Design of a microstrip antenna patch with a rectangular slot for 5G applications operating at 28 GHz

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ABSTRACT

In this paper, we present a study and design of a rectangular-shaped microstrip patch antenna with a rectangular shaped slot at the operating frequency is 28GHz, for fifth generation (5G) wireless applications, using the microstrip line technique for feeding. The objective of this slot is to contribute to the improvement of antenna performance. This antenna is built on a Roger RT duroid 5880 type substrate having a relative permittivity equal to 2.2, a height of h = 0.5 mm, and a loss tangent of 0.0009. The compact size of this antenna is 4.2 mm × 3.3 mm × 0.5 mm. The simulations of this antenna were performed using high-frequency structure simulator (HFSS) and computer simulation technology (CST) software whose main purpose is to confirm the results obtained for this proposed antenna. The results obtained during these simulations are as follows: resonant frequency of 27.97 GHz and reflection coefficient (S_{11}) of -20.95 dB, bandwidth of 1.06 GHz, a gain of 7.5 dB, radiated power of 29.9 dBm, and efficiency of 99.83%. These results obtained by this proposed antenna are better than those obtained from already existing antennas that are published in current scientific journals. Consequently, this antenna is likely to satisfy the needs for 5G wireless communication applications.

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1. INTRODUCTION

The 5th generation (5G) of communication systems has emerged due to new requirements for compactness, high throughput, and high bandwidth. Currently, many of the researchers working in the telecommunication sector are interested in millimeter-wave communication technology. They want to achieve and guarantee high data transfer rates and increase the performance of their systems [1], [2].

In fourth-generation (4G) networks, video downloads, as well as mobile application usage are the essential radio resources [3], [4]. But, to significantly increase the range of uses as well as the multiplicity of operators and users, numerous tests and research works are gradually leading to the creation of the 5G of telecommunications, in other words, a new generation of technology, whose objectives are highly diversified and correspond to the indispensable elements in daily life, such as energy, health, media, industry or transport. The goal of 5G is to meet the deficits related to bandwidth or increased speed but to achieve ultra-short latency and reduce energy consumption with a ubiquitous quality service. The fifth generation of wireless technologies is a new standard for these communication systems. Its objectives are to meet the requirements of the mobile telecommunications market, as well as the needs of users. Among these technologies, we can mention millimeter bands, massive multiple input multiple output (MIMO), ultra-dense networks (UDN) [5], [6].

The official launch of the 5G has been underway since early 2020. Indeed, it is the largest wireless communication network in the world today and it will meet all the constraints related to the needs of consumers, which is not without problems. Indeed, the most recent developments in terms of characteristics focus at this stage on the reinforcement of the capillarity of the networks as well as the increasing data rate (10 GB/s, i.e. 10 times more than 4G), as well as their better availability with a response time in the range of 1 ms to 5 ms and finally, a better energy saving [7], [8]. In addition, the new frequency band called the millimeter-wave (mm-wave) band, between 30 GHz and 300 GHz, was created to improve network performance and capacity [9]. On the other hand, these mm waves have disadvantages, in particular high disturbances caused by atmospheric phenomena as well as attenuations of the path of propagation in the vacuum as well as the higher production cost [10], [11]. Curiously, among the frequency band in millimeter waves, we found some frequency bands such as the 28 GHz band, which has a great advantage in reducing losses during data transfer than other frequency bands [12]. 5G systems use very high-performance antennas to satisfy specific user requirements. This requires the design and realization of antennas with efficient performance [13], [14]. Furthermore, millimeter wave antennas for 5G have high characteristics in terms of gain, bandwidth, reflection coefficient, efficiency as well as directivity. Through many studies in the telecommunication sector have shown that patch or printed antennas are the most suitable for 5G, for several advantages including small size, low design cost, simple design and the fact that they can be worn and integrated on the external side of spacecraft and high-performance devices such as airplanes, as well as satellites, rockets, automobiles, military equipment, human body, wearables, and wearable communications systems [15], [16].

Indeed, in the communication chain, antennas occupy the largest compartment and, this imposes a size problem that prevents their implementation in 5G electronic devices such as cell phones. To overcome this problem, we use miniaturization techniques such as slots. In this paper, we propose a design of a microstrip patch antenna with a rectangular slot shape. This antenna occupying a size of 4.2 mm × 3.3 mm × 0.5 mm has better performance, with a resonant frequency of 28 GHz for 5G wireless communication technology.

This study is organized into four sections as follows: In the first section, we provide a practical general introduction. In the second section, we give details of the procedure associated with the creation of this proposed antenna, and then in the third section, we run simulations of it in high frequency structure simulator (HFSS) and computer simulation technology (CST) simulation tools. We will analyze in-depth and detail all the simulation results obtained and compare the different results provided by this proposed antenna with those currently available. Finally, in the fourth section, we conclude this study with a conclusion.

2. RESEARCH METHOD

The microstrip patch antenna design starts with the determination of its width and length; for this, we apply the usual formulas of [17], [18] at 28 GHz. The first thing to do is to select the corresponding substrate with a suitable height (h). The support chosen for this research is a plate Roger RT duroid 5880; its dielectric constant is equal to 2.2, and its coefficient or tangent of dissipation is equal to 0.0009, and its thickness was fixed at 0.5 mm. In addition, the sizes of the plate (patch) and the power cable are defined; the latter is suitably positioned to operate at 28 GHz. Then some modifications are made to the antenna structures to get a good operating result of this antenna. To ensure good radiation performance, the characteristics of the patch must be studied in the following phases: selection of the substrate height is a crucial point in the construction of an antenna, since it significantly influences the performance of the microstrip antenna. For this antenna, one of the assumptions is to achieve the best possible bandwidth. By increasing the thickness of the support, a better bandwidth of the antenna is obtained while its efficiency decreases.

- The calculation of the maximum value of the substrate height was determined from the following relationship [19], [20]:

$$h \leq \frac{0.3c}{2\pi f_{res}\sqrt{\varepsilon_r}} \quad (1)$$

With: c corresponds with the velocity of light such that $c = 3 \times 108\ m/s$, f_{res} resonance frequency such that $f_{res} = 28\ GHz$, and ε_r dielectric constant of 2.2.

- Second phase: the width of the W_A patch must be calculated [21]:

$$W_A = \frac{c}{2f_{res}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{\lambda}{2}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (2)$$

- The third phase: we determine the length of the patch L_A. Then, we calculate the effective dielectric constant εeff using [20]:

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r+1}{2}(1 + 12\frac{h}{W_A})^{\frac{-1}{2}} \quad (3)$$

When ε_{reff} is determined, the effective patch length L_{eff} is obtained by applying the following rule [20]:

$$L_{eff} = \frac{c}{2f_{res}}\varepsilon_{eff}^{-\frac{1}{2}} \quad (4)$$

Then we calculate the extension of the patch length, applying the following relation [20]:

$$\Delta L = 0.412\frac{(\varepsilon_{eff}+0.3)(\frac{W_A}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{W_A}{h}+0.8)} \quad (5)$$

Then we determine the length of the L_A patch,

$$L_A = L_{eff} - 2\Delta L = \frac{c}{2f\sqrt{\varepsilon_{eff}}} - 2\Delta L \quad (6)$$

- Fourth phase: after determining the size of the radiating element, the size of the ground plane is also to be calculated. It is assumed that the size of the ground plane will be larger than that of the radiating element by about six thicknesses of the substrate, both in width and length. The size of the reference plane is established according to the following method [21]:

  $W_{sub} = W_A + 6h$ *and* $L_{sub} = L_A + 6h$

- Five phase: we define the feed slot of the insert by applying the following relationship [21]:

$$g = \frac{4.65\times10^{-18}\times c\times f_{res}}{\sqrt{2\varepsilon_{eff}}} \quad (7)$$

- Sixth phase: determination of the resonant input resistance Rin thus:

$$R_{in\acute{e}}(y = y_0) = \frac{1}{2(G_1 \pm G_{12})}cos^2(\frac{\pi y_0}{L_A}) \quad (8)$$

$$G_{12} = \frac{1}{120\pi^2}\int_0^{\pi}\left[\frac{sin(\frac{kW_A\cos\theta}{2}}{\cos\theta}\right]^2 J_0(kL_A\sin\theta)\sin^3\theta\, d\theta \quad (9)$$

$$G_1 = \frac{I_1}{120\pi^2}\,;\, k = \frac{2\pi}{\lambda_{air}}\, X = kW_p \quad (10)$$

$$I_1 = -2 + \cos X + Xsi(X) + \frac{\sin X}{X} \quad (11)$$

Where Jo is the zero-order Bessel function of the first species, and G_1 is the conduction coefficient of the microstrip, and G_{12} is the reciprocal-conductance of the micro-strip. For this work, we have chosen an impedance of 50 Ω for the input.

- Seventh phase: To determine the parameters y_0 and Wfed, using the formula associated with the resonant input impedance, such that $y0$ and W_{fed} are, present embedding the power supply and transmission line respectively, thus:

$$y_0 = \frac{L_A}{\pi}cos^{-1}\left[\sqrt{\frac{Z_C}{R_{in(edg)}}}\right] \quad (12)$$

- The final phase: in the digital antenna, the design process determines the size of the feed line. For calculating the width and length of a microstrip feed cable, it is necessary the value of $ZC = 50\,\Omega$ of specific impedance, and we begin the determination of the auxiliary variables x and y as:

$$x = \frac{Z_C}{60}(\frac{\varepsilon_r+1}{2})^{0.5} + \frac{\varepsilon_r-1}{\varepsilon_r+1}(0.23 + \frac{0.11}{\varepsilon_r}) \quad (13)$$

$$y = \frac{60\pi^2}{z_C\sqrt{\varepsilon_r}} \quad (14)$$

Using the formulas described in [22], the dimensions of the power transmission cable can be calculated:

$$W_{fed} = \frac{2h}{\pi}\left[x - 1 - ln(2x-1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}(ln(x-1) + 0.39 - \frac{0.61}{\varepsilon_r})\right] \quad (15)$$

$$L_{fed} = 3h \quad (16)$$

At this point, the process of developing a numerical model of the designed antenna is complete. The above calculations have resulted in the antenna dimensions shown in Table 1. The developed antenna design, as calculated, is shown in Figure 1. This data is used to optimize the antenna in terms of bandwidth and to miniaturize its dimensions.

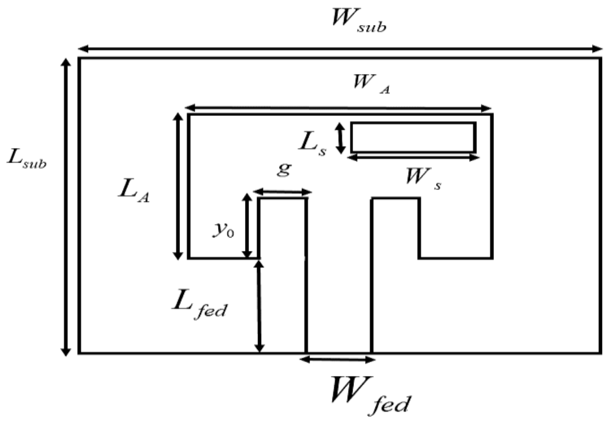


Figure 1. The shape of the antenna studied in this document with and without slot

Table 1. Shows the antenna dimensions

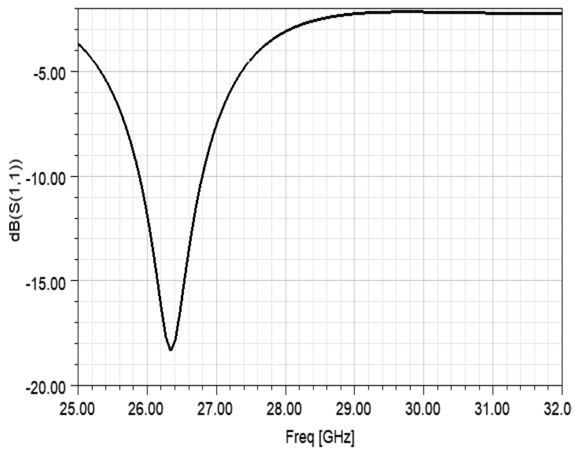
Parameters	Values (mm)
L_{sub}	9
W_{sub}	10.3
h	0.5
W_A	4.2
L_A	3.3
L_{fed}	3.26
W_{fed}	1.54
y_0	1
g	0.77
L_s	0.06
W_s	0.15

3. RESULTS AND DISCUSSION

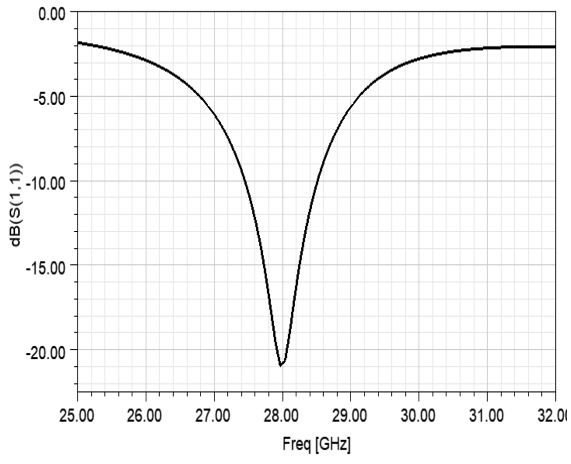
Figure 2 shows the simulation of the reflection coefficient associated with the proposed antenna structure, with and without slots. This is a measure of the amount of power returned to the antenna port by the dissimilarity with the feed line. The coefficient S_{11} is expressed in dB and lower than -10 dB, it corresponds to the relation between the reflected power (PRE) and the incident power (PIN) at the input port. Equally, if the value of the S_{11} index is less than 10 dB, it means that 90% of the exciting value is transmitted.

$$S_{11} = 20\, log(\frac{P_{RE}}{P_{IN}})(dB)$$

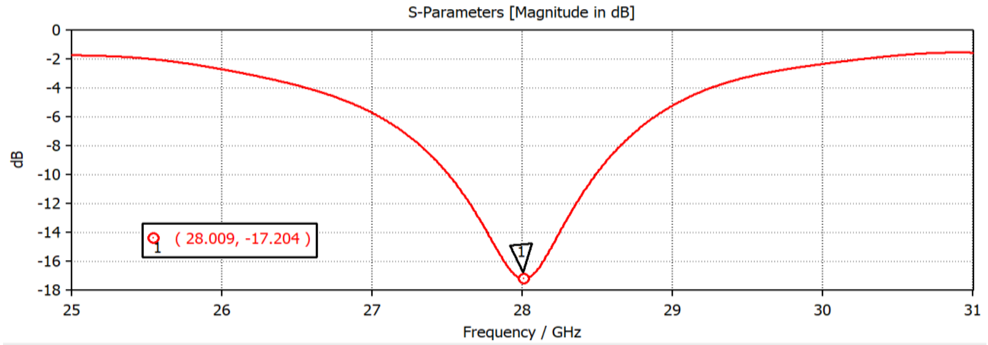
We have performed simulations of the proposed antenna using CST and HFSS. The main parameters of this antenna include the reflection coefficient S_{11} shown in Figure 2. This is used to determine the bandwidth and impedance matching characteristics.



(a)



(b)



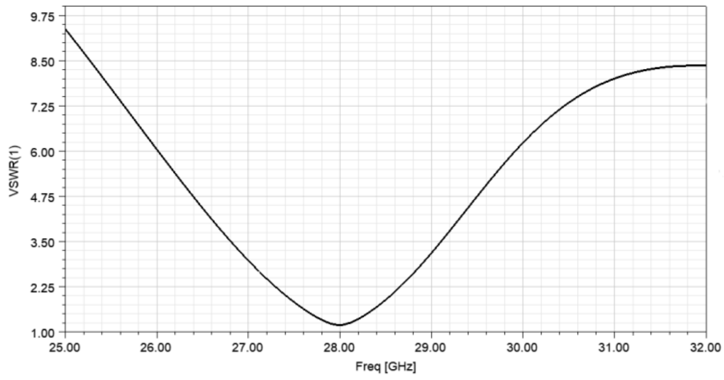
(c)

Figure 2. S_{11} return loss curves of the proposed antenna using: (a) HFSS, (b) HFSS, and (c) CST

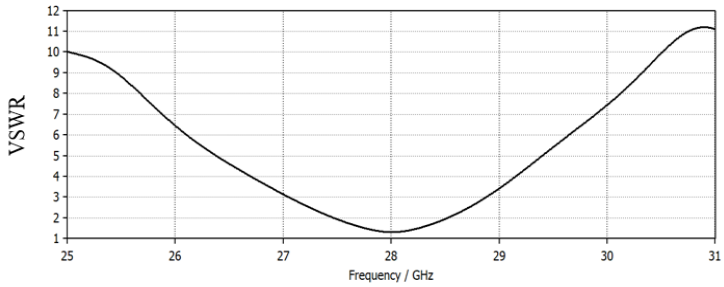
It works at 26.34 GHz with S_{11} of -18.35 dB for antenna without slot, so a bandwidth of 0.91 GHz (25.89 GHz - 26.8 GHz) is shown in Figure 2(a), which represents the S_{11} curve without slot. When we add the slot, we get better results than the previous ones, as shown in Figure 2(b) and Figure 2(c), these are represented the S_{11}: the operating frequency is 27.97 GHz, S_{11} = -20.95 dB, the bandwidth is 1.06 GHz, and VSWR = 1.197. The simulated S_{11} coefficient proves that the antenna resonates with high bandwidth on 5G communication frequencies. The simulation of the voltage standing wave ratio (VSWR) is realized by the simulator HFSS and CST (illustration in Figure 3(a) and Figure 3(b)). The VSWR is due to the reflection of a large portion of the generated energy. The value of this SWR over the bandwidth should be between 1 and 2. For the transmission of power from the antenna to be maximized, this ratio must tend towards 1. The value of the VSWR is 1.197 at the operating frequency of this antenna, as shown in Figure 3.

The radiation pattern is also another important characteristic of antenna performance. This radiation pattern represents the variations in the power radiated by the antenna in different directions in space. It shows the directions in space (θ_0, φ_0) in which the radiated power is maximum. It is important to note that the radiation pattern is only meaningful if the wave is spherical. Figure 4 shows the three-dimensional and two-dimensional radiation patterns of the proposed antenna.

Figure 4 and Figure 5 show the gain and directivity curves for the suggested slot antenna designs using the HFSS tool, and Figure 6 and Figure 7 show gain and directivity curves for this antenna with another CST tool. Table 2 shows a summary of all simulation results around this antenna with and without a slot. Table 2 shows the comparative performance with and without slots for this suggested antenna, including gain, directivity, bandwidth, S_{11}, VSWR, radiated power, and accepted power. The characteristics associated with a non-aperture antenna, namely gain, directivity, and VSWR are better than those associated with the aperture antenna, but the performance of the aperture antenna such as bandwidth, S_{11}, radiated power, and accepted power are better than those of the non-aperture antenna. Table 3 shows the comparison between the proposed antenna's performance with the HFSS and CST tools. Again, both tools are almost identical in their simulation results.



(a)



(b)

Figure 3. VSWR coefficient using: (a) HFSS and (b) CST

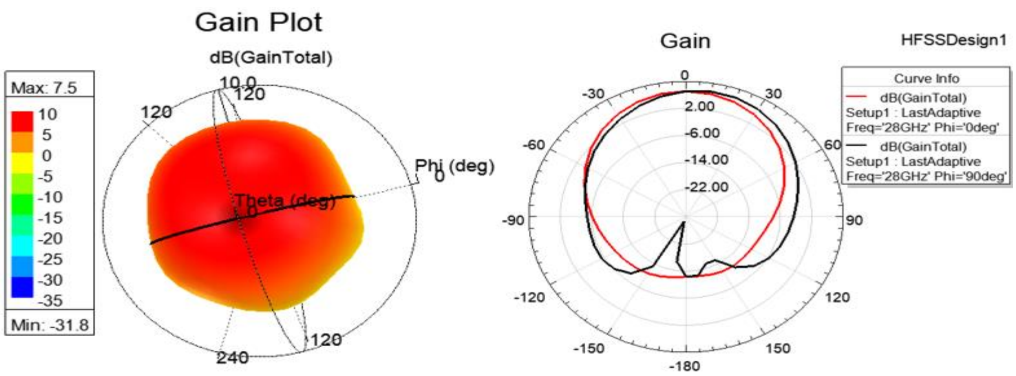


Figure 4. Graphical representation of the gain in three dimensions and two dimensions, using HFSS

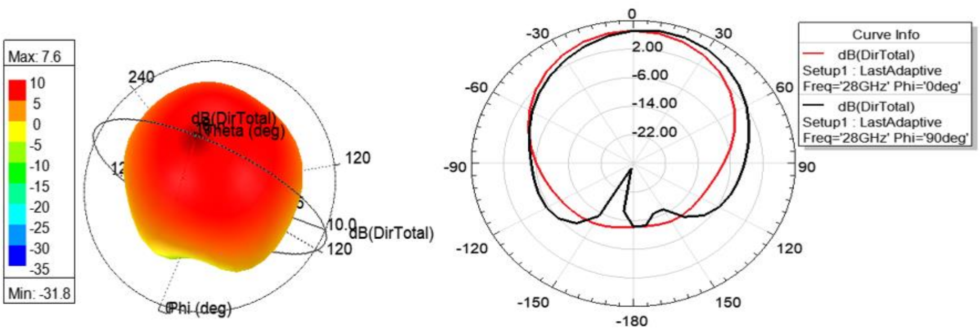


Figure 5. Representation of the directivity to the proposed antenna in two and three dimensions by using the HFSS

Table 4 provides a summary of the critical characteristics of the above research studies. The performance of the proposed antenna, such as gain, directivity and bandwidth, S_{11}, efficiency, radiated power, accepted power, and overall size. The reflection coefficient is higher for the antenna [23] than for the other antennas. Its efficiency is higher than that of the antennas [24]-[26]. On the other hand, the gain is higher in the antenna [24] than in the other antennas [23]-[26] and the dimensions of the latter are more significant than those of the antenna [24]. The antenna [26] has a wide bandwidth compared to the other antennas, but its gain is lower than the other antennas with the disadvantage of its larger size. On the other hand, the gain and efficiency of the antenna [25] are higher than the other antennas except the proposed one, but it has two disadvantages: its larger size and its low bandwidth. Furthermore, the performance of the proposed antenna is much better than the other antennas, except for the S_{11} and its bandwidth.

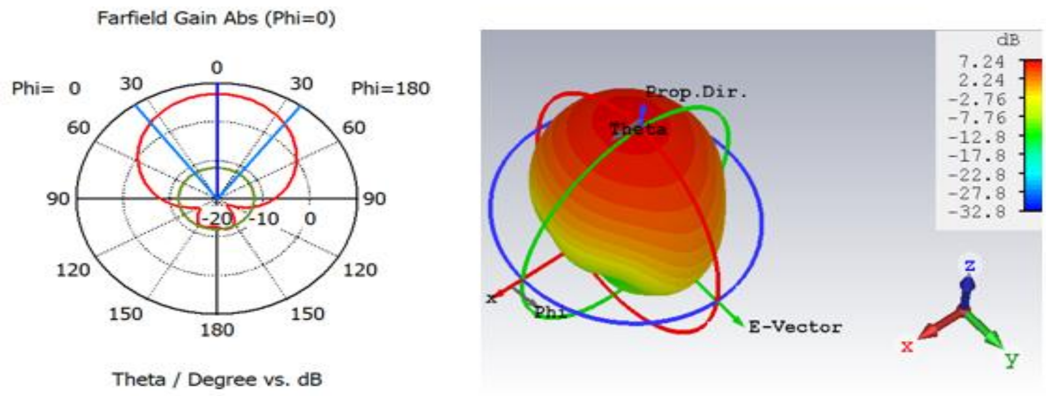


Figure 6 Three-dimensional and two-dimensional radiation pattern of this antenna proposed on CST

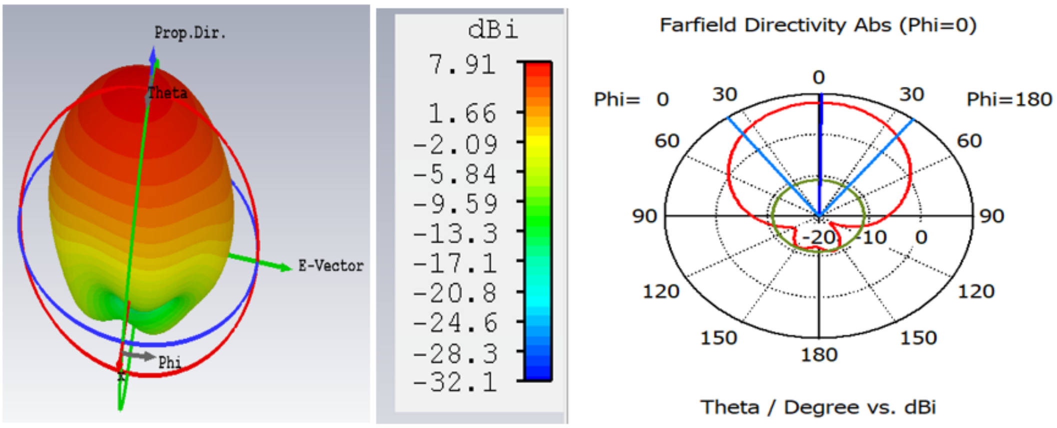


Figure 7. Representation of the directivity to the proposed antenna in three dimensions and two dimensions by using the CST

Table 2. Result of the simulations of this antenna

Parameters	Slotless antenna	Antenna with slot
Return loss (dB)	-18.35	-20.95
Gain (dB)	8	7.5
Directivity (dB)	7.9	7.6
VSWR	1,275	1.197
Band width (GHz)	0.91	1.06
Efficiency	-	99.83%
Radiated power (dBm)	27.23	29.90
Accepted power (dBm)	27.09	29.95

Table 3. Comparison of the results of the simulations with the HFSS and CST tools

Simulator	CST	HFSS
Frequency (GHz)	28.008	27.97
Return loss (dB)	-17.2	-20.95
Gain (dB)	7.24	7.5
Directivity (dB)	7.9	7.6
VSWR	1,32	1.197
Bandwidth (GHz)	0.97	1.06
Efficiency %	87.75	99.83

Table 4. The result of the comparison between this antenna and the existing ones

References	Sizes	S_{11} (dB)	Gain (dB)	Directivity (dB)	Bandwidth (GHz)	η %	Radiated power (dBm)
[23]	7 $mm^3 \times$ 7 $mm^3 \times$ 0.8 mm^3	-27.79	6.59	7.45	-	82.08	29.12
[24]	6.285 $mm^3 \times$ 7.235 $mm^3 \times$ 0.5 mm^3	-13.48	6,63	-	0.847	70.18	-
[25]	19 $mm^3 \times$ 25 $mm^3 \times$ 0.5 mm^3	-	7.88	-	0,445	92.2	-
[26]	13.59 $mm^3 \times$ 12 $mm^3 \times$ 1.75 mm^3	-22.5	5.06	-	5.57	80.18	-
[27]	6 $mm^3 \times$ 6 $mm^3 \times$ 0.1 mm^3	-18.062	-	6.94	-	-	-
[28]	5.5 $mm^3 \times$ 5.4 $mm^3 \times$ 0.4 mm^3	-18.25	6.83	-	1.074	-	-
Suggested antenna	4.2 $mm^3 \times$ 3.3 $mm^3 \times$0.5 mm^3	-20.95	7.5	7.6	1.06	99.83	29.9

4. CONCLUSION

Designers are currently facing several difficulties related to the design of patch antennas. The goal of this research work was to create and design a rectangular patch antenna for a 5G communication system. In this paper, a rectangular microstrip antenna design with a slot has been studied, which improves the performance of this antenna. Better bandwidth promotes better employee productivity, and in the case of the 5G wireless network, it is a critical component. Suggested antenna sizes are 4.2 mm × 3.3 mm × 0.5 mm. This antenna operates at 27.97 GHz with a reflection coefficient of -20.95 dB, a bandwidth of 1.06 GHz, a gain of 7.5 dB, directivity of 7.6 dB, and an efficiency of 99.98%. This antenna performed much better than comparable items in terms of bandwidth, gain, directivity, reflection coefficient, and radiation efficiency. Therefore, this antenna would be a good candidate for 5G wireless applications.

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