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A High Gain Multi Slotted and Compact Planar Microstrip Millimeter Wave Antenna for 5G Networks

Shazia Ashraf, Javaid A. Sheikh*, and Zahid A. Bhat

Abstract—The present scenario that demands a high data rate by the consumers in wireless communication has imposed a challenge in the present market. Therefore, millimeter wave technology is attracting the interest of researchers and industries. This paper proposes a rectangular planar microstrip antenna with slots in radiating elements as well as in the ground plane. The proposed structure has been designed, simulated, and fabricated at a center frequency of 28 GHz using 5880 RT Duroid as a substrate, which has a relative permittivity of 2.2, loss-tangent of 9×10^{-4}, and thickness of 1.6 mm. By performing the simulation using HFSS Ansys Software and also fabrication and testing, the proposed design attains a maximum gain of 8.735 dBi and a frequency bandwidth of around 2.817 GHz. The impedance bandwidth response ranges from 26.755 GHz to 29.572 GHz (10.1%) below the −10 dB line of the S_{11} plot. The proposed antenna is compact with dimensions of $2.19 \times 3.95\,\text{mm}^2$ and has wide bandwidth along with high gain, hence is a good candidate for mm-wave applications besides several innovative antenna-based gadgets. Measured S_{11} and VSWR results are consistent with the simulated ones.

1. INTRODUCTION

Nowadays the developmental stages of mobile broadband services are adopting different techniques because the consumer demands high speed, capacity, and efficiency. The tremendous increase in traffic is estimated to be 100 times greater by 2030 [1, 2] than what we have at present. In addition, it is expected in the future that the number of devices and services will grow at an immense rate, thereof the desire for cost-effective and user experience, which is going to give birth to revolutionary solutions. Furthermore, by 2025, the number of linked devices on the internet is expected to reach 50 billion or more [24]. Also, pandemic like COVID-19, which has affected the world socially and economically, has accelerated the dependence of the world on technology trends like telehealth, digital payment, online shopping, robotics, online classes, remote work for companies, etc. For making these current trends work properly, we need internet availability, remote monitoring, virtual meeting, cloud technology, and these technologies rely on stable and high-speed internet. The solution to the above problems is 5G, as it can improve the main elements such as throughput, reliability, latency [1, 3] increased energy efficiency, and scalability. It is worthwhile to mention that this generation of mobile technology is going to connect data, people, applications, things, cities, and transport systems. Applications like smart buildings and homes, remote medical services, 3D video, smart cities, augmented and virtual [4–6] reality play and work in the cloud, and massive device-to-device communication for the automation of the industry are getting possible with this technology [22].

The term IMT-2020 (Information Management Technology) [9] is a synonym for 5G [10]. The 5G technology may use frequency spectrum variations that may communicate massive data over a small distance. The approaching 5G and millimeter wave technology is expected to turn up from numerous

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* Corresponding author: Javaid Ahmad Sheikh (sheikhjavaid@uok.edu.in).
The authors are with the Department of Electronics and Instrumentation, University of Kashmir, Srinagar, India.

dealers and is going to be composed of systems that provide solutions intended to provide low latency and quick download speeds [7, 14, 22].

Current research suggests that the millimeter-wave (MM-Wave) [4, 11–13] range of frequencies (20 GHz–300 GHz) might be an alternative to replacing the existing congested and saturated radio frequency spectrum in wireless communication systems [15]. Designing an antenna at the mm-Wave range has various advantages like capacity, coverage, and data rate at short-range communication [4, 11–13]. Right now, a great deal of study is going on 5G networks exploiting the advantages of mm-Wave. This mm-Wave has wavelengths in the range of 0.1 mm–10 mm. In addition, 5G proposes to achieve all Sustainable Development Goals (SDGs), from economical and clean energy to zero hunger [24].

2. BRIEF OVERVIEW OF RELATED WORK

Current literature presents many proposed antenna design solutions for microstrip antenna for 5G networks at the center frequency of 28 GHz. Authors in [16] present a rectangular microstrip antenna (with inset feed) design solution to the growing demand for mobile data. It is operated at 28 GHz frequency and expecting its application for the Local Multipoint Distribution Service (LMDS) band. This paper provides bandwidth with a value of 5.57 GHz (19.89%) and higher throughput. However, the gain of an antenna obtained in this work is 5.06 dBi. A slotted loop air-filled dual-band MIMO-antenna is reported by the authors in [17], for 5G smartphone applications. The authors have used a low-cost FR-4 asubstrate in the design, and the percentage impedance bandwidth provided at 28 GHz is 3.5%. However, this bandwidth is still low to meet the present demands. In addition, the design is complex and offers low gain. An elliptical slot circular antenna is presented in paper [19]. For the excitation of an array, the concept of the center series fed technique has been used and provides the gain value of 13.5 dB at 28 GHz. The authors' aim in this work was to surpass the design intricacy and poor performance of microstrip patch for 5G network applications, but this design offers very little bandwidth. A tilted beam antenna design proposed herein [20] by the authors uses the concept of a parasitic patch which increases the gain of the microstrip antenna without using the concept of arrays. The antenna, on the other hand, is not compact enough to be assimilated into real-life mobile devices. In addition, it provides low gain. A dual-band planar printed monopole millimeter-wave and 2×2 MIMO antenna has been suggested in work [21] for 5G wireless network communications. The design covers wide bandwidth and has a via-free planar compact geometry. In paper [25], the authors have introduced a compact antenna with a coplanar waveguide feed. The antenna presented is based on a Rogers substrate and has attained a maximum gain of 6.6 dB at 28 GHz. However, the proposed design in this paper provides a bandwidth of a few MHz. Sam and Mokayef [26], in their work, propose a microstrip slotted 5G antenna with a compact size of $22 \times 19\,\text{mm}^2$ and a resonant frequency of 11 GHz. The antenna provides a directivity of 6.348 dB and a peak gain of 6.3 dB. The introduced concept in paper [17] uses the idea of paper [27], which presents a low profile and simple structure for 5G mm-wave applications. The design consists of a square patch with F and L slots for triband operation. This proposed design attains a bandwidth of 840 MHz at 28 GHz and a peak gain of 7.22 dB. This structure is inexpensive, small in size, has dimensions of $5.1 \times 5 \times 0.254\,\text{mm}^3$, is easy to fabricate, and works in three frequency bands.

All the papers presented above have either used Rogers Duroid or FR-4 as a substrate. However, in many recent studies, new dielectric substrate materials like magneto-dielectrics, sol-gel-based synthesized substrate, and ilicon on glass (SoG) technology have been in focus to maximize the performance of microstrip antenna for 5G and IoT communications. Authors in [18] have presented a compact microstrip patch antenna that uses a micro-wave dielectric ceramic for 5G communication networks with small dimensions of $14 \times 14\,\text{mm}^2$. The introduced novel idea provides a bandwidth of 2.66 GHz, radiation efficiency of 93%, and maximum realized gain value of 5.82 dB at the 28 GHz millimeter-wave frequency band. However, the fabrication steps for this design are complex. An inventive magneto-electro-dielectric waveguide meta-material (MED WG MTM) has been suggested in [28]. This can be modulated with a higher value of the index of refraction used for the miniaturization of an antenna and a higher value of impedance for the enhancement of bandwidth. In the operation band, a gain higher than 4.6 dB is observed with comparable radiation patterns. In addition, in this antenna, there are not any metallic via holes and parasitic loading elements, but the fabrication process is lengthy and complicated. In addition, the bandwidth is not much improved. An embedded meander line (EML) is etched by the authors in [29], inside the ground layer just beneath the radiating patch to realize the artificial-magneto-dielectric loading for the microstrip antenna. Both the simulated and measured results depict that the purposed EML array antenna has a broad range of impedance bandwidth over the traditional microstrip antenna of the same dimensions. However, the antenna needs additional shield metal and offers a bandwidth of a few MHz only. In [30], the authors have achieved the performance improvement and miniaturization of passive RF components by incorporating magneto-dielectric metamaterials. It is revealed that the configuration of the EBG (electromagnetic-band-gap) structure that uses magneto dielectrics has improved the band-gap rejection levels and achieved compact size. The authors have used both magnetic and dielectric materials that allow for parallel ease of patch antenna miniaturization and impedance-matching.

3. CONTRIBUTION AND ORGANIZATION

The proposed work presents a single band millimeter-wave antenna with planar compact geometry that can cover a wider bandwidth for 5G network applications. The suggested structure has been devised and simulated in an HFSS software tool and finally fabricated and measured. It also provides a better value of the simulated gain of 8.74 dB for the desired center frequency of 28 GHz. The design is compact with dimensions of $2.19 \times 3.95\,\text{mm}^2$, hence can be integrated with portable 5G wireless devices. The proposed design provides bandwidth from 26.755 GHz to 29.572 GHz, which is considered under the ITU-n257 band by the 5G NR spectrum [31]. The paper is organized as: Section "proposed design and methodology" gives the details of the proposed prototype that has been drafted and analyzed in an HFSS Ansys tool. The simulated and measured parameters are discussed in the "simulated and measured results" section where the simulated S_{11} parameters are compared with the measured values, and the proposed design is compared with other papers. Finally, this paper ends with the "conclusion" section.

4. PROPOSED DESIGN AND METHODOLOGY

In this work, a microstrip rectangular antenna is designed, analyzed, and fabricated. The direct microstrip feeding technique has been used to form the base of the antenna structure. The substrate used in the prototype is 5880 RT Duroid, with a relative permittivity of 2.2 and loss tangent of 0.0009. Figure 1 depicts the popular layout of a rectangular microstrip patch antenna in which a radiating element, known as a patch, is embedded on the substrate material, which has a typical value of relative permittivity depending on the center frequency of application. Another side of the substrate is attached to conducting ground layer. Feedline is attached to the patch through which excitation is provided to the antenna.

For improving the performance of the prototype, the patch structure is modified by introducing slots of different dimensions at different positions. The proposed design takes into consideration the advantage of the presence of slots and the partial ground concept for improving the appropriate bandwidth and gain of the structure. The proposed prototype drawn in the Ansoft HFSS window is shown in Figure 2.

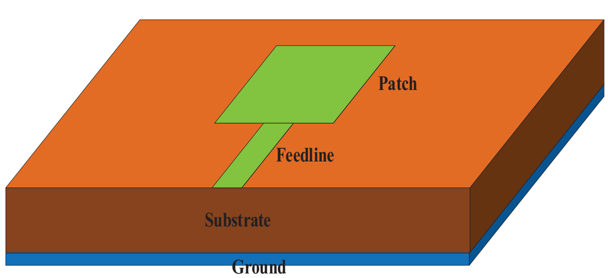


Figure 1. General layout of microstrip antenna.

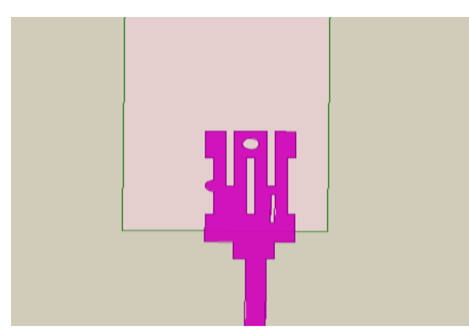


Figure 2. Proposed prototype in HFSS window.

Different slots and their values along with the position over the radiating patch are shown in Figures 3(a) and (b), where the blue color is used for the ground plane and green color for radiating element, i.e., patch. Figure 3 also represents the top and bottom view schematics of the prospective design. Table 1 tabulates numerical values of distinct variables. The antenna prototype is devised to function in the millimeter-wave range of application for a 5G network system. Initially a rectangular patch is designed with a "T" shaped feed line, which has the function of impedance matching at the desired center frequency of 28 GHz. Various dimensions are calculated using the formula of MSA [1, 8, 12] at the center frequency of 28 GHz, and the height of the substrate (h) is taken as 1.6 mm with a relative permittivity value of 2.2. Slot dimensions are optimized, and their values are mentioned in Table 1. It has been observed that unsymmetrical structure and tapered feedline increases bandwidth. The bandwidth can also be improved by using the concept of defective ground or the ground plane with slot/slots. Length of the vertical slots in the radiating element increases the resonance i.e., the impedance matching can also be determined by the dimensions of slot/slots, in addition to the proper feeding point.

Table 1. Dimensions of different variables used in the design.

Variable	Value (mm)	Variable	Value (mm)	Variable	Value (mm)
a	0.5	g	2	p	0.19
b	0.95	i	0.2	q	2
c	0.8	j	0.7	r	0.3
d	0.2	k	0.2	s	0.5
e	1	m	1	t	0.6
f	0.4	n	0.1	u	3.4
x	2	y	0.2	v	0.49
A	3	B	10	C	5
D	4	Lg	12	Wg	14
Wsubstrate	14	Lsubstrate	12	h	1.6
Width of patch (W)	3.95	length of patch (L)	2.19		

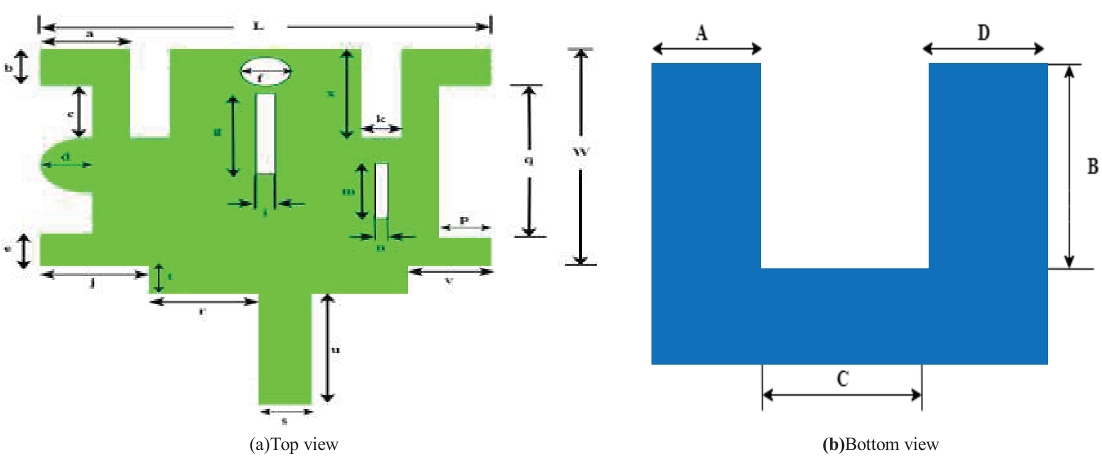
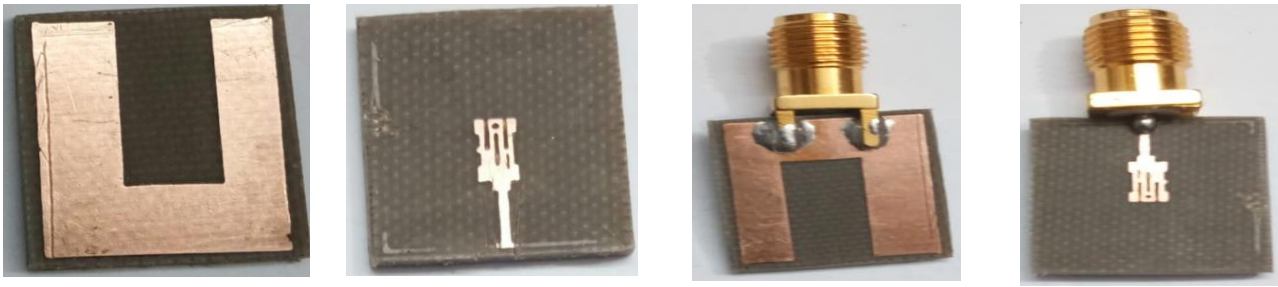


Figure 3. Schematics showing different dimensions of the prospective design. (a) Top and (b) bottom.

The final fabricated prototype is depicted in Figure 4. Figure 4(a) shows the copper conducting ground plane with a U shaped slot. Figure 4(b) depicts the top conducting patch structure on an RT/Duroid Rogers substrate. Figures 4(c) and 4(d) show these two planes with an SMK connector connected to the feed line through the port.



(a) (b) (c) (d)

Figure 4. Fabricated proposed antenna without and with SMA connector. (a) (c) Bottom conducting ground plane and (b) (d) top radiating element.

5. SIMULATED AND MEASURED RESULTS

The simulation of the design has been performed in the Ansoft HFSS platform. The proposed structure illustrates good reflection coefficients for the frequency range from 26.755 GHz to 29.572 GHz and shows a bandwidth around 2.817 GHz, which is in tune with an mm-wave 5G cellular handset. Figure 10 shows the simulated value of the reflection coefficient (S_{11}) parameter, which indicates the percentage impedance bandwidth of 10.1%. Likewise, the other figures show other parameters like VSWR (voltage-standing-wave-ratio), gain polar plot, and radiation pattern.

The design steps by incorporating slots on the rectangular patch are shown in Figure 5 below. The effect of incorporation of slots in different steps is clear from the graph shown in Figure 6 below that fractional bandwidth is improved from 9.34% to 10.1% from step 1 to step 7. In addition, it can be revealed from the same graph that slot 1 shifts the resonance point rightwards. There is also a relative improvement in gain from step 1 to the final design as is clear from the gain plot of Figure 7. Furthermore, the comparison in Table 2 provides insight into the improvement of antenna parameters along the developmental stages.

Table 2. Comparison of different design steps.

Design steps	Frequency range (GHz)	Bandwidth (GHz)	Fractional bandwidth (%)	Gain (dBi)
Step 1	26.665 to 29.28	2.615	9.34	8.589
Step 2	26.75 to 29.399	2.649	9.46	8.603
Step 3	26.79 to 29.478	2.688	9.6	8.641
Step 4	26.86–29.58	2.727	9.74	8.709
Step 5	26.763–29.529	2.766	9.88	8.643
Step 6	26.773–29.559	2.786	9.95	8.712
Step 7	26.75–29.565	2.815	10.1	8.735

Parametric sweep analysis was performed by changing the dimensions of different slots to see the effect on antenna parameters and obtaining the optimized value of the slot dimensions for the final proposed design, where we get a better tradeoff among the parameters. The introduction of slots provides a different path to the current and changes the current length, and hence the characteristics get modified. Figure 8 depicts the effect of changing slot dimensions on the S_{11}, and similarly Figure 9 shows the effect on gain parameter (only two graphs are shown here) of the proposed antenna. Do not mix the variables used in graphs in Figures 8 and 9 with the variables used in the schematics in Figure 1.

The proposed design has a peak gain value of 8.735 dBi for the center frequency value of 28 GHz.

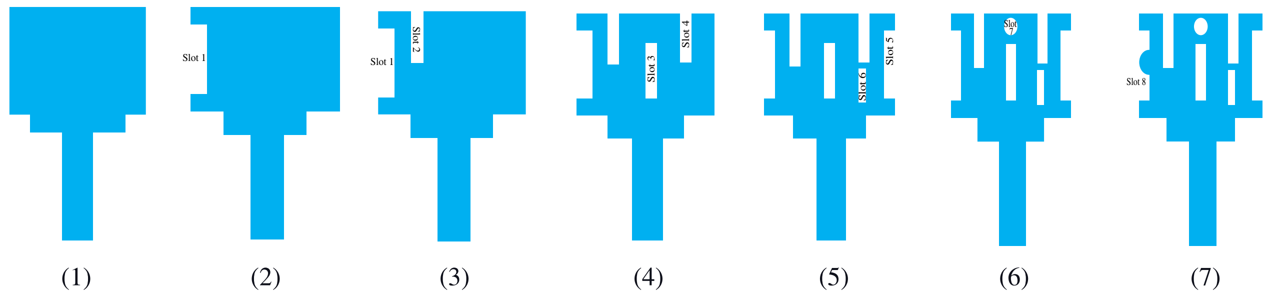


Figure 5. Step wise evolution of proposed design.

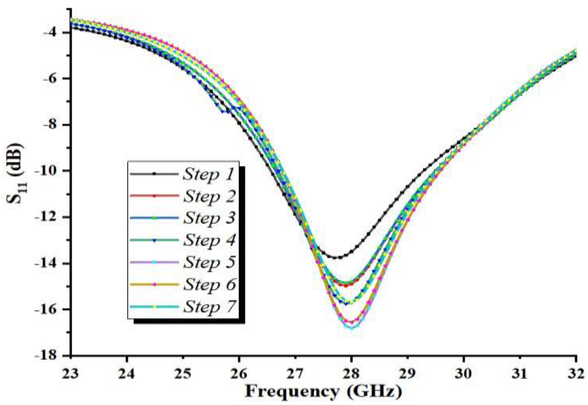


Figure 6. S_{11} vs frequency simulated plot.

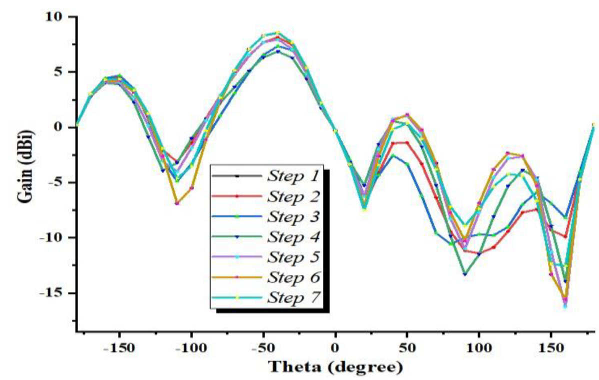
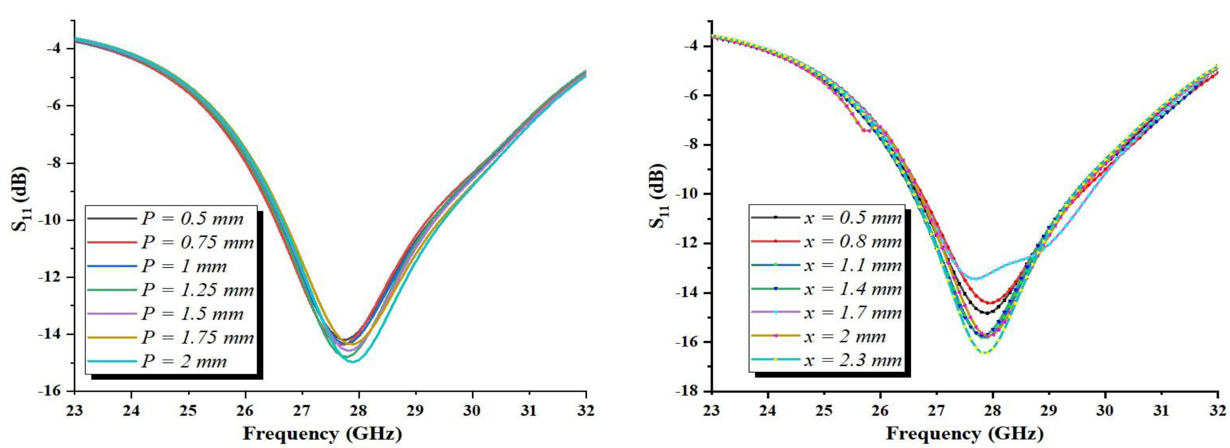


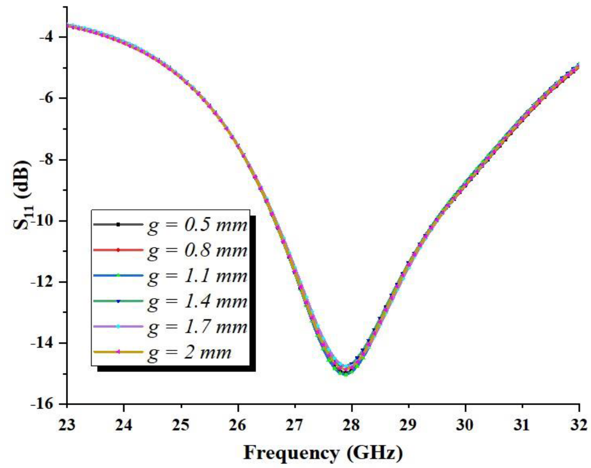
Figure 7. Gain vs theta plot.

The percentage impedance bandwidth of 10.1% is achieved, which corresponds to 2.815 GHz bandwidth for the frequency range of 26.75 GHz to 29.565 GHz, all beneath the −10 dB mark in the S_{11} plot. It is shown that a wider bandwidth is obtained with the proposed antenna structure. The stability of the proposed prototype is demonstrated by the similarity of the simulated and experimental results, making it competent for incorporation in 5G applications. The center frequency of 28 GHz, for which the prototype was designed and analyzed, encounters a bandwidth of 2.79 GHz after fabrication.

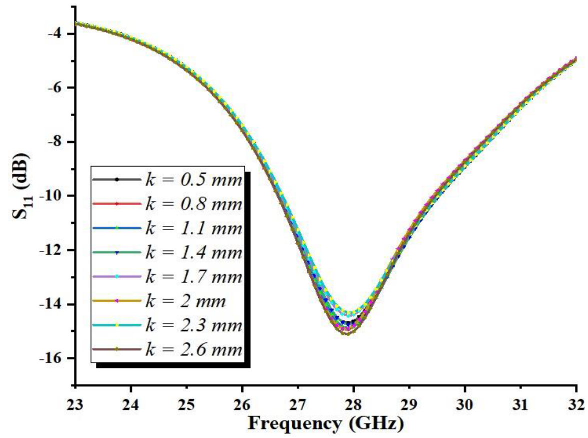
S_{11} and VSWR parameters have been measured successfully. The value of VSWR is less than 2 for the frequency range of 26.64 GHz to 29.65 GHz, having a minimum value of 1.37 at 28 GHz, and Figure 11 shows the same. The VSWR bandwidth of the designed prototype is 3.01 GHz below the magnitude of 2 from the VSWR plot. Figure 12 indicates the radiation pattern of the design at phi



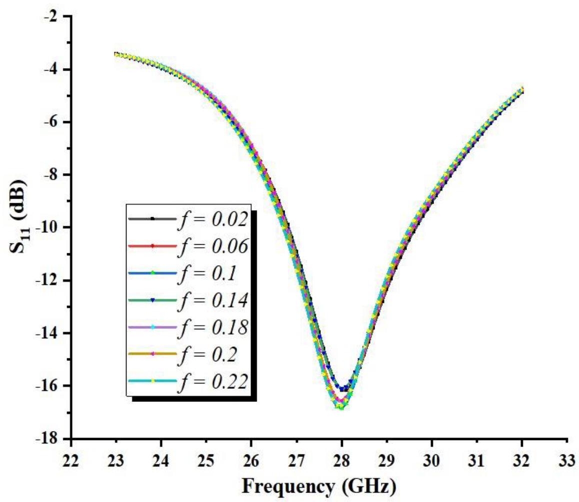
(a) When slot 1 length is changed (b) When slot 2 length is changed



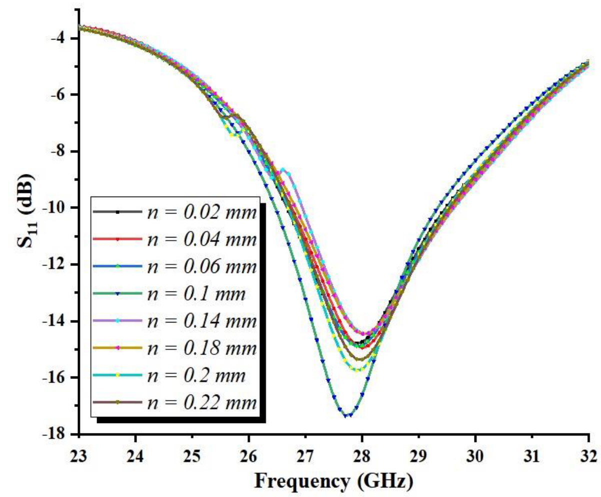
(c) When slot 3 length is changed



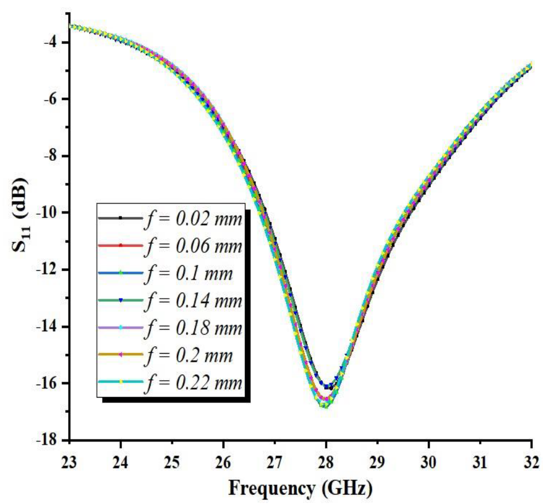
(d) When slot 1 length is changed



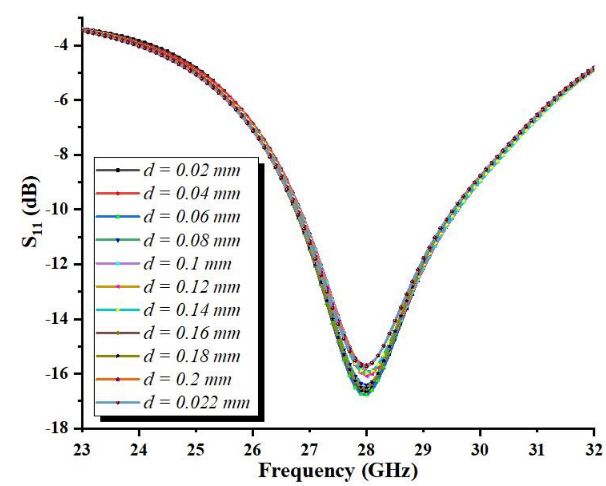
(e) When width slot 5 is changed



(f) When slot 6 length is changed

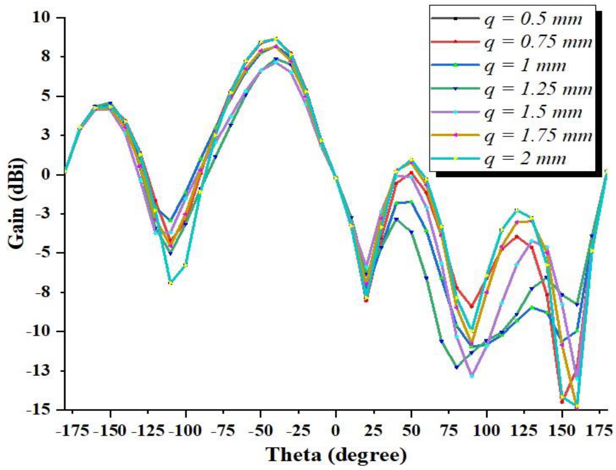


(g) When diameter of slot 7 is varied

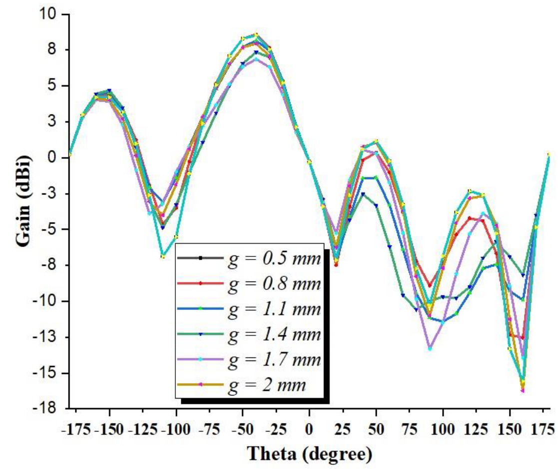


(h) When slot 8 radius is varied

Figure 8. Parametric analysis of the slot dimension and its effect on S_{11}.



(a) Effect of slot 1 dimensions on Gain



(b) Effect of slot 2 dimensions on Gain

Figure 9. Parametric analysis of the slot dimension and its effect on gain.

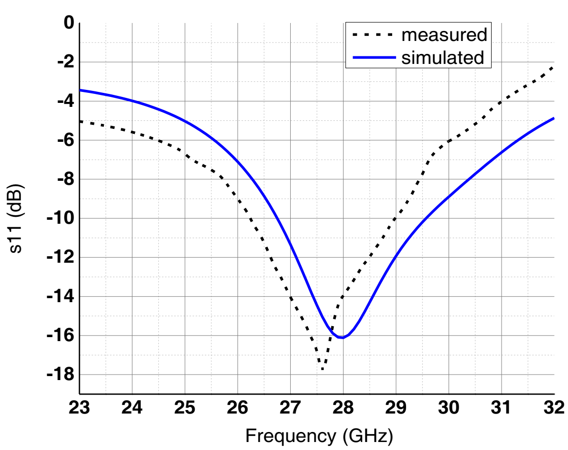


Figure 10. S_{11} vs Frequency plot (simulated and measured).

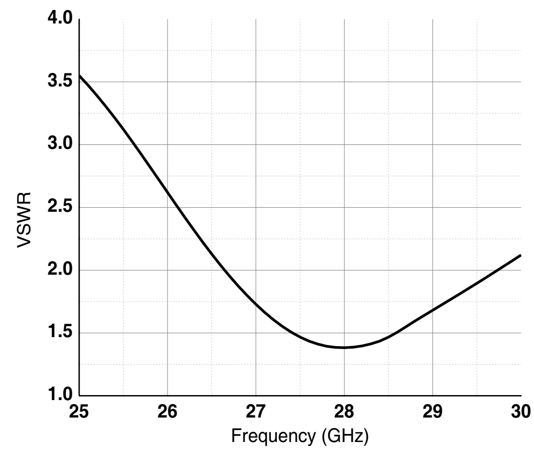
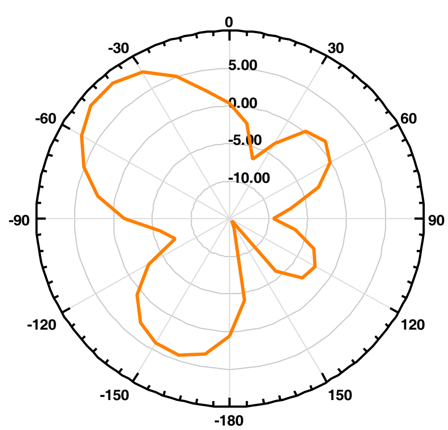
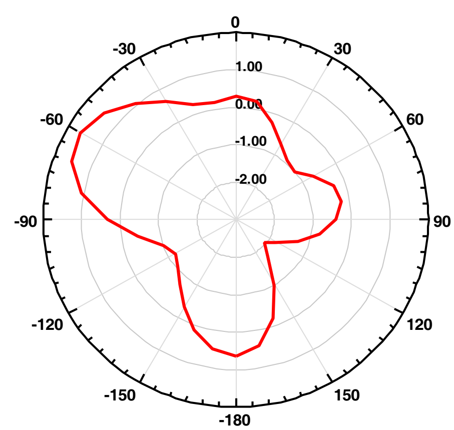


Figure 11. Simulated VSWR Parameter with a value of 1.37 at 28 GHz.



(a)



(b)

Figure 12. Antenna radiation pattern at different phi values. (a) phi = 0°, (b) phi = 90°.

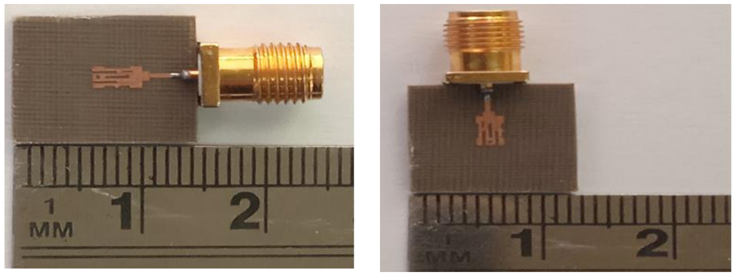


Figure 13. Fabricated sample of the proposed design.

Table 3. Comparison of proposed work with others work.

Reference	**Dimensions of Substrate (mm^3)**	**Dimensions of Radiating Patch (mm^2)**	**Height of Substrate (mm)**	**Substrate Material used (relative permittivity)**	**Frequency Spectrum (GHz)**	**S_{11} Value (dB)**	**Peak Gain (dBi)**	**Bandwidth (GHz)**
[**Przesmycki et al.**]	$12 \times 14 \times 1.57$	2.58×4.17	1.57	RT/Duroid 5880 (2.2)	28	−22.51	3.6	5.57 (19.89%)
[**Marzouk et al.**]	$55 \times 110 \times 1.6$	7×22.6	1.6	FR4 (4.3)	28 38	−13.79 −30.36	5.13 4.61	1 (3.5%) 1.3 (7%)
[**Rahman et al.**]	$14 \times 14 \times 1$	5.45×3.2	1	*MDC (7)	28	−25	5.82	2.66 (9.5%)
[**Khattak et al.**]	$6 \times 6 \times 0.578$	NA	0.578	RT/Duroid 5880 (2.2)	28 45	−40 −14	7.6 7.21	1.3 1
[**Park et al.**]	$19.9 \times 30 \times 0.79$	NA	0.79	Taconic TLY-5	28	−15	7.41	1.5
[**Hasan et al.**]	$12 \times 14 \times 0.38$	3.88×5.92	0.38	RT/Duroid 5880 (2.2)	28 38	NA NA	1.27 1.83	2 (9.1%) 2.3 (5.5%)
[**Teresa et al.**]	$7 \times 7 \times 0.8$	2.16×3.26	0.8	FR4 (4.4) do do	28 28 28	−20.59 −24.76 27.79	5.35 6.37 6.59	2.8 (design- I) 2.54 (design- II) 2.62 (design-III)
[**Sharma et al.**] [**23**]	$40 \times 34 \times 4.8$	2.19×3.95	4.8	FR4 (4.3)	20–40 50–70	NA NA	6	Not given
Proposed work	$12 \times 14 \times 1.6$	2.19×3.95	1.6	RT/Duroid 5880 (2.2)	28	−16.12	8.74	2.817 (10.1%)

* MDC means Microwave Dielectrics Ceramics.

values of 0° and 90° for the E and H planes, which indicates a maximum lobe gain towards 45.2° having a gain value of 8.738 dB in the E plane. The peak gain value obtained in the H plane is 1.745 dB and is directed towards 60°. Different performance parameters obtained in the HFSS software for the purposed antennas are compared with other works and summarized in Table 3.

The fabricated model of the purposed design is depicted in Figure 13. It was tested and measured for the S_{11} parameter for verifying the simulated results. An adequate deal was achieved within the simulated and measured results in terms of impedance bandwidth and return loss coefficient. The simulated HPBW (half-power-beam-width) for the proposed antenna is about 44.39° in the E plane and H plane. In Figure 14, the simulated and measured antenna radiation efficiency graphs are depicted which show that around 94.3% efficiency has been achieved in the design.

Figure 15 indicates the 3D gain polar plot of the schemed design, and in Figure 16, the current distribution over the surface of radiating element is indicated. The current distribution is maximum at the slits (left and right) and at the junction of the T shaped microstrip line and radiating rectangular

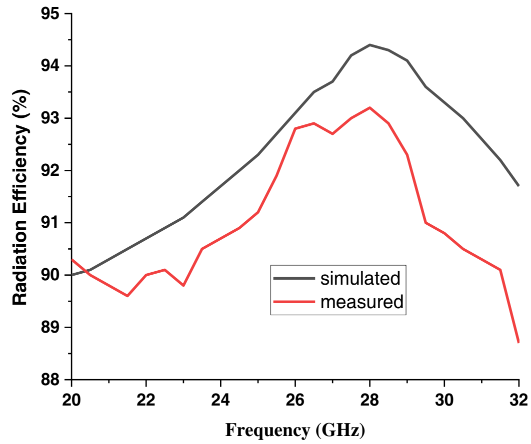


Figure 14. Radiation efficiency vs frequency plot.

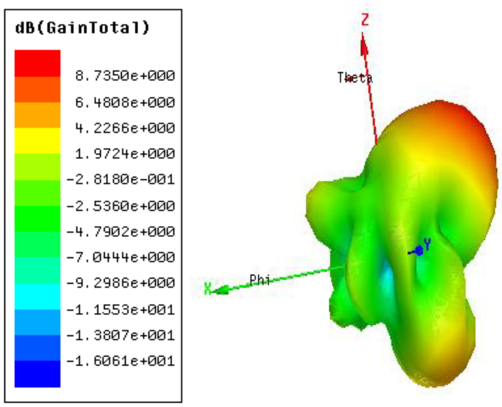


Figure 15. 3D view of gain polar plot of the design.

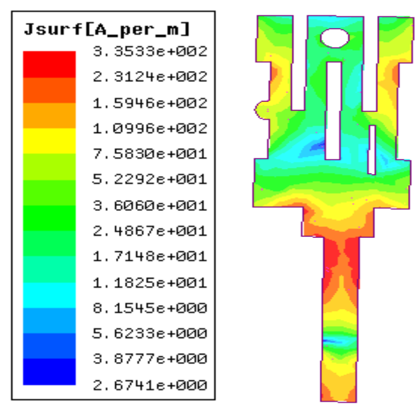


Figure 16. Current distribution over the patch surface.

patch. The radiation characteristics show how the antenna radiates energy depending on direction. It represents a standardized distribution of the electric field or the relative distribution of surface power density, which can also be represented in three-dimensional format.

Although in some papers mentioned in Table 2 antenna arrays have been designed, the comparison is done only with a single antenna element from which the array has been designed.

6. CONCLUSION

This work introduces a planar rectangular structure of microstrip antenna, which takes the advantage of slots and defective ground structure. This antenna structure is having wider bandwidth and is compact in dimensions and hence used for millimeter-wave 5G network applications. To study its performance, the proposed antenna profile has been analyzed, designed, and simulated in terms of different parameters like S_{11}, VSWR, gain, and impedance bandwidth. Simulated results predict that the antenna provides wider bandwidth and higher gain for a single frequency band than the work mentioned in [17–22], and the simulated bandwidth from the S_{11} plot is later proved by the measured results. Through comparing the return loss and VSWR, the measured response is quite close to the simulated values, verifying the simulated results. The proposed antenna can find applications in the radio broadcast, TV, and 5G cellular mobile communications. The bandwidth and radiation gain of the presented antenna in this paper can make it desirable for future state of art millimeter-wave applications and 5G technology systems.

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REFERENCES

1. Sharaf, M. H., A. I. Zaki, R. K. Hamad, and M. M. Omar, "A novel dual-band (38/60 GHz) patch antenna for 5G mobile handsets," *Sensors*, Vol. 20, No. 9, 2541, 2020.
2. Muhammad, S., A. S. Yaro, I. Ya'u, and A. T. Salawudeen, "Design of 5G mobile millimeter wave antenna," *ATBU Journal of Science, Technology and Education*, Vol. 7, No. 2, 178–184, 2019.
3. Jilani, S. F. and A. Alomainy, "Millimetre wave T shaped MIMO antenna with defected ground structures for 5G cellular networks," *IET Microwaves, Antennas & Propagation*, Vol. 12, No. 5, 672–677, 2018.
4. Mallat, N. K., M. Ishtiaq, A. Ur Rehman, and A. Iqbal, "Millimeter-wave in the face of 5G communication potential applications," *IETE Journal of Research*, 1–9, 2020.
5. Akpakwu, G. A., B. J. Silva, G. P. Hancke, and A. M. Abu-Mahfouz, "A survey on 5G networks for the Internet of Things: Communication technologies and challenges," *IEEE Access*, Vol. 6, 3619–3647, 2017.
6. Smith-Ditizio, A. A. and A. D. Smith, "Exploring the growth of wireless communications systems and challenges facing 4G networks," *Advanced Methodologies and Technologies in Network Architecture, Mobile Computing, and Data Analytics. IGI Global*, 889–902, 2019.
7. Diawuo, H. A. and Y. B. Jung, "Broadband proximity-coupled microstrip planar antenna array for 5G cellular applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 17, No. 7, 1286–1290, 2018.
8. Youcheng, W., Y. Yanjiao, C. Qingxi, and P. Hucheng, "Design of a compact ultra wideband MIMO antenna," *The Journal of Engineering*, Vol. 2019, No. 20, 6487–6489, 2019.
9. Liu, G. and D. Jiang, "5G: Vision and requirements for mobile communication system towards year 2020," *Chinese Journal of Engineering*, Vol. 2016, 8, 2016.
10. Ancans, G., V. Bobrovs, A. Ancans, and D. Kalibatiene, "Spectrum considerations for 5G mobile communication systems," *Procedia Computer Science*, Vol. 104, 509–516, 2017.
11. Islam, N., and A. W. A. Wahab, "5G networks: A holistic view of enabling technologies and research challenges," *Enabling Technologies and Architectures for Next-Generation Networking Capabilities*, 37–70, 2019.
12. Ahmed, I., H. Khammari, A. Shahid, A. Musa, K. S. Kim, E. De Poorter, and I. Moerman, "A survey on hybrid beamforming techniques in 5G: Architecture and system model perspectives," *IEEE Communications Surveys & Tutorials*, Vol. 20, No. 4, 3060–3097, 2018.
13. Bjornson, E., L. Van der Perre, S. Buzzi, and E. G. Larsson, "Massive MIMO in sub-6 GHz and mmWave: Physical, practical, and use-case differences," *IEEE Wireless Communications*, Vol. 26, No. 2, 100–108, 2019.
14. Şeker, C., T. Ozturk, and M. T. Güneşer, "A single band antenna design for future millimeter wave wireless communication at 38 GHz," *European Journal of Engineering and Formal Sciences*, Vol. 2, No. 2, 35–39, 2018.
15. Ghazaoui, Y., A. El Alami, M. El Ghzaoui, S. Das, D. Barad, and S. Mohapatra, "Millimeter wave antenna with enhanced bandwidth for 5G wireless application," *Journal of Instrumentation*, Vol. 15, No. 01, T01003, 2020.
16. Przesmycki, R., M. Bugaj, and L. Nowosielski, "Broadband microstrip antenna for 5G wireless systems operating at 28 GHz," *Electronics*, Vol. 10, No. 1, 1, 2021.

17. Marzouk, H. M., M. I. Ahmed, and A. A. Shaalan, "A novel dual-band 28/38 GHz AFSL MIMO antenna for 5G smartphone applications," *Journal of Physics: Conference Series*, Vol. 1447, No. 1, 012025, IOP Publishing, 2020.
18. Rahman, A., Y. Ng M, A. U. Ahmed, T. Alam, M. J. Singh, and M. T. Islam, "A compact 5G antenna printed on manganese zinc ferrite substrate material," *IEICE Electronics Express*, Vol. 13, No. 11, 20160377–20160377, 2016.
19. Khattak, M. I., A. Sohail, U. Khan, Z. Barki, and G. Witjaksono, "Elliptical slot circular patch antenna array with dual band behaviour for future 5G mobile communication networks," *Progress In Electromagnetics Research C*, Vol. 89, 133–147, 2019.
20. Park, J. S., J. B. Ko, H. K. Kwon, B. S. Kang, B. Park, and D. Kim, "A tilted combined beam antenna for 5G communications using a 28-GHz band," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, 1685–1688, 2016.
21. Hasan, M. N., S. Bashir, and S. Chu, "Dual band omnidirectional millimeter wave antenna for 5G communications," *Journal of Electromagnetic Waves and Applications*, Vol. 33, No. 12, 1581–1590, 2019.
22. Merlin Teresa, P. and G. Umamaheswari, "Compact slotted microstrip antenna for 5G applications operating at 28 GHz," *IETE Journal of Research*, 1–8, 2020.
23. Sharma, M., A. K. Gautam, N. Singh, N. S. Garigapati, and N. Agrawal, "Design of a novel dual band printed antenna for future mobile applications," *Procedia Computer Science*, Vol. 171, 917–923, 2020.
24. https://www.itu.int/en/mediacentre/backgrounders/Pages/5G-fifth-generation-of-mobile-technologies.aspx, accessed on Oct. 02, 2021 at 3:00pm.
25. Ali, M. M. M. and A. R. Sebak, "Dual band (28/38 GHz) CPW slot directive antenna for future 5G cellular applications," *2016 IEEE International Symposium on Antennas and Propagation (APSURSI)*, 399–400, Jun. 2016.
26. Sam, C. M. and M. Mokayef, "A wide band slotted microstrip patch antenna for future 5G," *EPH-International Journal of Science and Engineering*, Vol. 2, No. 7, 19–23, 2016.
27. Ur-Rehman, M., M. Adekanye, and H. T. Chattha, "Tri-band millimetre-wave antenna for body-centric networks," *Nano Communication Networks*, Vol. 18, 72–81, 2018.
28. Cai, T., G. M. Wang, X. F. Zhang, Y. W. Wang, B. F. Zong, and H. X. Xu, "Compact microstrip antenna with enhanced bandwidth by loading magneto-electro-dielectric planar waveguided metamaterials," *IEEE Transactions on Antennas and Propagation*, Vol. 63, No. 5, 2306–2311, 2015.
29. Yang, X. M., Q. H. Sun, Y. Jing, Q. Cheng, X. Y. Zhou, H. W. Kong, and T. J. Cui, "Increasing the bandwidth of microstrip patch antenna by loading compact artificial magneto-dielectrics," *IEEE Transactions on Antennas and Propagation*, Vol. 59, No. 2, 373–378, 2010.
30. Mosallaei, H. and K. Sarabandi, "Magneto-dielectrics in electromagnetics: Concept and applications," *IEEE Transactions on Antennas and Propagation*, Vol. 52, No. 6, 1558–1567, 2004.
31. Kuo, C., H. Zhang, A. Sarkar, X. Yu, V. Bhagavatula, A. Verma, and T. B. Cho, "A 5G FR2 (n257/n258/n261) transmitter front-end with a temperature-invariant integrated power detector for closed-loop EIRP control," *2021 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*, 175–178, Jun. 2021.