

A Compact Triband Antenna with Metamaterial Integration for Efficient Sub 8 GHz Application and Satellite Communication

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Abstract: This paper presents the design of a compact tri-band monopole antenna for wireless applications operating below 8 GHz, employing split-ring resonators (SRRs) to enhance performance. The antenna is realized in two phases, resulting in an offset-fed monopole structure with strategically positioned SRR elements. The antenna operates at three distinct frequencies: 5.34 GHz, 7.64 GHz, and 7.94 GHz, with corresponding operational bandwidths of 5.25-5.40 GHz, 7.43-7.73 GHz, and 7.87-8.15 GHz, offering bandwidths of 150 MHz, 302 MHz, and 280 MHz, respectively. The return losses at these frequencies are -16.66 dB, -15.39 dB, and -18.71 dB. Surface current analysis reveals multiple modal excitations across the three bands, confirming efficient multi-frequency operation. The antenna exhibits a stable gain between 2.5 and 3.8 dBi, indicating sufficient directionality for multi-standard communication systems, such as WLAN, ISM, and satellite uplink. The proposed antenna design successfully balances high performance with structural simplicity and compact dimensions. These characteristics make it suitable for a variety of wireless communication applications, where size and multi-band functionality are critical. The use of SRRs contributes to enhanced bandwidth and performance, while the offset-fed monopole configuration ensures broad compatibility with diverse wireless standards. The design achieves a practical and effective solution for future communication systems requiring compact yet high-performance antenna structures.

Keywords: bandwidth enhancement; monopole antenna; split-ring resonators (SRRs); tri-band antenna; wireless communication

1 INTRODUCTION

The rapid advancements in wireless communication technologies, particularly in the context of 5G, satellite communication, and Internet of Things (IoT) applications, have necessitated the development of novel antenna designs that can support high-frequency operation with minimal size while delivering superior performance. Among the various antenna configurations, microstrip patch antennas are widely recognized for their compactness, ease of fabrication, and suitability for integration into modern communication systems. However, as communication systems evolve to demand broader bandwidths, higher frequencies, and more compact solutions, the traditional antenna designs face significant challenges in meeting these requirements [1].

In this context, the need for antennas that not only provide high performance but are also optimized for specific frequency ranges has led to the development of various innovative designs, such as narrowband and wideband antennas. Narrowband antennas, in particular, are preferred for applications that require efficient radiation over a fixed frequency, such as satellite communication, point-to-point communication, and other high-frequency systems where channel stability and reduced interference are critical. While wideband antennas provide greater flexibility by covering a broad spectrum of frequencies, narrowband antennas offer improved selectivity, directivity, and overall efficiency in their operational range [2].

This paper proposes a new design for a narrowband antenna, which addresses the limitations of traditional antennas by utilizing a high-dielectric constant substrate and an integrated metamaterial structure. The unique approach focuses on optimizing the antenna's resonance at a single fixed frequency, providing high gain and efficient radiation within a narrow bandwidth. The use of a rectangular patch design combined with the metamaterial structure enhances the antenna's directivity and minimizes cross-polarization, key factors in ensuring high-quality

signal transmission and reception. The proposed antenna avoids the complexity and limitations associated with reconfigurable components such as diodes and switches, making it more reliable and cost-effective for commercial and industrial applications [3].

The antenna is designed to operate at a specific frequency of 5.8 GHz, which is commonly used in communication systems such as Wi-Fi, 5G, and satellite communication. The proposed antenna design achieves a narrow bandwidth of approximately 3%, which is ideal for applications that require stable and consistent performance in a designated frequency range. By avoiding the need for active components, the design ensures that the antenna's performance remains unaffected by external factors, thus making it more stable and predictable in real-world environments. This is a significant advantage over reconfigurable antennas, which, while offering versatility, may suffer from reduced reliability and performance inconsistency due to the switching mechanisms and additional complexity involved [4].

A major challenge in antenna design is maintaining high performance while minimizing the physical size of the antenna. In high-frequency applications, compactness is essential, as antennas need to fit into the limited space available in devices and systems. The proposed design addresses this challenge by utilizing a high-dielectric constant material that allows for miniaturization without sacrificing performance. This innovative approach ensures that the antenna remains compact, making it suitable for integration into various communication devices, including those used in 5G networks, satellite terminals, and other high-frequency systems [5].

Furthermore, the antenna's simple and efficient design is cost-effective to manufacture, which is another critical aspect of its applicability in commercial products. Traditional antenna designs that rely on complex components such as diodes or tunable elements can increase manufacturing costs and reduce reliability. In contrast, the proposed design offers a robust solution by utilizing passive elements and eliminating the need for active switching components [6].

This paper presents a detailed analysis of the antenna's design, including the materials used, the fabrication process, and the performance characteristics such as gain, bandwidth, and radiation pattern. A comparison with other state-of-the-art narrowband antenna designs highlights the superior performance of the proposed antenna in terms of size, efficiency, and directivity. The results demonstrate that the proposed antenna offers a promising solution for modern communication systems that require reliable and high-performance antennas operating in fixed frequency bands.

2 LITERATURE SURVEY

A thorough literature review reveals the evolution of antenna designs driven by the increasing demand for high-performance communication systems. As wireless technologies continue to advance, particularly in 5G, satellite communication, and the Internet of Things (IoT), antennas have become a critical component in achieving reliable, efficient, and high-frequency communication. This has led to the exploration of new antenna designs and methodologies that address the growing need for compact, efficient, and multi-functional solutions [7].

The integration of metamaterial structures into antenna designs has been explored as a means of enhancing the performance of traditional microstrip antennas. These metamaterial-based antennas offer the potential for increased bandwidth, improved radiation efficiency, and enhanced performance at higher frequencies. However, despite their advantages, the size and complexity of the designs remain a challenge, particularly when miniaturization is required for mobile applications [8].

Fractal geometry has also been investigated as a method to reduce the physical size of antennas while maintaining their performance characteristics. By employing self-similar structures, these fractal antennas can achieve compactness without compromising bandwidth and gain. However, such designs often exhibit limited performance in terms of radiation efficiency and directivity, which can restrict their use in high-performance applications like 5G communication [9].

Reconfigurable antennas have become another area of focus, especially in applications such as cognitive radio and dynamic spectrum access, where the ability to switch between frequency bands is essential. By incorporating active components like PIN diodes or switches, these antennas can adapt to changing frequency requirements. However, the introduction of active components introduces power consumption and design complexity, which can impact the overall performance and reliability of the antenna [10].

Wideband antennas have also been extensively studied, particularly for applications in broadband communication. These antennas offer the advantage of supporting a wide range of frequencies, making them ideal for systems that require broad spectrum coverage. However, while they provide flexibility, they often suffer from issues related to radiation efficiency and gain, especially at the edges of the operating bandwidth. As such, their application in high-frequency systems like 5G and satellite communication may be limited by these factors [11].

The use of split-ring resonators (SRRs) in antenna designs has proven effective in enhancing both bandwidth and gain. The SRR-based antennas can operate over broader frequency ranges, making them suitable for systems that require high-frequency operation. However, these designs tend to be larger and may not always meet the size constraints required for portable devices, such as mobile phones and IoT sensors [12].

Another approach involves the use of microstrip patch antennas with hybrid structures, combining elements such as slots, fractals, or parasitic elements to achieve multi-band or wideband operation. While such designs offer significant performance improvements in terms of bandwidth and directivity, the added complexity often results in larger physical sizes and increased manufacturing costs [13].

Compact antennas for IoT applications have become increasingly important due to the need for efficient communication in small devices with limited space. Slot-based and fractal structures have been employed to achieve miniaturization while maintaining acceptable performance levels. However, these designs often exhibit narrow bandwidths, which may limit their applicability in systems that require wider frequency coverage [14].

Dual-band antennas are another popular area of research, especially for applications such as Wi-Fi and Bluetooth. By using structures such as circular rings or parasitic elements, dual-band antennas can operate at distinct frequencies with high efficiency. However, these designs are typically limited to specific frequency ranges and may not be suitable for broader applications like 5G or multi-band communication systems [15].

In satellite communication, high-gain antennas have been a key focus, especially for applications that require stable and strong signal transmission over long distances. Parabolic reflectors combined with microstrip patch elements are often used to achieve high gain. However, these designs are typically large and unsuitable for portable or mobile applications, which requires further research into compact high-gain solutions [16].

Array antennas have also been explored for 5G applications, where beamforming and directivity are crucial for efficient signal delivery. Microstrip patch arrays have been used to enhance the directivity and gain of antennas, but the complexity of the design and increased power consumption associated with multiple elements pose challenges for energy-efficient operation [17].

The integration of new materials, such as high-dielectric constant substrates, has been shown to allow for miniaturization of antennas without sacrificing performance. These materials enable the design of compact antennas that can operate at higher frequencies, which is essential for 5G and beyond. However, the selection of suitable materials is critical, as the dielectric constant influences not only the size of the antenna but also its radiation characteristics [18].

In summary, the literature highlights the diverse range of antenna designs and techniques that have been developed to meet the challenges posed by modern communication systems. From wideband antennas to reconfigurable designs, and from compact solutions to high-gain systems, each approach has its strengths and limitations. As the demand for faster, more efficient, and

versatile communication systems grows, the focus will continue to shift toward optimizing antenna performance, ensuring that they meet the evolving needs of the industry.

3 MATERIALS AND METHODS

The primary goal of this research is to design and develop a compact, high-performance antenna that can operate efficiently over a fixed frequency range for advanced communication systems such as 5G, satellite communications, and IoT applications. The antenna is designed to achieve narrowband performance with a focus on enhancing gain, bandwidth, and directivity while maintaining a compact footprint suitable for integration into portable devices. To meet these objectives, we propose an antenna that combines a microstrip patch design with a metamaterial structure, specifically a rectangular patch antenna integrated with a split-ring resonator (SRR). Fig. 1 illustrates the evolution of the proposed antenna's design. The initial phase involves a basic monopole devoid of split ring resonators (SRRs). The second level introduces structural modifications by using dual ring codirectional SRRs to facilitate multi-band functionality. The design optimisation progressively modifies the antenna to resonate at three distinct frequencies. This reduces size and enhances impedance matching.

The antenna is constructed on a 1.6 mm thick FR4 substrate with a relative permittivity of 4.4. This option achieves an optimal equilibrium among cost, performance, and availability. Fig. 2 illustrates the configuration of the proposed SRR-loaded monopole antenna, while Tab. 1

enumerates the dimensions in millimetres. Altering the values of $l_1, l_2, l_3, l_4, a, b, c,$ and d is crucial for modifying the SRR resonances. Significantly, SRR enables the excitation of many modes, which is essential for triband functionality.

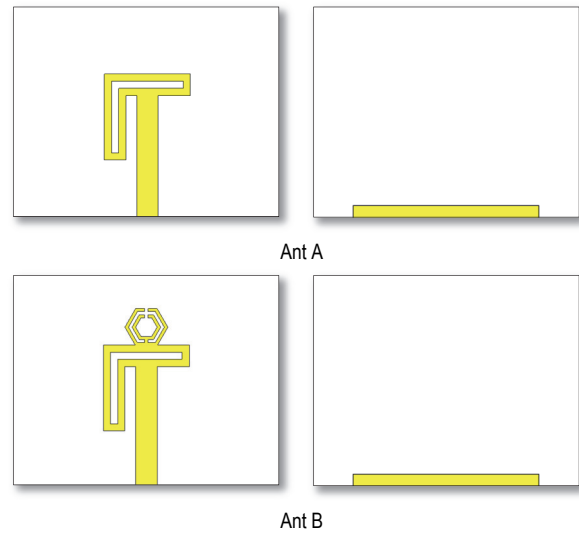


Figure 1 Two stages of proposed SRR inspired triband monopole antenna

Table 1 SRR inspired triband monopole antenna parameter values in mm

w_s	l_s	w_g	l_g	w_f	l_f	w_1
30	38	26	2	3	17	3
l_1	l_2	$l_3 = l_4$	a	b	$c = d$	h
13	3	1	3	1.5	0.5	1.6

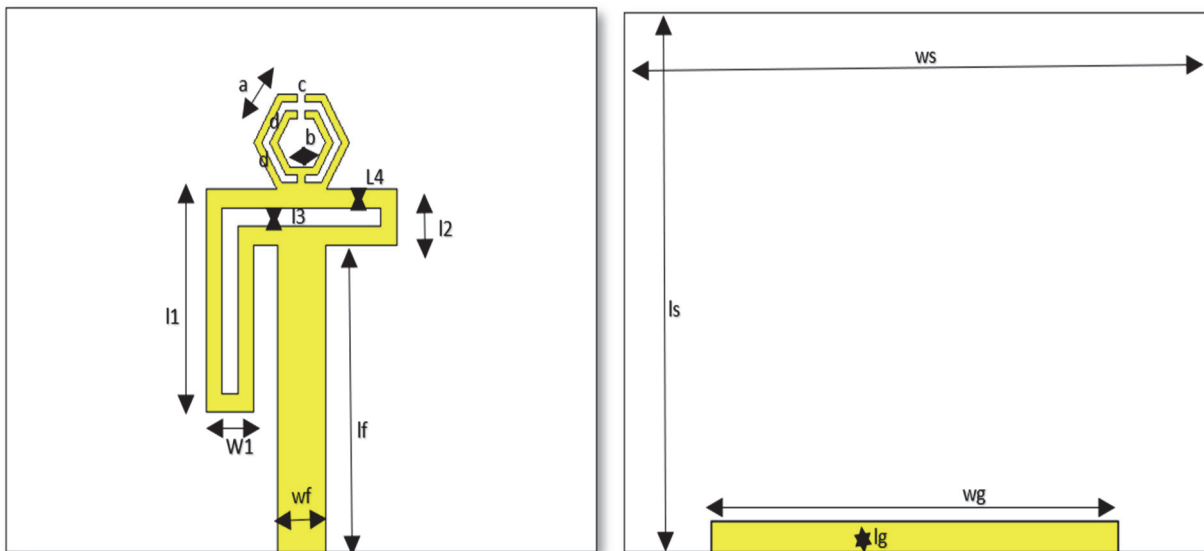


Figure 2 SRR inspired triband monopole antenna parameters

4 RESULTS AND DISCUSSION

Fig. 3 illustrates a comparison of the return loss characteristics at both stages. The last step exhibits three distinct resonant dips at 5.34 GHz, 7.64 GHz, and 7.94 GHz, indicating successful triband operation. Conversely, the initial stage does not exhibit distinct multi-resonance behaviour. Incorporating SRR structures and improving the geometry in the final design enhances impedance matching, evidenced by return loss values below -15 dB across all bands.

Fig. 4 VSWR plot indicates values below 2 throughout all three operating bands, signifying effective impedance matching at 5.34 GHz, 7.64 GHz, and 7.94 GHz. The minimum VSWR occurs at approximately 7.94 GHz, coinciding with the peak return loss. This demonstrates that the antenna design functions effectively at its resonant frequencies by transmitting power and minimising reflections. Fig. 5 depicts the surface current distributions at the three resonant frequencies. These indicate that various segments of the antenna construction are being

activated. Significant current exists at the feedline and the base of the radiating patch at 5.34 GHz. Higher-order modes activate distinct components of the SRRs at 7.64 GHz and 7.94 GHz. The current distributions indicate the

presence of distinct physical resonators within the structure that sustain each band. The integrated metamaterial structure comprises two concentric split-ring resonators (SRRs) carved in the same orientation on the patch.

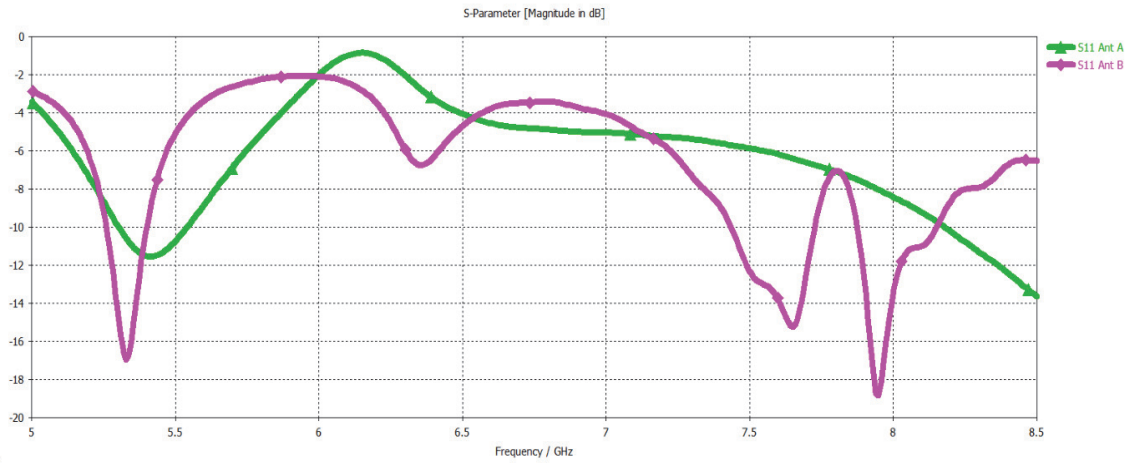


Figure 3 Return loss comparisons of two stages SRR inspired triband monopole antenna

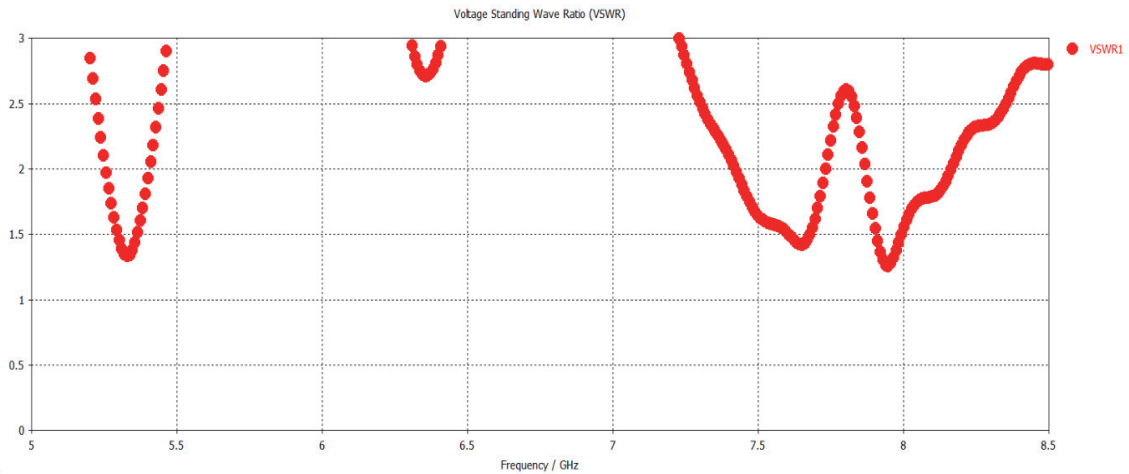


Figure 4 VSWR of SRR inspired triband monopole antenna

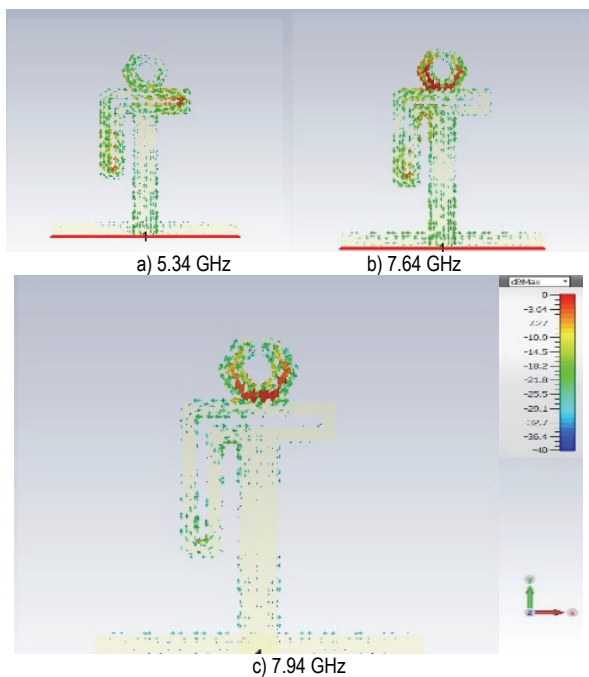


Figure 5 Surface current of various resonating frequencies SRR inspired triband monopole antenna

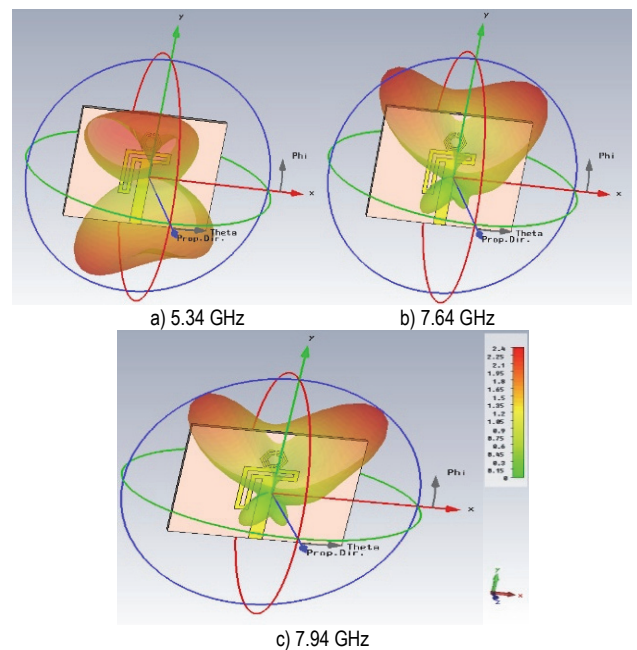


Figure 6 Radiation pattern of various resonating frequencies SRR inspired triband monopole antenna

The SRRs introduce additional resonant channels, enabling the excitation of higher-order modes and facilitating tri-band behaviour. The SRRs facilitate miniaturisation and regulate the distribution of surface current, seen by the altered resonance and expanded impedance bandwidth. The radiation pattern is depicted in a three-dimensional illustration in Fig. 6. The outcomes of the proposed SRR-inspired triband monopole antenna are presented in Tab. 2.

Table 2 Results of the proposed SRR inspired triband monopole antenna

Band	Resonant Frequency / GHz	Operating Band / GHz	Bandwidth / MHz	Return loss / dB
1	5.34	5.25- 5.40	150	-16.66
2	7.64	7.43 - 7.73	302	-15.39
3	7.94	7.87 - 8.15	280	-18.71

The directivity trends illustrated in Fig. 7 closely resemble those of gain, exhibiting a peak about 7.94 GHz. The increase in directivity with frequency indicates that radiation is more effectively concentrated in space at higher bands, which benefits point-to-point communication. The antenna maintains its compact dimensions while effectively functioning in all orientations.

Fig. 8 illustrates the gain plot, indicating that the gain values are acceptable throughout all three bands. The maximum gain is approximately 7.94 GHz (~ 3.8 dBi),

whereas the remaining bands exhibit values ranging from 2.5 to 3.2 dBi. The gain variation is stable; thus, the antenna is suitable for usage in the sub-8 GHz range for applications requiring consistent radiation performance. Although the antenna offers narrowband operation (~ 3% bandwidth), it aligns well with 5G use cases such as FR1 sub-6 GHz bands (e.g., n77, n79) and fixed wireless access (FWA), where frequency selectivity and minimal interference are critical. Narrowband antennas are particularly suitable for dedicated point-to-point 5G links or industrial IoT systems requiring stable frequency operation.

Table 3 Comparison of SRR inspired triband monopole antenna with literature

Ref. No	Resonant Frequencies / GHz	Bandwidth / MHz	Gain / dBi	Size / mm ²	Structure Type
2	2.4/5.2	180/230	2.5/2.9	40 × 45	Dual-band SRR
4	3.5/5.8	120/160	2.2/3.0	38 × 42	Reconfigurable patch
1	2.4/3.5/5.8	150/180/220	2.7-3.5	45 × 45	Switchable multi-band
15	3.3/5.5/7.9	160/200/250	3.0-3.6	37 × 40	ELC Metamaterial
16	2.4/5.8/8.2	200/220/280	3.1-3.9	42 × 48	Thin square MPA
Proposed Work	5.34/7.64/7.94	150/302/280	2.5-3.8	30 × 38	Tri-band SRR-loaded monopole

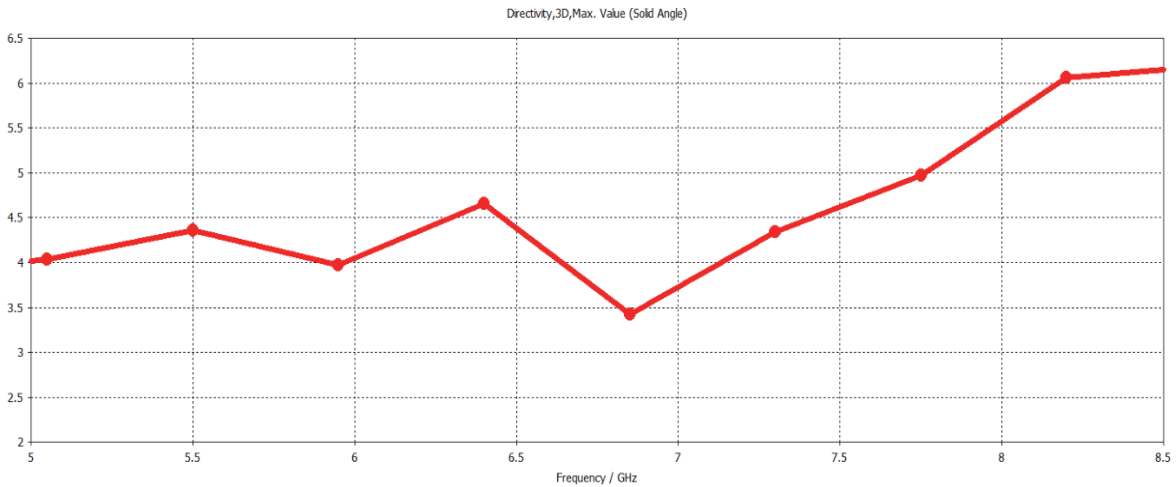


Figure 7 Directivity vs operating frequency - SRR inspired triband monopole antenna

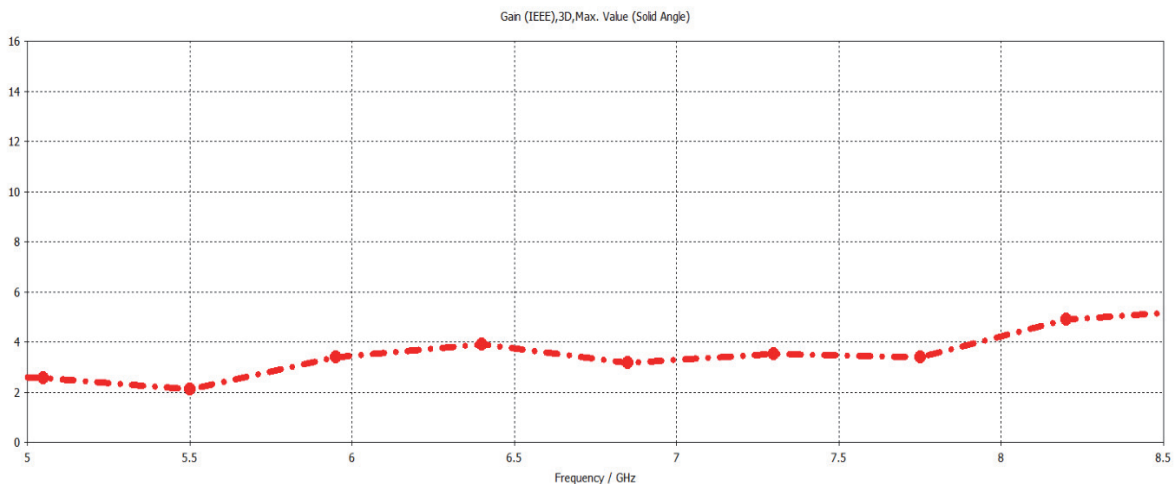


Figure 8 Gain vs operating frequency - SRR inspired triband monopole antenna

5 CONCLUSION AND FUTURE SCOPE

The proposed SRR-inspired tri-band monopole antenna successfully meets the objectives of compactness, multi-band resonance, and consistent radiation performance. The final design exhibits three distinct resonant frequencies at 5.34 GHz, 7.64 GHz, and 7.94 GHz, with operational frequency ranges of 5.25-5.40 GHz, 7.43-7.73 GHz, and 7.87-8.15 GHz, respectively. The antenna achieves bandwidths of 150 MHz, 302 MHz, and 280 MHz, with corresponding return losses of -16.66 dB, -15.39 dB, and -18.71 dB, ensuring efficient energy transfer. Excellent impedance matching ($VSWR < 2$) is observed across all bands, coupled with stable gain and directivity. These characteristics demonstrate the antenna's suitability for multi-standard communication systems, including WLAN, ISM, and satellite communications, operating below 8 GHz. The integration of split-ring resonators (SRRs) into the monopole design proves to be an effective and simple method for achieving multi-band resonance without complicating the overall structure. For future work, the design can be optimized further by exploring the use of different SRR geometries and positioning techniques to achieve wider bandwidths and improved gain across the frequency bands. Additionally, the antenna's performance in real-world environments, such as integration within mobile devices or base stations, can be evaluated to assess its robustness and adaptability to varying operational conditions. Exploring miniaturization techniques and the use of advanced materials for improved performance is also a potential avenue for enhancing the antenna's capabilities in next-generation communication systems.

6 REFERENCES

- [1] Ullah, S., Ahmad, S., Khan, B. A., & Flint, J. A. (2018). A multi-band switchable antenna for Wi-Fi, 3G Advanced, WiMAX, and WLAN wireless applications. *International Journal of Microwave and Wireless Technologies*, 10(8), 991-997. <https://doi.org/10.1017/S1759078718000776>
- [2] Roja, G., Maheswara Venkatesh, P., & Jayasankar, T., (2023). Split Ring Resonator Inspired Dual-Band Monopole Antenna for ISM, WLAN, WIFI, and WiMAX Application. *Technical Gazette*, 30(5), 1533-1538. <https://doi.org/10.17559/TV-20230210000344>
- [3] Çalışır, B. & Akbal, A. (2022). A New RF Satellite Link Analyzing and Antenna Effect on Satellite Communication. *Tehnički glasnik*, 16(4), 550-556. <https://doi.org/10.31803/tg-20220405153200>
- [4] Ermiş, S. & Demirci, M. (2023). Improving the Performance of Patch Antenna by Applying Bandwidth Enhancement Techniques for 5G Applications. *Tehnički glasnik*, 17(3), 305-312. <https://doi.org/10.31803/tg-20220819001236>
- [5] Prasad Jones Christydass, S., Suresh Kumar, S., Nishok, V. S., Saravanakumar, R., Devakirubakaran, S., Deepa, J., & Sangeetha, K. (2023). Design of Metamaterial Antenna Based on the Mathematical Formulation of Patch Antenna for Wireless Application. *International Journal of Antennas and Propagation*. <https://doi.org/10.1155/2023/2543923>
- [6] Thiruvankadam, S. & Parthasarathy, E. (2023). Compact multiband monopole antenna design for IoT applications. *Journal of Electromagnetic Waves and Applications*, 37(5), 629-643. <https://doi.org/10.1080/09205071.2022.2163191>
- [7] Aliqab, K., Lavadiya, S., Alsharari, M., Armghan, A., Daher, M. G., & Patel, S. K. (2023). Design and Fabrication of a Low-Cost, Multiband and High Gain Square Tooth-Enabled Metamaterial Superstrate Microstrip Patch Antenna. *Micromachines*, 14(1), 163. <https://doi.org/10.3390/mi14010163>
- [8] Islam, T. & Roy, S. (2023). Low-Profile Meander Line Multiband Antenna for Wireless Body Area Network (WBAN) Applications with SAR Analysis. *Electronics*, 12(6), 1416. <https://doi.org/10.3390/electronics12061416>
- [9] Christydass, S. P. J. & Gunavathi, N. (2021). Octa-Band Metamaterial Inspired Multiband Monopole Antenna for Wireless Application. *Progress in Electromagnetics Research C*, 113, 97-110. <https://doi.org/10.2528/PIERC21041102>
- [10] Boopathi Rani, R. & Pandey, S. K. (2017). ELC metamaterial based CPW-fed printed dual-band antenna. *Microwave and optical technology letters*, 59(2), 304-307. <https://doi.org/10.1002/mop.30292>
- [11] Liu, X. Y., Wu, Z. T., Fan, Y., & Tentzeris, E. M. (2016). A miniaturized CSRR loaded wide-beamwidth circularly polarized implantable antenna for subcutaneous real-time glucose monitoring. *IEEE Antennas and Wireless Propagation Letters*, 16, 577-580. <https://doi.org/10.1109/LAWP.2016.2590477>
- [12] Dakulagi, V. & Bakhar, M. (2020). Advances in smart antenna systems for wireless communication. *Wireless Personal Communications*, 110(2), 931-957. <https://doi.org/10.1007/s11277-019-06764-6>
- [13] Kumar, A. & Al-Hasan, M. A. J. (2020). A coplanar-waveguide-fed planar integrated cavity backed slotted antenna array using TE₃₃ mode. *International Journal of RF and Microwave Computer-Aided Engineering*, 30(10), e22344. <https://doi.org/10.1002/mmce.22344>
- [14] Kumar, A. & Althuwayb, A. A. (2020). Wideband triple resonance patch antenna for 5G Wi-Fi spectrum. *Progress in Electromagnetics Research Letters*, 93, 89-97. <https://doi.org/10.2528/PIERL20071605>
- [15] Sam, P. J. C. & Gunavathi, N. (2020). A tri-band monopole antenna loaded with circular electric-inductive-capacitive metamaterial resonator for wireless application. *Applied Physics A*, 126, 1-11. <https://doi.org/10.1007/s00339-020-03952-1>
- [16] Lakshmi, M. L. S. N. S., Prasad Jones Christydass, S., Kannadhasan, S., Anguraj, K., & Chatterjee, J. M. (2023). Polarization Stable Triband Thin Square-Shaped Metamaterial Absorber. *International Journal of Antennas and Propagation*. <https://doi.org/10.1155/2023/6065300>
- [17] Goswami, S., Sarmah, K., Sarma, A., Sarma, K. K., & Baruah, S. (2017). Design of a CSRR based compact microstrip antenna for image rejection in RF down-converter based WLAN receivers. *AEU-International Journal of Electronics and Communications*, 74, 128-134. <https://doi.org/10.1016/j.aeue.2017.02.004>
- [18] Christydass, S. P. J. & Gunavathi, N. (2021). Dual-band complementary split-ring resonator engraved rectangular monopole for GSM and WLAN/WiMAX/5G sub-6 GHz band (new radio band). *Progress in Electromagnetics Research C*, 113, 251-263. <https://doi.org/10.2528/PIERC21052007>

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