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TECHNICAL REPORT

Millimeter wave antenna with enhanced bandwidth for 5G wireless application

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ABSTRACT: 5G has been planned to meet the strong data advancement and accessibility of the present society. In the proposed work, a new rectangular antenna that has high bandwidth millimeter-wave, stable radiation patterns, and improved reflection coefficient at 28 GHz for future 5G applications, has been designed and fabricated. The FR-4 substrate having a very compact dimension $(5.5 \times 4.35)\,\mathrm{mm}^2$ with a dielectric constant of 4.4, the thickness of 1.6 mm and loss tangent of 0.002 is used for the design and fabrication of the proposed antenna. The proposed configuration has been designed and simulated by using HFSS (High-Frequency Structure Simulator) simulator which is based on the finite element method. The impedance bandwidth achieved by the designed antenna is about 4.10 GHz (25.8 GHz–29.9 GHz) and has a reflection coefficient of about -39.70 dB, with a maximum gain of 5.32 dBi. The measurement results are in good agreement with the simulated results.

KEYWORDS: Antennas; Microwave Antennas

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Contents

1 Introduction

Currently, the telecommunications field has taken a big step to achieve the strong demands of population and industry [1]. Among the apprehensions for this area, we have the microstrip antennas which are essential elements to ensure the emission or reception of electromagnetic waves present in wireless communication systems [2]. 5G is the next generation of wireless technology systems and will be the first generation to use millimeter waves. Besides, 5G is not only an evolutionary upgrade of the previous cell generation, but it is a promising solution focused on removing the limits of access, bandwidth enhancement, radiation performance and latency limitations on connectivity worldwide [3, 4]. Also, future 5G wireless communication networks will likely use millimeter-wave frequency bands [5] namely 28 GHz, 38 GHz, 60 GHz, and 70 GHz. These bands will be considered as operating bands for 5G mobile networks [6–10]. Experimental tests show that atmospheric absorption at 28 GHz and 38 GHz is relatively small by about 200 meters, while frequencies from 70 GHz to 100 GHz and 125 GHz to 140 GHz also show low attenuation. Even the Federal Communications Commission (FCC) has proposed to authorize mobile operations in the 28 GHz band (27.5 GHz–28.35 GHz), but this band isn't sufficient for 5G applications. 5G band could be suitable for deployment of high-capacity, high-throughput small cells as part of mobile broadband deployments, At the same time, FFC suggested rules that would provide licensees with the flexibility to conduct fixed and mobile operations. In fact, new applications and services will emerge when this technology is available. The 5G wireless network's transmission chain is made up of a key element which is the antenna. Mobile antenna technology for 5G will be subjected to a huge change in coverage and capacity. Furthermore, it is relevant to note that the 5G millimeter wave antenna's radiation performance is significantly better compared to those of other generations (2G, 3G, and 4G) in terms of radiation coverage, power, adaptive, bandwidth, gain and radiation efficiency [11]. In recent years, many countries have accelerated scientific research on 5G. Indeed, several research studies have been dedicated and intended for the design and realization of antennas for 5G applications in millimeter bands [6, 12–14]. Awan et al. [6] proposed a new structure of a 5G antenna with a bandwidth of 1.44 GHz, from 27.12 GHz to 28.56 GHz for 28 GHz. Jandi et al. [12] proposed a dual-band patch antenna for 5G application, with resonant frequencies at 10.15 GHz and 28 GHz and maximum gains of 5.51 dBi and 8.03 dBi respectively. The antenna was designed using a Rogers-5880 substrate with thickness of 0.787 mm and total area of $(19 \times 19)\,\mathrm{mm}^2$, having a bandwidth of around 0.278 GHz at 10.15 GHz and 1 GHz at 28 GHz. In the ref. [13], Jiang et al. designed an antenna based on the near-zero refractive index metamaterial. Firstly, the near-zero refractive index metamaterial unit cell is designed by the parameter extraction method and then loaded into the designed 5G antenna through a reasonable arrangement to have the maximum gain of 13.9 dBi at 28 GHz, and a bandwidth of 26.5 GHz to 29.3 GHz. Arizaca-Cusicuna et al. [14] presented a design of 4×4 patch antenna array for 5G applications that provides a reasonable bandwidth of about 0.3 GHz around at 28 GHz. The basic element of this arrangement is a rectangular patch antenna designed on the Rogers RT/Duroid 5880 substrate, which provides a bandwidth of about 0.47 GHz. Indeed, all the values of the bandwidths found in the references cited above are not sufficient to cover the bandwidth of 5G applications, that's why, we are willing to develop the proposed work.

In this work, a new microstrip antenna structure having a wide bandwidth, a relatively standard gain and a small size, dedicated to 5G applications around a resonance frequency of 28 GHz are presented. The proposed antenna consists of a corner truncated E-shaped rectangular patch, printed on an FR4 type substrate and fed by a microstrip line having a power port adapted to $50\,\Omega$. The assembly is placed on a total ground plane. The main objective of this work is to improve the bandwidth of the proposed antenna while maintaining its small size and relatively high gain at the same center frequency of 28 GHz. To do this, two design steps have been suggested and presented: the first step concerns the design of the basic elements of the proposed geometric shape with the absence of slots. The second step is dedicated to the geometric changes in the basic structure while inserting each time slots to achieve our desired objectives in terms of adaptation, bandwidth, gain, and size to a resonance frequency 28 GHz. The proposed mmW antenna for 5G has a wide bandwidth, a relatively high gain, and a smaller size compared to other proposed antennas for 5G applications [6, 7, 12–19]. The benefits of the proposed antenna include:

i. simple structure,

ii. wide operating bandwidth,

iii. stable radiation patterns,

iv. significant gain.

This paper is divided into five sections: the first is reserved for the description of the theoretical formula of a rectangular antenna. The second is dedicated to the design of a basic rectangular-shaped antenna without slots. The third presents the evolution of the simulation and optimization results made for the fourth proposed structures while preserving the same size as the base antenna. The fourth section illustrates the experimental measurements of the optimized antenna and the

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fifth section summarizes the performance comparison of the proposed antenna with other recently published research.

2 Theoretical formulas for a rectangular microstrip antenna

Recently, microstrip antennas have been one of the most innovative topics of intense investigation and development due to their innumerable benefits [20, 21]. Among these benefits we recognize: It is lightweight, lower cost, low profile, smaller dimensions, easy fabrication and can be integrated easily with an electronic circuits like LNA (Low-Noise-Amplifier) and SSPA (Solid-State Power Amplifier) [22]. Most models used to characterize microstrip antennas generally require long and tedious computation. In this work, we will use a simpler and more precise analytical model, which is the transmission line model. It was the first model used to analysis the rectangular microstrip antennas [23, 24]. This model is based on the distribution of the magnetic current antenna.

Based on this model, we will calculate antenna parameters as shown in figure 1. The first part of the design of an antenna is to estimate its length L and width W which are calculated using equations (2.1)–(2.4) [25].

$$W = \frac{c}{2 f_\mathrm{r}} \sqrt{\frac{2}{\varepsilon_\mathrm{r} + 1}} \tag{2.1}$$

With f_r is the resonance frequency of the antenna, ε_r is the dielectric constant of the substrate and c is the velocity of light in free space. The effective dielectric constant $\left(\frac{W}{h} > 1\right)$ is given by:

$$\varepsilon_\mathrm{reff} = \frac{\varepsilon_\mathrm{r} + 1}{2} + \frac{\varepsilon_\mathrm{r} - 1}{2} \left[\frac{1}{\sqrt{1 + 12\frac{h}{W}}} \right] \tag{2.2}$$

The extension of the correction length ΔL of the microstrip antenna due to the fringe effect (edge effects) can be obtained by:

$$\Delta L = 0.412h \frac{(\varepsilon_\mathrm{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_\mathrm{reff} - 0.258)\left(\frac{W}{h} + 0.8\right)} \tag{2.3}$$

So, after considering edge effects, the final effective length of the patch antenna can be calculated by:

$$L = \frac{C}{2 f_\mathrm{r}.\sqrt{\varepsilon_\mathrm{reff}}} - 2\Delta L \tag{2.4}$$

In fact, the design and optimization are two essential steps to execute the fabrication process, since they allow a correct selection of the geometric parameters and operating conditions based on an objective that has been set before. In the next section, we will focus on a design methodology, by means of the theoretical concepts mentioned above.

3 The basic element patch antenna design and analysis

The basic antenna consists of a microstrip patch rectangular shape with a length L_p and width W_p, printed on an inexpensive FR4 substrate with relative permittivity of 4.4, the thickness of 1.6 mm, length $L_\mathrm{s} = 4.35$ mm, width $W_\mathrm{s} = 5.5$ mm and loss tangent $\tan\delta = 0.0025$. The antenna is excited by a microstrip line having dimensions $L_m = 1.35$ mm, $W_m = 0.8$ mm and with a power port adapted to 50 Ω. The ground plane size for the patch antenna is (4.35×5.5) mm^2 as shown in figure 1. The geometric dimension of the antenna is calculated using MATLAB code based on the transmission line model described in detail above. The related dimensions of this basic antenna are depicted in table 1. The parameters defining the radiating element ($L_p$andW_p) have been modified in order to investigate their effects on the performance of the overall structure, in particular in terms of resonance frequency, reflection coefficient, and bandwidth. The different simulations made for this antenna have been performed using the electromagnetic simulator HFSS (High Frequency Structure Simulator) which is based on the finite element method.

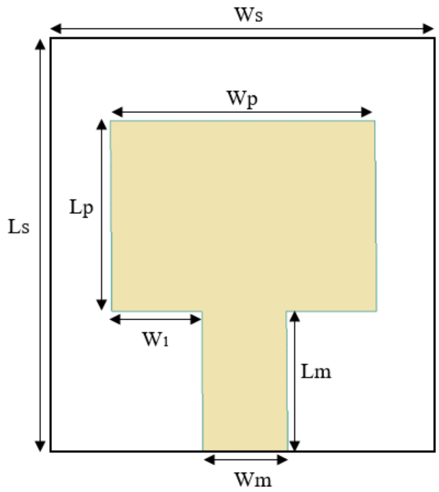

Figure 1. Geometry of the basic element antenna.

Table 1. Dimensions of the basic element antenna.

Parameters	Value (mm)
L_s	4.35
W_s	5.5
L_p	1.8
W_p	2.5
L_m	1.35
W_m	0.8
W_1	0.7

The variation of the reflection coefficients as a function of the dimensions of the patch of this basic antenna is shown in figure 2. The simulation results show that the reflection coefficients present a single frequency band for each variation of the dimensions of the radiating element. Note also that when the length and width of the radiating element have been changed, the levels of the reflection coefficients, the resonant frequencies and the bandwidths change. The various simulations found values are recorded in table 2. It is clearly observed that the proposed dimensions $W_p = 2.5$ mm

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and L_p = 1.8 mm offer best results in terms of resonance frequency, reflection coefficient, and bandwidth. For these dimensions, the antenna has a minimum level of S_{11} of about -20.60 dB at a resonant frequency of 24.78 GHz with a bandwidth of about 2.38 GHz ranging from 23.61 GHz to 25.99 GHz. In the other dimensions, the performance is much worse in term of resonance frequency, reflection coefficient, and bandwidth. Therefore, the performance for the basic antenna did not allow us to achieve expected objectives in terms of resonance frequency, which is about 28 GHz, bandwidth, and reception coverage. Indeed, the resonance frequency of the basic element is far from the desired resonance frequency which is 28 GHz. In addition, the basic antenna offers a bandwidth of about 2.5 GHz which is insufficient for 5G application. Furthermore, this basic element can't cover the specified 5G applications band (26.5 GHz–29.5 GHz). For these reasons, we will proceed by following a series of simulation and optimization of the radiating element, by inserting slots at the basic antenna. This optimization study will be performed using the HFSS simulator and presented in the next section.

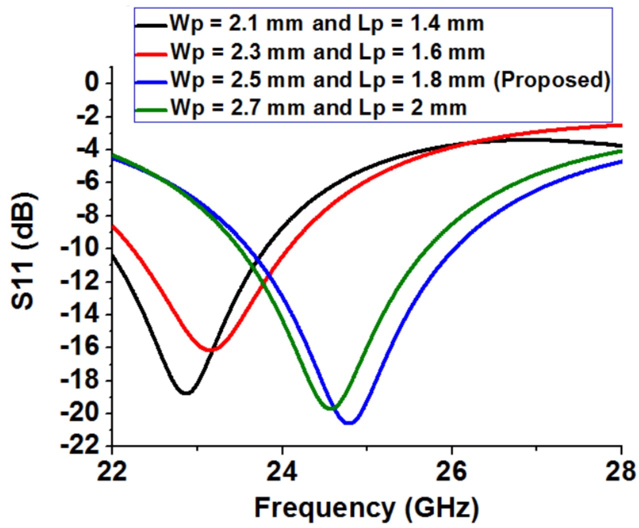

Figure 2. Simulated reflection coefficients versus frequency of the basic element patch antenna for different values of the patch parameters W_p and L_p.

Table 2. Simulation results of the basic element antenna for different values of the patch parameters W_p and L_p.

Parameters	Frequency (GHz)	S_{11} (dB)	Bandwidth (GHz)
W_p = 2.1 mm and L_p = 1.4 mm	22.86	-18.78	1.86
W_p = 2.3 mm and L_p = 1.6 mm	23.14	-16.15	1.83
W_p = 2.5 mm and L_p = 1.8 mm **(Proposed)**	**24.78**	**-20.60**	**2.38**
W_p = 2.7 mm and L_p = 2 mm	24.56	-19.71	2.21

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4 Optimization steps of the proposed rectangular antenna

To improve the antenna's radiation performance presented in the previous section in terms of resonance frequency, reflection coefficient, and bandwidth, we have focused on a design and optimization methodology that is based on theoretical concepts and goes through several successive steps. The optimization methodology that we have proposed in this work is based on the technique of inserting the slots at the radiating element, by selecting the right position, length, and width of these slots. This technique is the simplest way to do a strong modification of the resonant frequency which affects the overall system performance and to obtain high bandwidth in this compact size microstrip patch antenna.The different optimization steps performed for the basic antenna are illustrated in figure 3. First of all, we started our first optimization step by inserting a single rectangular slot having a length L_2 and a width W_2 in the same basic element and this is shown in figure 3 (case I). We find that the antenna has a minimum reflection coefficient of about -22 dB for a resonance frequency of 25.79 GHz and a fairly high bandwidth of around 2.43 GHz. These results show that this antenna performs relatively better than those shown in figure 2 of the previous section. For this reason, we have added another additional rectangular slot and we keep the same total size of the basic antenna. The optimization procedure carried out allowed us to achieve our expected objectives in terms of improved bandwidth and adaptation. The geometric parameters of the slots selected after several optimizations are shown in table 3. The various optimization results obtained from the proposed antenna are shown in figure 4 and grouped in table 4.

From figure 4, we notice that the antenna of the second optimization step (case II) shows a slight improvement in terms of the reflection coefficient (-24 dB), resonance frequency (26.44 GHz) and bandwidth (2.88 GHz) compared to that of the first step (case I). On the other hand, the addition of the third slot (case III) makes a huge improvement in terms of bandwidth which is about 3.08 GHz (26.04 GHz–29.12 GHz) and reflection coefficient of about -27.96 dB at the frequency of 27.42 GHz. However, we are looking for an adequate structure in which its resonance frequency is 28 GHz and its bandwidth exceeds 4 GHz in the Korean band (26.5 GHz–29.5 GHz). That's why we have added the fourth rectangular slot (case IV). So that the simulated antenna has a minimum reflection coefficient of about -42.25 dB at the resonance frequency of 28.02 GHz and a wide bandwidth from 25.92 GHz to 29.99 GHz.

As can be seen from table 4, the antenna based on four rectangular slots offers a very high bandwidth of about 4.07 GHz, which is significantly better than the other cases. Indeed, the use of slots technology has allowed us to improve the performance of the proposed antenna in terms of adaptation and bandwidth. To give a good overview of the operation of the proposed antenna, the distribution of the surface current at the 28 GHz resonance frequency via the HFSS software is depicted in figure 5. It is clear that the surface current distribution is distributed near the edge of the power line at the frequency of 28 GHz. It is observed that the distribution of the surface current is concentrated mainly at the edges of the rectangular slots inserted at the level of the radiating element and more powerful than that of the power line.

In the next section, we will compare and validate the simulation results obtained by experimental measurements of the proposed antenna (case IV) in terms of resonance frequency, reflection coefficient, bandwidth, E and H planes radiation patterns, and gain.

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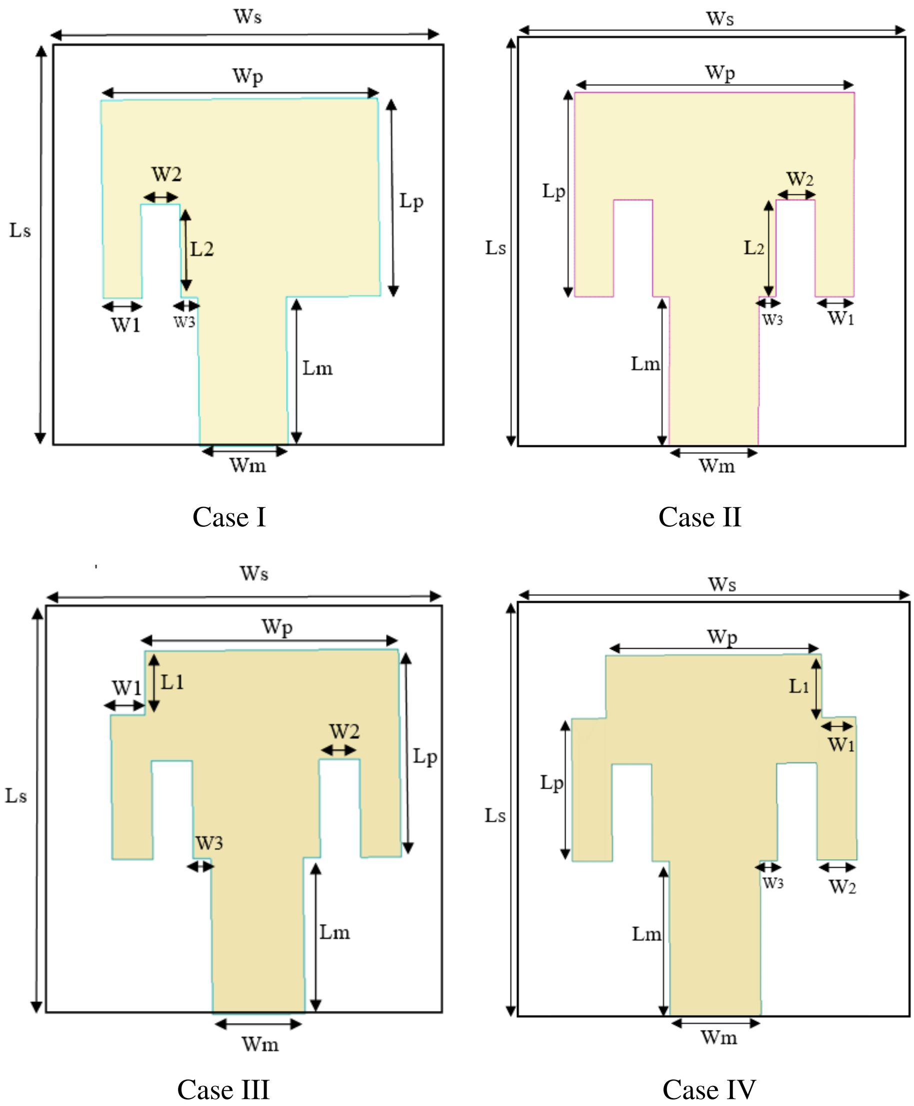

Figure 3. Geometric evolutions of the proposed rectangular antenna.

5 Simulation and experimental measurements

The fabricated prototype of the proposed antenna is shown in figure 6. Its configuration is fabricated on a low-cost FR4 substrate using the NVIS 72 prototype machine (semi-automated prototype machine). It was tested and measured to verify the results of the simulation, which are the reflection coefficient, the gain, and the radiation pattern.The reflection coefficient (S_{11} parameter) of the fabricated prototype is measured using Rohde & Schwarz VNA. A good agreement was obtained between the simulated results and measured in terms of reflection coefficient and bandwidth for this antenna as shown in figure 7. The simulated resonance frequency of the same antenna is obtained at 28.02 GHz with a reflection coefficient of about -42.25 dB. The result of the measured reflection coefficient of the antenna for a resonance frequency of 28 GHz is in order of -39.70 dB.

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Table 3. Geometric parameters of the proposed rectangular antenna for the four optimization steps.

Parameters	Dimensions (mm)			
	Case I	Case II	Case III	Case IV
W_S	5.5	5.5	5.5	5.5
L_S	4.35	4.35	4.35	4.35
W_p	2.5	2.5	2.2	1.9
L_p	1.8	1.8	1.25	1.25
W_m	0.8	0.8	0.8	0.8
L_m	1.35	1.35	1.35	1.35
W_1	0.35	0.35	0.3	0.3
W_2	0.35	0.35	0.35	0.35
L_2	0.85	0.85	0.85	0.85
W_3	0.15	0.15	0.15	0.15
L_1	-	-	0.55	0.55

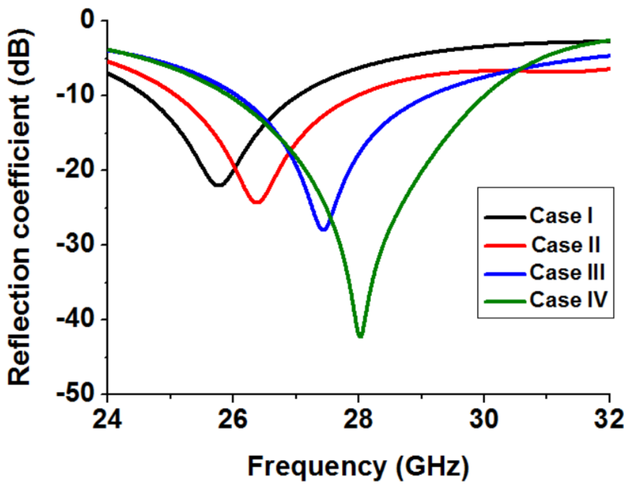

Figure 4. Optimization results of reflection coefficients versus frequency of the antenna proposed for the four slots.

Table 4. The obtained result for the four cases of the proposed antenna.

Optimization cases	Frequency (GHz)	S_{11} (dB)	Bandwidth (GHz)
Case I	25.79	-22	2.43
Case II	26.44	-24	2.88
Case III	27.42	-27.96	3.08
Case IV (Proposed)	**28.02**	**-42.25**	**4.07**

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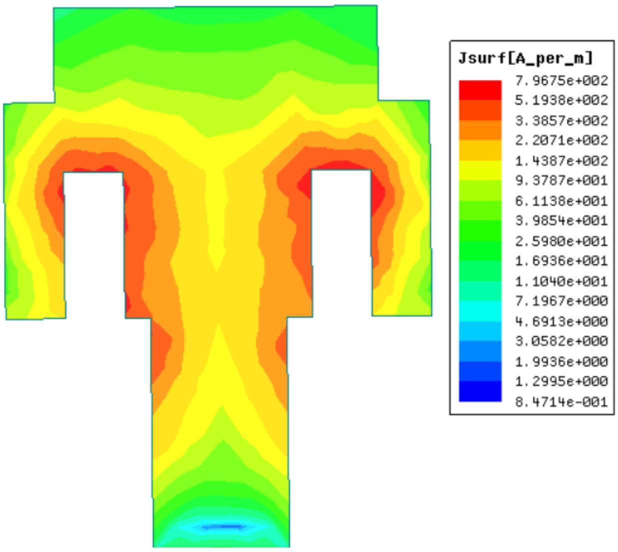
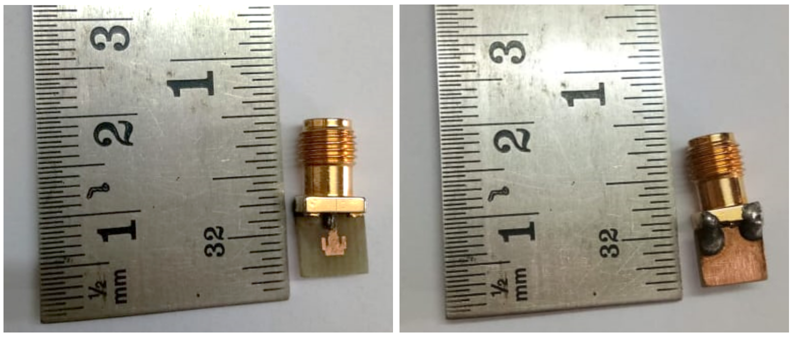


Figure 5. Surface current distribution of the antenna proposed in the resonant frequency of 28 GHz.

The simulated and measured impedance bandwidth of this antenna is approximately 4.07 GHz (25.92 GHz–29.99 GHz) and 4.10 GHz (25.8 GHz–29.9 GHz) respectively.



(a) (b)

Figure 6. Photograph of fabricated prototype of the proposed antenna, (a) top view and (b) bottom view.

The simulated and measured gains versus frequency for the proposed antenna are illustrated in figure 8. The results of the simulated and measured gains at 28 GHz of the proposed antenna are about 5.61 dBi and 5.32 dBi respectively. This gain value is measured in the anechoic chamber and shows a fairly high gain. The far-field radiation patterns of the proposed antenna were measured according to the E plane and H plane. The measured E plane and H plane radiation pattern curves at 28 GHz are compared with the simulated results in figure 9. A good agreement has been obtained between the measured and simulated polarization for the E plane and H plane. The two-dimensional plot of the radiation pattern of this antenna allows visualizing its electrical and magnetic components, especially its lobes in both vertical and horizontal planes. From the same figure 9, we can see that the radiation pattern of the proposed antenna for both E-plane and H-plane remains directional.

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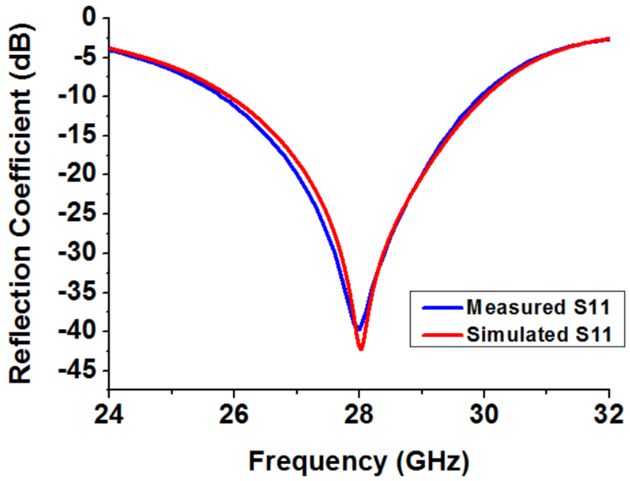


Figure 7. Comparison between the simulated and measured reflection coefficients (S_{11}) of the proposed antenna.

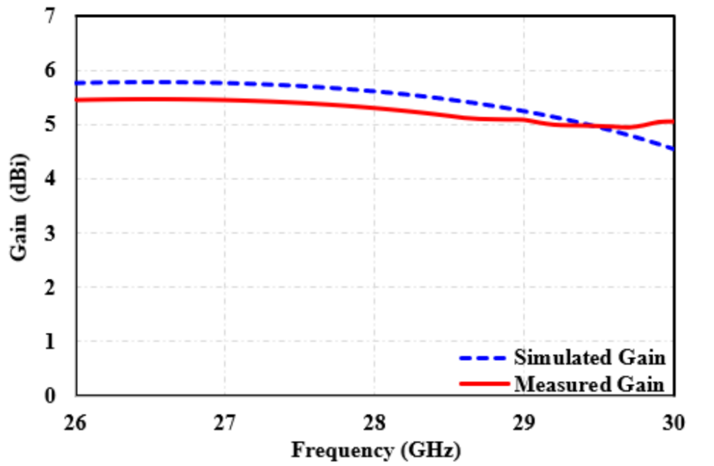
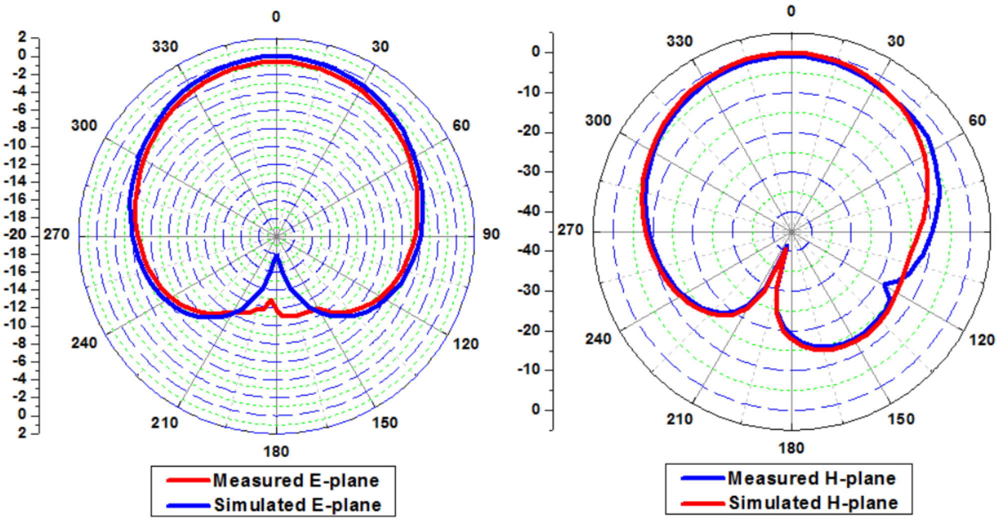


Figure 8. Comparison between the simulated and measured gains of the proposed antenna.

Indeed, the comparison between the simulation and measurement results for the proposed antenna in terms of resonance frequency, reflection coefficient, bandwidth, and gain are summarized in table 5. It is observed from the table that the simulated and measured results are in good agreement which validates the designed concept.

Table 5. Comparison of simulation and measurement results of the proposed antenna.

Comparison results	Frequency (GHz)	S_{11} (dB)	Gain (dB)	Bandwidth (GHz)
Simulation	28.02	-42.25	5.61	4.07
Measurement	28	-39.70	5.32	4.10



(a) E-plane (b) H-plane

Figure 9. Simulated and measured radiation patterns for E-plane and H-plane of the proposed antenna at 28 GHz.

6 Performance comparison of the proposed rectangular antenna with other reference works

The performance comparison of the proposed rectangular antenna with some other antennas for the next generation of wireless technology (5G) is shown in table 6. It is clear from the table that the proposed rectangular antenna has a small size and much higher bandwith compared to other reference works.

Table 6. Performance comparison of the proposed antenna with other antennas.

References	Antenna Dimensions (mm^2)	Frequency GHz	Bandwidth GHz
[6]	5×5	28	1.44
[7]	55×110	28	1.06
[12]	19×19	28	1
[13]	3.2×3.2	28	2.8
[14]	5.3×5.35	28	0.47
[15]	3×7	28	3.34
[16]	11×5	28	0.82
[17]	6×6	28	1.3
[18]	10×10	28	2.94
[19]	12×14	28	2.55
This work	$\mathbf{5.5 \times 4.35}$	**28**	**4.10**

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7 Conclusion

In this paper, a new compact rectangular microstrip antenna structure has been designed, modeled, fabricated, and tested for 5G applications at 28 GHz. Throughout this work, we have focused on a design and optimization methodology that is based on theoretical concepts and goes through several successive steps. The optimization methodology we have proposed in this work is based on the technique of inserting the slots at the radiating element, by selecting the right position, length, and width of these slots. The use of this methodology has improved the radiation performance of this antenna for adaptation and bandwidth in the Korean band from 26.5 GHz to 29.5 GHz. The experimental results show that the proposed antenna offers a wide bandwidth of 4.10 GHz, a good reflection coefficient of about -39.70 dB, and a peak gain of 5.32 dBi across the band of operation. Furthermore, good stable radiation patterns and an acceptable amount of -3 dB beamwidths are also obtained for the proposed rectangular antenna. Moreover, the proposed antenna is simple to manufacture and a good prototype for future 5G wireless communication systems.

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