Indonesian Journal of Electrical Engineering and Informatics (IJEEI)
Vol. 12, No. 3, September 2024, pp. 659~666
ISSN: 2089-3272, DOI: 10.52549/ijeei.v12i3.5677

A Compact Inset Coupled-Fed Triangular Patch Antenna For Wideband 5G Applications

Mohan C[1], Silamboli J[2], Divya S[3], Shantha Sheela R[4]
[1]Assistant Professor, Department of ECE, St.Joseph's Institute of Technology, Tamilnadu, India.
[2]Assistant Professor, Department of ECE, CSI College of Engineering, Tamilnadu, India.
[3]Assistant Professor, Department of Biomedical, Dr.N.G.P, Institute of Technology, Tamilnadu, India.
[4]Assistant Professor, Department of ECE, M.I.E.T Engineering College, Tamilnadu, India.

Article Info

Article history:

Received Jul 3, 2024
Revised Aug 31, 2024
Accepted Sep 18, 2024

Keyword:

Patch Antenna,
Inset Coupling Feed,
Wideband,
Miniaturization

ABSTRACT

For 5G applications, a compact inset coupled-fed high bandwidth triangle antenna is demonstrated. A large bandwidth can be achieved by combining the inset and coupling feeding with a triangle-shaped patch. With a VSWR of less than 2, the suggested antenna's working frequency of 3.6 GHz spans the frequency range needed for 5G applications, which is between 2.8 and 5.6 GHz. The primary characteristics of the suggested antenna are its smaller dimensions (20.5 × 17.5 mm2) and about 35% increased bandwidth. Significant factors that match the simulated results exactly are S11, radiation pattern, radiation efficiency, and peak gain in the proceeding of the proposed antenna. With the addition of two parallel rectangular strips with a triangular-shaped patch, the antenna is capable to achieve 40% reductions in size, 81.74% radiation efficiency, and 2.61 dB peak gain for the suggested antenna. With a center frequency of 3.6 GHz and a reflection coefficient of 28.6 dB, the fractional bandwidth is 66.67% (2.8 GHz to 5.6 GHz). With a smaller surface wave and an excellent omnidirectional radiation pattern, the antenna's inset coupling feeding arrangement makes it appropriate for Sub-GHz 5G applications.

Copyright © 2024 Institute of Advanced Engineering and Science.
All rights reserved.

Corresponding Author:

Mohan.C,
Assistant Professor, Department of ECE,
St.Joseph's Institute of Technology,
Tamilnadu, India.
Email: mohanrc803@gmail.com

1. INTRODUCTION

The current state of technology is moving toward 5G. The GSM standard is associated with the second generation, while the analogue mobile telecommunications standards of the first generation are well-known. It is an improvement over 2G, 2.5G, GPRS, and 2.75G for GSM Evolution networks. Higher speech quality and faster data transmission are offered by enhanced data rates [1,2]. Eventually, this network was replaced by 4G and 5G. Unlike 4G networks, it is also feasible to create a theoretically dedicated network that fits each service's requirements to effectively serve massive IoT, mission critical IoT, and enhanced mobile broadband. One of the primary objectives of wireless communications systems is to cater to the needs of the next generation. To this end, greater data rate applications and services, such web surfing, wireless teleconferencing, picture in local coverage networks, and multimedia, must be achieved [3]. In indoor wireless communication systems, antenna distribution becomes more important for most mobile data where internal traffic is created. Furthermore, a variety of frequency bands are created and commercially employed in various communication systems, including 4G Wireless Local Area Network (WLAN) and WiMAX, to improve communication services. Therefore, to simultaneously meet several service frequencies bands, a suitable broadband distribution antenna is needed [4].

While 5G aims to connect people with things (cloud-based technologies), 4G's primary goal is to connect people. Massive MIMO, beamforming, perfect duplex, millimetre waves, and network identification with tiny cells can all provide 5G services. To extend the cellular spectrum to unlicensed bands above 6 GHz, new fields of study were motivated by the concept of spectrum extensions. Additionally, the 5G Core Network (5GCN) is showcasing the rapid advancements in radio access networks by combining service-based interfaces for end-to-end architectural slicing. The main obstacle to developing the necessary 5G technology is that, while 4G offers excellent call quality, it is not fast enough to access cloud services via the internet. The main architectural thought of the 5G network is to separate the control plane from the data plane and to build the next-generation mobile communication network around network function rather than node basis [5-7]. Because of its lightweight nature, small patch antennas are commonly used by antenna researchers in modern wireless communication applications. Recently, many wireless system customers have demanded a future of wireless applications with compact antennas, greater speeds, and wideband. Microstrip (MSA) antennas are commonly employed in printed circuits because of its light weight, cheap, and ease of integration with active circuits. They are also suited for multi-band design and dual-polarisation antennas [8,9]. However, the typical microstrip antenna fails to meet the customer's wireless technology requirements due to its small bandwidth [10]. Consequently, the researchers used a variety of design techniques to address the patch antenna's reduced bandwidth [11]. Adding various shapes of fractal geometry [12], multiple strips[13], varied combinations of feeding methods [14], multi-split slots [15], and a Coplanar Waveguide (CPW) configuration [16] are some of the effective strategies for controlling such issues.

The dual-band behaviour is obtained by designing a unique eye-shaped patch with a semi-circular slotted ground plane. This combination technique achieves a greater bandwidth than the usual dual-band monopole antenna. In [17], enhanced peak gain and bandwidth are achieved by employing a new Frequency Selective Surface (FSS) construction with an antenna. The proposed architecture produced an overall peak gain of 17 dB at 28 GHz. Furthermore, it improves bandwidth by 9% while maintaining radiation efficiency at 90%. An article suggested a simple slotted wideband antenna for 5G communication. Another design is shown in [18] and is a rectangular patch with a U-shaped parasitic cut surrounding the radiating element. First band obtained between 4.8 GHz to 6.2 GHz, second band from 5.2 GHz to 5.3 GHz, and third band from 5.72 GHz to 5.82 GHz are all covered by the suggested antenna [19]. Metamaterials, that are man-made periodic structures with unique characteristics that cannot be discovered in the natural world on their own. Metamaterials are mainly used to enhance the realised gain, directivity, and impedance of antenna [20] adds a metamaterial split ring resonator to the microstrip patch antenna. 400 MHz of bandwidth between 4.8 GHz and 5.2 GHz is achieved with this suggested configuration. Another study [21] suggested a circular slip ring resonator, which resulted in an 87% reduction in antenna size. Thus, a metamaterial slip ring resonator can be used to achieve maximum miniaturization. One practical method for increasing bandwidth is to use the microstrip patch antenna's slot structure. The antenna in [22] uses a C-shaped slot in the ground plane and a T-shaped slot in the patch to obtain a gain and directivity of 5.49 dB and 7.12 dB, respectively, while retaining the compact size.

Improving an antenna's bandwidth is essential to antenna design, particularly for patch antennas renowned for having a limited bandwidth. Variations in feeding systems can majorly impact these antennas' bandwidth performance [23-26]. The feeding mechanism that is used relies on the application's needs, including those related to bandwidth, fabrication simplicity, component integration, and overall antenna performance. By eliminating undesired radiation and cancelling out even-mode currents, differential feeding can offer good bandwidth performance. Additionally, it effectively doubles the bandwidth over single-ended feeding, improving impedance bandwidth. A useful method for increasing the bandwidth of microstrip patch antennas is the inset coupling feed, which strikes a good compromise between cost, convenience of use, and performance. The research often demonstrates that inset feeds can significantly increase antenna bandwidth with accurate preparation and optimization [27-31]. The ability to provide accurate impedance matching with an easy design and fabrication method, minimizing complexity and expense while retaining high efficiency and minimal radiation loss, is what makes the inset coupling feed innovative. This feeding method's improved efficiency, low-profile design, cost-effectiveness, and versatility in a wide range of applications demonstrate its value. Because of its versatility, it is a crucial approach in the design of microstrip antennas, particularly where factors such as moderate bandwidth increase, fabrication simplicity, and reliable operation are important. In order to increase planar antenna's effectiveness and meet multiband requirements, a range of feeding techniques is essential. Furthermore, the patch antennas' bandwidth can be expanded by using various feeding mechanisms. Among these configurations, quarter-wave transformer matching feed, Microstrip feed, Co-Planar Waveguide (CPW) feed, and Asymmetric Coplanar Strip (ACS) feed are often employed feeding approaches for bandwidth increase. The following are a few instances of hybrid structures: dual-mode coplanar waveguide and waveguide feed [32], magneto-electric feed and differential feed [33], meandered strip and aperture-coupled feed [34], complex electromagnetic-feed structure [35], and parasitic feed and asymmetric feed [36].

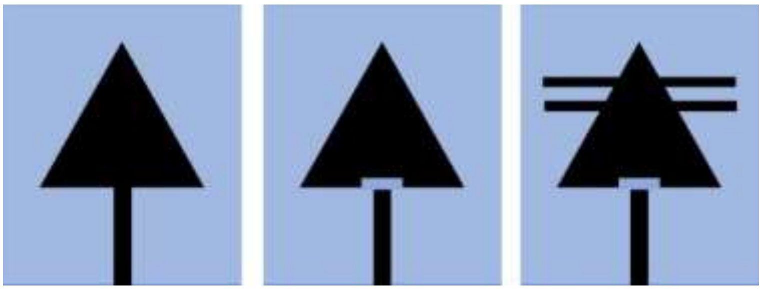


Figure 1. Design Evolution of the proposed antenna. a) Stage 1, b) Stage 2 and c) Stage 3.

This study analyses a small inset coupled-fed wideband triangular antenna for 5G applications operating at Sub-6 GHz. The suggested antenna's working on the frequency of 3.6 GHz spans the greater bandwidth range (from 2.8 to 5.6 GHz) needed for microwave 5G applications. This antenna have been manufactured on a basic FR-4 substrate measuring 20.5 x 17.5 mm^2. The designed antenna's achieved compactness, overall radiation efficiency, and peak gain of operating frequency are 40%, 81.74%, and 2.61 dB, respectively. For Sub-6 GHz operation, the fractional bandwidth is also 66.67% (2.8 GHz to 5.6 GHz) attained. This study is divided into the following subsections: the second portion deals with the layout and structural dimensions of the antenna. The collective outcomes and discussion are described in the third portion, and the anticipated work is eventually concluded in the final portion.

2. ANTENNA DESIGN

Figure 1a illustrates the manufacturing of a simple triangular patch antenna with a permittivity value of 4.3 on an FR4 substrate with height of 1.6 mm designated for 3.6 GHz. CST-MWS suite 2021 is used to evaluate the dimensions and shape of the antenna. Perfect Electric Conductor (PEC) with a height of 0.035 mm in an open boundary condition comprises the top and bottom layers of the suggested antenna. Using fundamental equation (1), the antenna's size initially gets calculated, and the optimized dimensions of the proposed are 20.5 x 17.5 mm^2.

$$fr = \frac{C}{2S}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

'*S'* is the side length, 'ε_r' is the relative permittivity of the substrate, '*C'* is the velocity in free space, and '*fr'* is the resonant frequency [37]. Modification and analysis of the fundamental antenna structure are done to attain improved performance. Figure 1b illustrates how a mix of inset coupling feeding structures can replace the traditional microstrip feeding method to provide a broad bandwidth for effective 5G applications. Furthermore, Figure 1c demonstrates the process of adding two identical-sized adjacent rectangles to the triangular patch in order to further reduce its size. The rectangular strip's chosen dimensions are Ls x Ws. The triangle patch's side length is selected as S, and the final design's overall dimensions are (L x W). A combined feeding arrangement with dimensions of Lf x Wf excites this suggested antenna. Furthermore, this combinational feeding configuration is intended to be 50Ω to correspond with the transmission line's typical impedance. Figure 2 illustrates the S-Parameter results for different stages. Figure 3 shows the entire constructional geometry and structural features of the suggested antenna. Table 1 provides accurate measurements of every parameter of the suggested antenna.

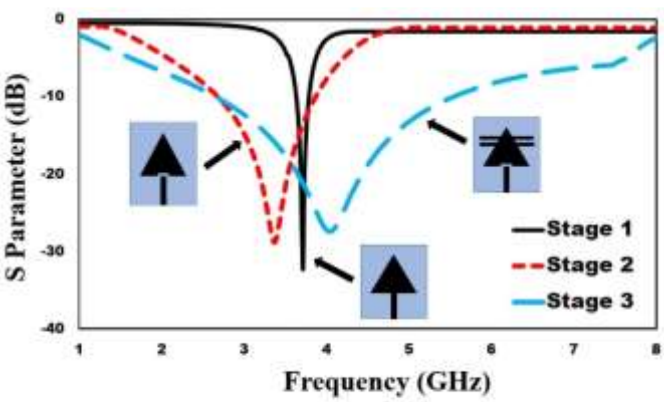


Figure 2. S-parameter results for different stages.

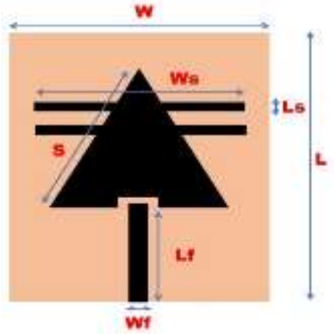


Figure 3. Design configuration of the designed antenna.

Table 1. Parameters of the Proposed Antenna

Parameter	Size (mm)	Parameter	Size (mm)
W	17.5	L_1	4.3
L	22.2	L_2	2.4
W_F	2.8	W_1	11.5
L_F	5		

3. EXPERIMENTAL RESULTS

The suggested antenna's prototype has been constructed and examined to verify the design, as shown in Figure 4. Additionally, testing to verify is completed effectively. An anechoic chamber is used for radiation measurement, and a Vector Network Analyzer is utilized for observing the S_{11} result. The recommended antenna is a great option for Sub-6 GHz and WiMAX operations based on the antenna characteristics' results.

Figure 4. Fabricated prototype of the inset coupled-fed triangular patch antenna.

Figure 5 plots and compares the proposed antenna's estimated and computed reflection coefficients. With an improved VSWR value, the antenna operates across a larger 2.56 GHz bandwidth, from 2.67 GHz to 5.23 GHz. Table 2 lists the obtained bandwidth of proposed antenna at different stages. The strip that results in better miniaturization is situated at the radiating patch of the antenna. Broader operating bandwidth is accomplished by the inset coupling feeding mechanism. The SMA connector's soldering effects could be the reason for the little variations. Although it is employed in the experiment, the impact of the cable connector is not taken into consideration in the simulated results.

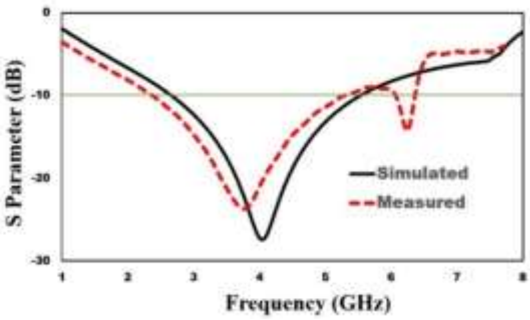
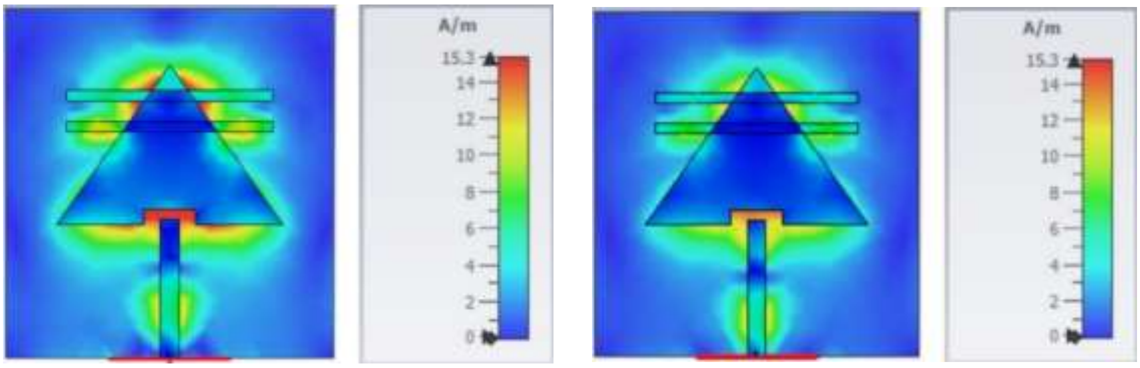


Figure 5. Combined reflection coefficients of the proposed antenna.

Table 2. Bandwidth of the proposed antenna

Stages	Bandwidth	Percentage
Stage 1 (Conventional Triangular Antenna)	110 MHz (3.5 GHz –3.61 GHz)	-
Stage 2 (Inset-Coupled Feed Antenna)	1.2 GHz (3.4 GHz – 4.01 GHz)	11
Stage 3 (Inset-Coupled Feed Antenna with Four Strips)	3.8 GHz (2.8 GHz – 5.6 GHz)	35

Figure 6 depicts the top surface of the proposed antenna with a simulated current concentration at 3.6 GHz. This design clearly shows that most of the energy flows at the inset coupling feed at 4.8 GHz, while most of the energy is dispersed throughout the exterior region surrounding the rectangular strips in the triangular patch at 3.6 GHz. The antenna's wideband behaviour is too much of an outcome of the inset coupling feed arrangement. The suggested antenna is constructed and tested under these antenna parameters.



(i) (ii)

Figure 6. Simulated current density of the proposed antenna. i) 3.6 GHz and ii) 4.8 GHz.

Figure 7 illustrates the analytic process of the radiation pattern computation of the designed antenna inside the chamber setup, which provides a free of noise environment.

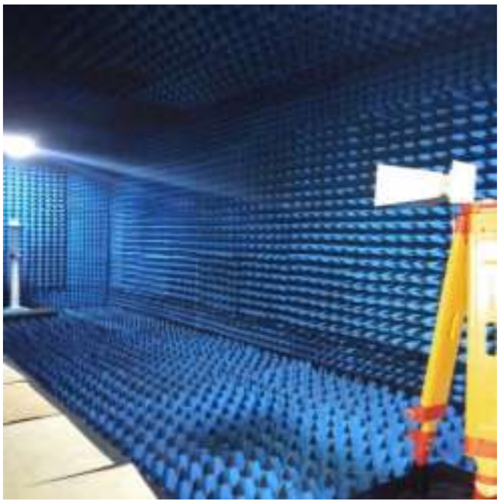


Figure 7. Measurement setup for radiation results.

The combined results of 2D and 3D E-plane and H-plane radiation characteristics at 3.6 GHz and 4.8 GHz, respectively, are shown in Figures 8a) and 7b). These results show that the measured results of the proposed antenna coincide with the simulated radiation patterns in both the E and H planes. This is so evident since the polarization plane and radiation patterns are the same across the working frequency band. The operating frequencies have a bidirectional configuration in the E-plane and a roughly omnidirectional configuration in the H-plane.

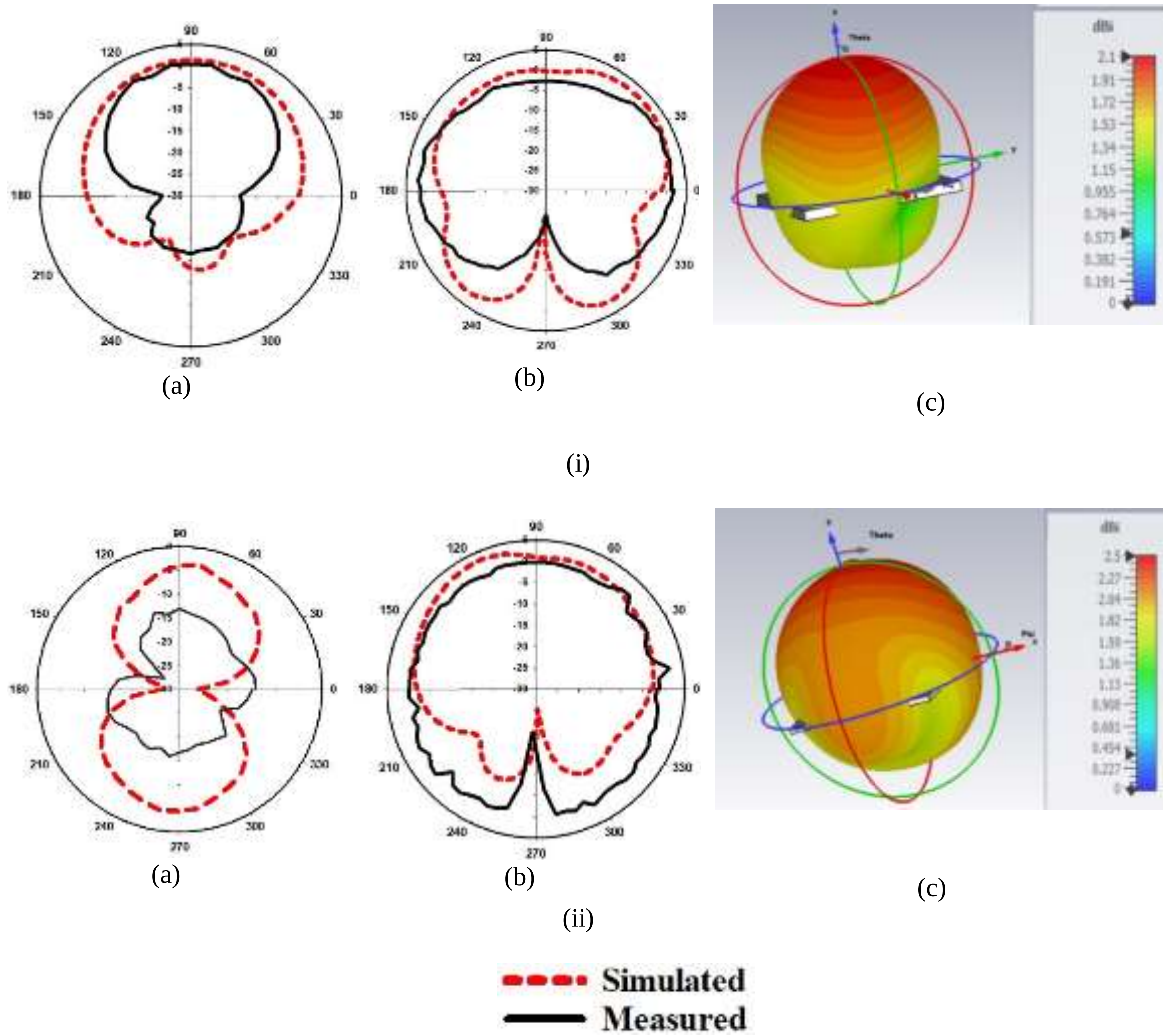


Figure 8. Combined radiation patterns of the designed antenna. a) E-plane, b) H-plane and c) 3-Dimentional, i) 3.6 GHz and ii) 4.8 GHz.

These values make it very evident that the H-plane pattern has a higher relative cross-polarization than the E-plane pattern. This phenomenon is mostly caused by strong horizontal components of the surface current and electric field. Because the horizontal part of the surface current causes cross-polarization and the vertical part is the primary source of radiation. The improved antenna's experimentally observed gain at broadside orientation, from 2.8 GHz to 5.6 GHz, is displayed in Figure 9. Throughout the working bandwidth, the obtained antenna gains ranges between 1.0 and 2.9 dBi. The greatest average gain of 2.95 dBi is reached at 3.2 GHz, and it remains nearly constant throughout the operational frequency range.

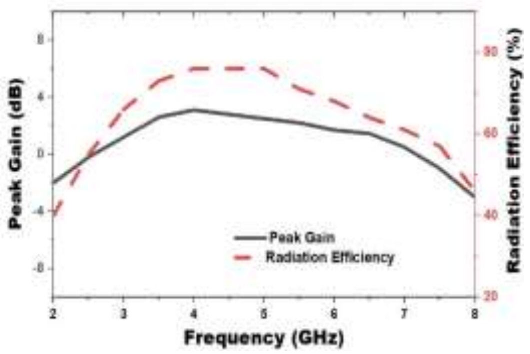


Figure 9. Peak Gain and Radiation Efficiency of the antenna.

Based on antenna type, size, substrate, and gain, Table 3 contrasts the suggested antenna with existing compact antennas that have been reported in the literature. Additionally, the following table demonstrates that the proposed antenna reduces size and bandwidth at the operating band compared to earlier work.

Table 3. Comparison with previously published antennas

Reference no.	Feeding Mechanism	Antenna size (mm)	Substrate used	Operating frequencies (GHz)	Bandwidth
[23]	Inset Feed	30.7 × 18.8	FR-4	3	180 MHz
[24]	Probe Feed	50 × 50	RT/Duroid 5880	6.6	780 MHz
[25]	Coplanar Coupled Feed	27 × 27	Quartz Glass	2.02	70 MHz
[26]	Aperture Coupled Feed	6 × 6	FR-4	12.8	1.1 GHz
[27]	Grounded Coplanar Waveguide (GCPW)	31 × 27	RT/Duroid 5880	13	2 GHz
[28]	Yagi-Uda-Shape Feed	26.1 × 14.3	Eccostock Hik	3.6	850 MHz
[29]	coplanar waveguide with ground (CPWG)	50 × 20	FR4	2.2	480 MHz
[30]	Dual Feed	50 × 50	FR4	2.5	420 MHz
[31]	Radiator Loop with chip capacitor	120 × 55	FR4	0.85	400 MHz
Proposed Work	**Inset-Coupled Feed**	**20.5 × 17.5**	**FR4**	**3.6**	**2.8 GHz**

4. CONCLUSION

This work presents a wideband triangular patch antenna structure and evaluation for microwave applications. The suggested antenna is a useful tool for 5G applications operating at sub-6 GHz. The antenna has performed exceptionally and has undergone a greater reduction in size. The suggested antenna has been designed and developed using a variety of techniques and structures depending on operational analysis, parameter results, and parameter sweeps. The proposed antenna's achieved compactness, radiation efficiency, and peak gain are 40%, 81.74%, and 2.95 dB, respectively. Additionally, a fractional bandwidth of 66.67% (2.8 GHz to 5.6 GHz) is attained. This work stands out from other published work due to the unique form and other excellent features that make this antenna appropriate for multiple 5G applications.

REFERENCES

[1] M. Shafi et al., "5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice," in IEEE Journal on Selected Areas in Communications, vol. 35, no. 6, pp. 1201-1221, June 2017.
[2] P. Suthar, V. Agarwal, R. S. Shetty and A. Jangam, "Migration and Interworking between 4G and 5G," 2020 IEEE 3rd 5G World Forum (5GWF), Bangalore, India, 2020, pp. 401-406.
[3] Dilsha M.D., Neenu Welson, 2015, Introduction to 5G Wireless Technology, International Journal of Engineering Research & Technology (IJERT), 2015 (Volume 4 – Issue 06).
[4] L. Chettri and R. Bera, "A Comprehensive Survey on Internet of Things (IoT) Toward 5G Wireless Systems," in IEEE Internet of Things Journal, vol. 7, no. 1, pp. 16-32, Jan. 2020.
[5] Hiwa Taha Sediq, Javad Nourinia, Changiz Ghobadi & Bahman Mohammadi (2023) A Novel Eye-shaped Monopole Antenna for Wideband and 5G Applications, IETE Journal of Research, 69:3, 1283-1293.
[6] Karim, R, Iftikhar, A, Ijaz, B & Mabrouk, IB 2019, 'The Potentials, Challenges, and Future Directions of On-Chip-Antennas for Emerging Wireless Applications - A Comprehensive Survey', IEEE Access, vol. 7, pp. 173897-y173934.
[7] Pires, N, Parra, T, Skrivervik, AK & Moreira, AA 2017, 'Design and Measurement of a Differential Printed Antenna for a Wireless Sensor Network Node', IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 2228-2231.
[8] Yang, M, Chen, ZN, Lau, PY, Qing, X & Yin, X 2015, 'Miniaturized Patch Antenna With Grounded Strips', IEEE Transactions on Antennas and Propagation, vol. 63, no. 2, pp. 843-848.
[9] Gao GP, Bin, H & Zhang, JS 2013, 'Design of a Miniaturization Printed Circular-Slot UWB antenna by the half-cutting method', IEEE Antennas Wireless Propagation Letters, vol. 10, no. 12, pp. 567-570.
[10] Hammache, B, Messai, A, Messaoudene, I & Denidni, TA 2019, 'A compact ultra-wideband antenna with three C-shaped slots for notched band characteristics', Microwave and Optical Technology Letters, vol. 61, no. 1, pp. 275–279.
[11] Zhang, H, Zhou, R, Wu, Z, Xin, H & Ziolkowski, RW 2010, 'Designs of ultra-wideband (UWB) printed elliptical monopole antennas with slots', Microwave and Optical Technology Letters, vol. 52, pp. 486–471.
[12] Mircea, V, Rusu & Roman Baican 2010, 'Fractal Antenna Applications, Microwave and Millimeter Wave Technologies from Photonic Bandgap Devices to Antenna and Applications', Igor Minin, IntechOpen.

[13] Peng, L, Ruan, C & Xuncai, Y 2009, 'Analysis of the small slot-loaded elliptical patch antenna with a band-notched for UWB applications', Microwave and Optical Technology Letters, vol. 51, no. 4, pp. 973–976.
[14] Jing-Yi Zhang, Fan Zhang & Wen-Peng Tian 2015, 'Compact 4-Port ACS-Fed UWB-MIMO Antenna with Shared Radiators', Progress In Electromagnetics Research Letters, vol. 55, pp. 81-88.
[15] Xiaole Kang, Hui Zhang, Zengrui Li, Qing-Xin Guo, Xueqin Zhang, Jun-Hong Wang & Yaoqing Lamar Yang 2013, 'A Band-Notched UWB Printed Elliptical-Ring Monopole Antenna', Progress In Electromagnetics Research C, vol. 35, pp. 23-33.
[16] Lakrit, S, Das, S, Ghosh, S & Madhav, BTP 2020, 'Compact UWB Flexible Elliptical CPW-fed Antenna with Triple Notch Bands for Wireless Communications', International Journal of RF and Microwave Computer-Aided Engineering, vol. 30, no. 7.
[17] Chen & Tao, Y 2011, 'Performance Improvement of a U-Slot Patch Antenna Using a Dual-Band Frequency Selective Surface with Modified Jerusalem Cross Elements', IEEE Transactions on Antennas and Propagation, vol. 59, no. 9, pp. 3482-3486.
[18] Ashish Gupta, Bansal, B, Mishra, Vimal & Agrawal, A 2020, 'A Miniaturized Tri-band Rhombus-Shaped Metamaterial-Inspired Antenna with Gain Enhancement using Complementary Closed Ring Resonators', IET Microwaves, Antennas and Propagation, vol. 14, no. 2, pp. 185-193.
[19] Gao GP, Bin, H & Zhang, JS 2013, 'Design of a Miniaturization Printed Circular-Slot UWB antenna by the half-cutting method', IEEE Antennas Wireless Propagation Letters, vol. 10, no. 12, pp. 567-570.
[20] M. Asaadi et al., "High gain and wideband high dense dielectric patch antenna using FSS superstrate for millimetre-wave applications," IEEE Access, vol. 6, pp. 38243-38250, 2018.
[21] C. Mohan and S. E. Florence, "Miniaturised triangular microstrip antenna with metamaterial for wireless sensor node applications", IETE J. Res., pp. 1-6, Jul. 2019.
[22] H. X. Lu et al. "Design and analysis of wideband U-slot patch antenna with U-shaped parasitic elements," International Journal of RF and Microwave Computer-Aided Engineering, vol. 28, no. 2, e21202, 2018.
[23] Ndujiuba, Charles U., Oluwafemi A. Ilesanmi, and Oboyerulu E. Agboje. "Bandwidth enhancement of an inset-fed rectangular patch antenna using partial ground with edge-cut method." International Journal of Electromagnetics and Applications 7, no. 1 (2017): 9-16.
[24] Cao, Wen-Quan, and Wei Hong. "Bandwidth and gain enhancement for probe-fed CP microstrip antenna by loading with parasitical patches." Progress In Electromagnetics Research Letters 61 (2016): 47-53.
[25] Yong-Zhong Chen , " Bandwidth Enhancement Using Coplanar Coupled Feeding Method With The Combination Of A Particular Shape Of Ground-plane Slot ", International Journal of Latest Research in Science and Technology . Vol. 3, Issue 6, pp 146-149 , 2014.
[26] Pandya, Prapti R., M. Sarada Devi, and Namrata Langhnoja. "Analytical Methods For Bandwidth Enhancement Of Microstrip Patch Antenna." ICTACT Journal on Microelectronics, Vol 7, No 1 (2021), 1095-1100.
[27] Patil, Shankaragouda M., and Rajeshkumar Venkatesan. "Bandwidth enhancement of substrate integrated waveguide cavity-backed half bow-tie complementary-ring slot antenna for Ku-band applications." Alexandria Engineering Journal 81 (2023): 46-54.
[28] Bari, Inam, Javed Iqbal, Haider Ali, Abdul Rauf, Muhammad Bilal, Naveed Jan, Usman Illahi, Muhammad Arif, Muhammad Amir Khan, and Rania M. Ghoniem. "Bandwidth enhancement and generation of CP of yagi-uda-shape feed on a rectangular DRA for 5G applications." Micromachines 13, no. 11 (2022): 1913.
[29] Zhang, Rui, Yang Liu, Hyung-Hoon Kim, and Hyeondong Kim. "Bandwidth enhancement of ground antenna using resonant feeding circuit." Electronics Letters 49, no. 7 (2013): 441-442.
[30] Alam, Syah, Indra Surjati, and Teguh Firmansyah. "Bandwidth enhancement of square microstrip antennas using dual feed line techniques." International Journal of Electrical and Electronic Engineering & Telecommunications 10, no. 1 (2021): 1-5.
[31] Li, Rui, Longyue Qu, Hyunwoong Shin, Hoseung Lee, Seokju Wi, Jeonghwan Kim, and Hyeongdong Kim. "Impedance Bandwidth Enhancement Using Capacitor-Controlled Series Resonance in an Antenna's Feeding Structure." Journal of Electromagnetic Engineering and Science 24, no. 2 (2024): 129-137.
[32] P. Bora, C. Paul, "Metamaterial loaded CSRR based antenna for WLAN and IOT band applications," Int. J. Sci. Technol. Res., vol. 8, no. 9, pp. 2060–2065, 2019.
[33] Dawar, P, Raghava, NS & De, A 2018, 'UWB and miniaturized meandered stripline fed metamaterial loaded antenna for satellite applications', IOP Conference Series, Materials Science and Engineering, vol. 377, no. 1, p. 012080.
[34] Ramdane, A, Richalot, E, Picon, O, Puech, J & Lapierre, L 2007, 'Rectangular waveguide-to-CPW transition without air-bridge in the Ka-band', Microwave and Optical Technology Letters, vol. 49, no. 3, pp. 510–513.
[35] Ullah, S, Ruan, C, Sadiq, MS, Haq, TU & He, W 2020, 'Highly Efficient and Ultra-Wide Band Monopole Antenna for Microwave Imaging and Communication Applications', Sensors Journal, vol. 20, p. 115.
[36] Xue, Liao, SW & Xu, JH 2013, 'A Differentially-Driven Dual-Polarized Magneto-Electric Dipole Antenna', IEEE Transactions on Antennas and Propagation, vol. 61, no. 1, pp. 425-430.
[37] Balanis CA. "Antenna theory: analysis and design", John Wiley & sons; 2015.