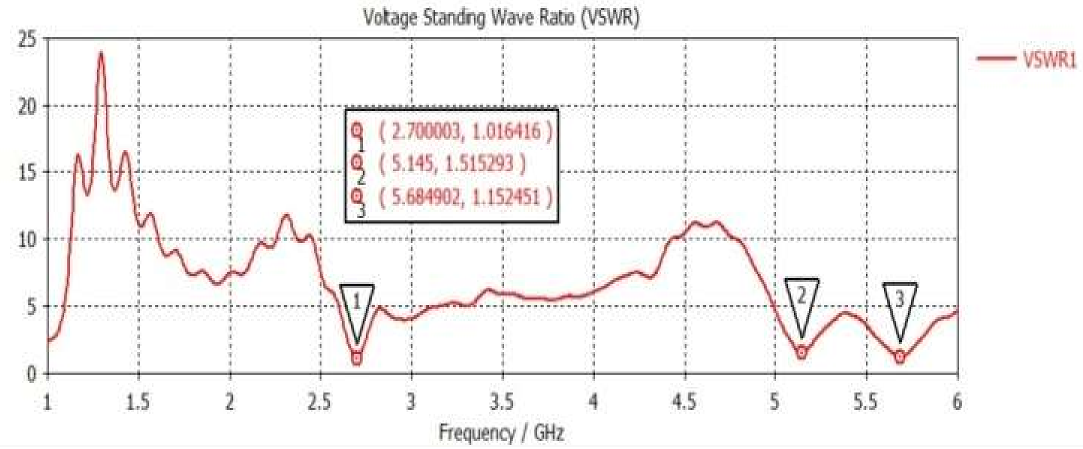


Fig. 4. Simulated VSWR of the proposed antenna.

The overall simulated performance of the antenna is summarized in Table II.

TABLE II: SIMULATED PERFORMANCE SUMMARY

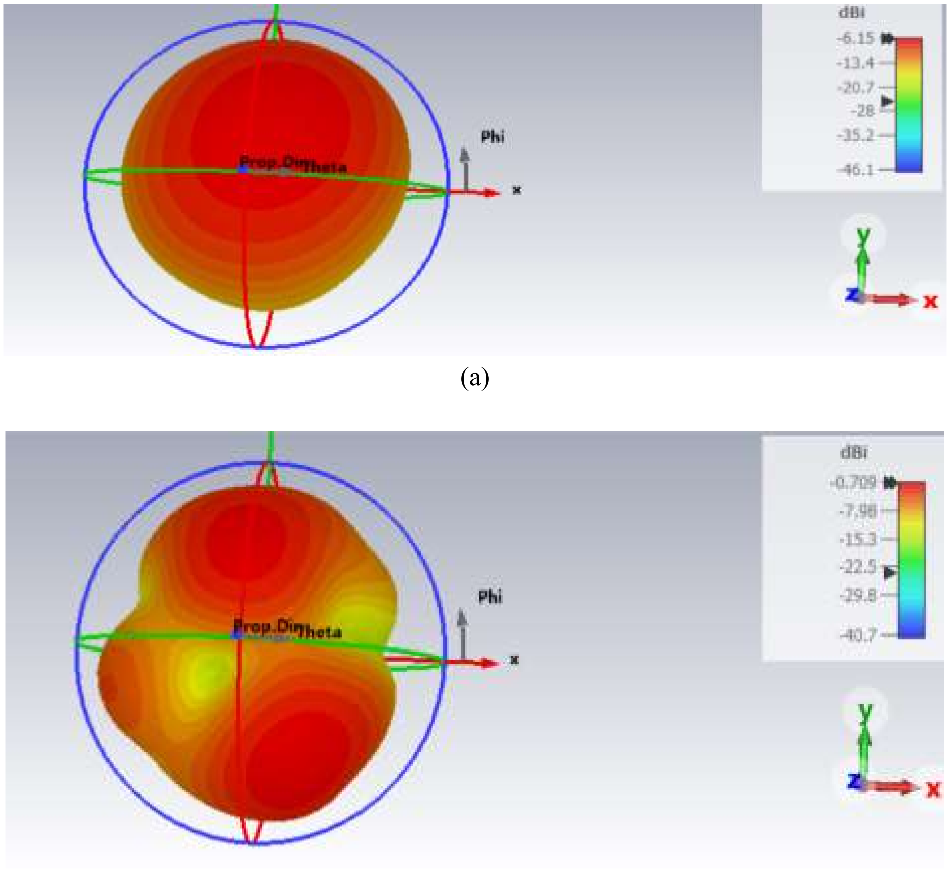
Resonant Frequency (GHz)	**Return Loss S11 (dB)**	**VSWR**
2.700 GHz (S-Band)	−41.81	1.016
5.145 GHz (C-Band)	−13.76	1.515
5.685 GHz (C-Band)	−23.00	1.152

The excellent multiband performance of the antenna is mainly attributed to its structural design. The circular patchprovides uniform current distribution, which contributes to stable radiation characteristics. The extremely low return loss at 2.7 GHz is a result of optimized patch dimensions and feed line configuration, which together enable near-perfect impedance matching.The three concentric ring slots etched on the patch play a crucial role in achieving multiband operation. These slots modify the current paths on the antenna surface, effectively increasing the electrical length and introducing additional resonant modes. As a result, the antenna is able to generate resonances at higher frequencies in the C-Band. The consistent slot width ensures uniform perturbation of current distribution, which helps maintain stable performance across all bands.

Additionally, the rectangular slots placed near the feed region enhance impedance matching by adjusting the current flow at the feed junction. This reduces signal reflection and improves overall efficiency. The symmetrical placement of these slots ensures balanced current distribution, contributing to reliable antenna operation.

The proposed antenna achieves triple-band performance using a single-layer structure without requiring complex configurations such as stacked patches or external matching circuits. The compact size of 55 × 55 mm² and the use of FR-4 substrate make the design cost-effective and suitable for practical implementation. The operating frequencies align well with applications such as satellite communication, WLAN systems, and radar sensing.

Overall, the results confirm that the proposed compact multiband concentric spiral patch antenna provides efficient radiation, good impedance matching, and reliable multiband performance, making it a suitable candidate for modern wireless communication systems.



(a)

(b)

Fig.5.(a) 3D plot at 2.7 GHz (b)3D plot at 8.64 GHz

V. CONCLUSION

Its compact structure, low fabrication cost, and reliable multiband performance make this antenna suitable for satellite communication, WLAN, radar sensing, and other S-Band and C-Band wireless applications. The antenna is implemented on a 55 × 55 mm² FR-4 substrate with a dielectric constant of 4.4 and thickness of 1.6 mm. Three concentric ring-shaped slots etched into a circular disc radiating patch introduce multiple resonant modes, enabling triple-band operation at 2.7 GHz, 5.145 GHz, and 5.685 GHz. Simulation results obtained using CST Studio Suite 2024 demonstrate excellent impedance matching with return loss values of −41.81 dB, −13.76 dB, and −23.00 dB, and VSWR values of 1.016, 1.515, and 1.152 at the respective resonant frequencies. The compact structure, low fabrication cost, and satisfactory multiband performance make the proposed antenna a strong candidate for satellite communication, WLAN, radar sensing, and other wireless applicationsin the S-Band and C-Band frequency range [6].

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