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Broadband microstrip patch antenna at 28 GHz for 5G wireless applications

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ABSTRACT

In this paper, a 28 GHz broadband microstrip patch antenna (MSPA) for 5G wireless applications is presented. The Rogers RT/Duroid5880 substrate material, with a dielectric constant of 2.2, the thickness of 0.3451 mm, and loss tangent of 0.0009, is used for the studied antenna to operate at 28 GHz center frequency. The proposed design of antenna is simulated by using CST studio suite. The simulation results highlight that the studied antenna has a return loss of -54.49 dB, a bandwidth of 1.062 GHz, a gain of 7.554 dBi. Besides, radiation efficiency and the sidelobe level of the proposed MSPA are 98% and -18.4 dB, respectively. As compared to previous MSPA designs reported in the recent scientific literature, the proposed rectangular MSPA has achieved significantly improved performance in terms of the bandwidth, beam-gain, return loss, sidelobe level, and radiation efficiency. Hence, it is a potential contender antenna type for emerging 5G wireless communication applications.

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1. INTRODUCTION

The fifth-generation (5G) network is anticipated to incredibly enhance the capacity of wireless technology by taking advantage of using a millimeter-wave (mm-wave) frequency band [1]. The supported data rate can reach maximum amount as one hundred times of fourth-generation network capability [2]. This creates new challenges for the antenna designers to meet the system necessities. Therefore, to realize the desired performances, the mobile market gears towards employing the mm-wave spectrum, carriers are probably to use the 6 GHz, 10 GHz, 15 GHz, 28 GHz, and 38 GHz as working frequency bands [3].

Antennas for the 5G technology are needed to be broadband to support high data rates, so various applications can be accessed [4]. Moreover, they should have a high gain to alleviate the impediments of the radio wave; among others, human bodies are probably blockers of the mm-wave interface and high propagation loss because of high working frequency [5].

Generally, the advancement in wireless technology needs antennas with light-weight, low profile (compact size), low-cost mass production, easy for installation, conformable to a planar and non-planar surface, and mechanically robust when mounted on the inflexible surfaces [6]. In this regard, microstrip patch antennas (MSPA) represent a lucid choice for wireless devices. The patch antennas are suitable for mounting on the exterior part of spacecraft, high-performance aircraft, satellites, rockets, cars, missiles, and hand-held portable communication devices. Therefore, the MSPA plays a significant role within the fastest-growing wireless communications industry [7, 8]. However, the main drawbacks of the MSPA are; losses due to dielectric and surface waves. Because of these losses, the bandwidth of MSPA is narrow, and the gain is low. Therefore, to overcome the drawbacks of MSPA mentioned above and enhance its performance for 5G communications, several designs of single element MSPA have been reported in the literature. These include modifying of feeding technique [9], using defected ground structure (DGS), and a slotted patch [10-12], using various substrate material types [13], changing the patch shapes [14-16], and using artificial material like metamaterial [17].

The DGS is an engraved defect in the ground plane of a planar transmission line with various shapes. This imperfection influences the shield current dissemination within the ground plane structure. For example, the transmission line attributes, line capacitance and inductance, are also influenced, and this deformity in the ground plane is the reason for change in the capacitance and inductance values [18]. Previously proposed rectangular MSPA reported in [19-21] achieves good beam-gain. Nevertheless, due to poor impedance matching between the interfaces, the MSPA return loss is large at the resonant frequency, and its bandwidth is narrow for 5G applications.

Similarly, the design demonstrated in [10] achieves wide bandwidth, but the feeding technique (coaxial feed) is not suitable for applications like cellular devices. The antenna reported in [22] has a good gain and directivity, but the achieved bandwidth is very narrow, and its radiation efficiency is low due to poor impedance matching. Another similar MSPA is presented in [5]. Although this antenna has wide bandwidth and good directivity, its return loss is large. Antenna with low return loss and good beam gain is discussed in [9]. However, the antenna bandwidth is narrow, which is against federal communications commission (FCC) proposal, and the magnitude of voltage standing wave ratio (VSWR) is large for wireless communications. Lastly, attempting to improve the performance, MSPA designs are given in [11, 12, 14], and wide bandwidth, good gain, and low return loss values are obtained. Besides, the overall size of a single patch is not good, which in turn creates incompatibility issues for the small handheld mobile devices. Generally, from the above summary of simulation results demonstrated by previous works, which are reported in the scientific literature, we can infer that most of the presented works tried to find improved performance in terms of one or two specific performance metrics of the antenna.

Hence, keeping the limitations of these works in view, in this work, we propose a broadband rectangular patch antenna structure with a wide bandwidth, a relatively high gain and radiation efficiency, minimum sidelobe level, and compact size for futuristic 5G communication systems at 28 GHz center frequency. To meet these requirements, we have used a partial ground structure, which is 75% of the substrate length, optimization of the physical structure of the antenna dimensions, inset-feed, and quarter-wavelength impedance matching techniques. The remaining part of this paper is given as follows. The proposed design method is given in section 2. In section 3, simulation results of the studied antenna and discussions are presented. Lastly, Section 4 discusses our concluding remarks.

2. THE PROPOSED DESIGN METHOD

The performance of the MSPA is mainly limited by the chosen shape of physical geometry, physical dimensions of the structures, and the material properties from which they are made. In this paper, the rectangular patch shape is chosen because it is easy to design and evaluate. Besides, it has a wider impedance bandwidth due to its broader shape as compared to other types of antenna. Moreover, Rogers RT/Duroid5880 has been selected as a dielectric substrate material having a thickness of 0.3451 mm, dielectric constant (ε_r) of 2.2, and tangent loss of 0.0009. Radiating copper metal thickness of 0.035 mm to function at 28 GHz center frequency has been used. Therefore, after the preliminary design parameters are selected, the remaining parameters of the proposed physical structure of the antenna, which are shown in Figure 1, are in the subsequent step calculated using general governing equations given in [24-27].

The performance of the rectangular MSPA is highly dependent on the selected dimensions of the physical structure. Hence, in this particular design, a metal patch of 3.5644 mm of length and 4.2352 mm of width is connected to a 50 Ω microstrip feed line with an inset on the top of the substrate. The overall physical dimension of the proposed rectangular MSPA is 3.5644x4.2352x0.3451 mm^3. In this work, the effects of the antenna dimensions on its performance are analyzed using the repetitive simulation. The CST antenna simulator has been used to enhance the performance of the studied antenna in terms of beam gain, directivity, bandwidth, and radiation efficiency by tuning its parameters. The values are altered manually, and the effects are observed from the simulation results. While tuning the antenna dimension parameters, its impact on all the performance metrics is considered. The final values of the antenna parameters, which are optimal for all the performance metrics of the given design, are chosen. The initially calculated and optimized physical dimensions of the proposed antenna are tabulated in Table 1.

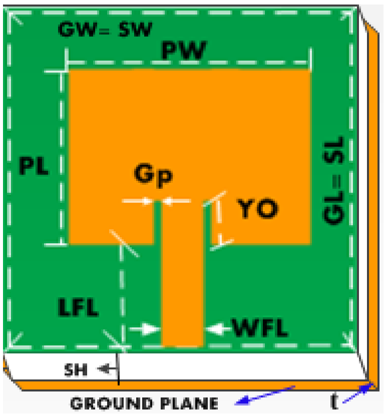


Figure 1. Physical structure of the proposed rectangular MSPA

Table 1. The calculated and optimized physical dimensions of the proposed antenna

Symbol	Design parameters	Calculated values (mm)	Optimized values (mm)
SH	Substrate Height	0.3451	0.325
PW	Patch width	4.2352	5.0999
PL	Patch length	3.5644	3.3791
SW	Substrate width	6.3058	8.5
SL	Substrate length	5.635	8.5
GW	Ground width	6.3058	8.5
GL	Ground length	4.2262	6.375
Y0	Inset length	1.259	0.8199
Gp	Inset gap	0.41	0.3
LFL	Length of a feeder line	1.8059	2.55
WFL	Width of feeder line	0.8219	0.9

3. SIMULATION RESULTS AND DISCUSSION

The performance of the MSPA is evaluated using different metrics. Among these, the return loss, bandwidth, VSWR, beam gain, and radiation efficiency are often utilized. The return loss (S_{11}) versus frequency plot of the proposed MSPA is given in Figure 2. From the plot, we observe that the antenna return loss is about -54.49 dB at the resonant frequency. The bandwidth of the rectangular MSPA is determined between the regions where a return loss is less than -10 dB, i.e., between 27.426 GHz and 28.488 GHz. Therefore, the -10dB return loss of the proposed rectangular MSPA bandwidth is 1.062 GHz. The return loss at the center frequency is found to be -54.49 dB.

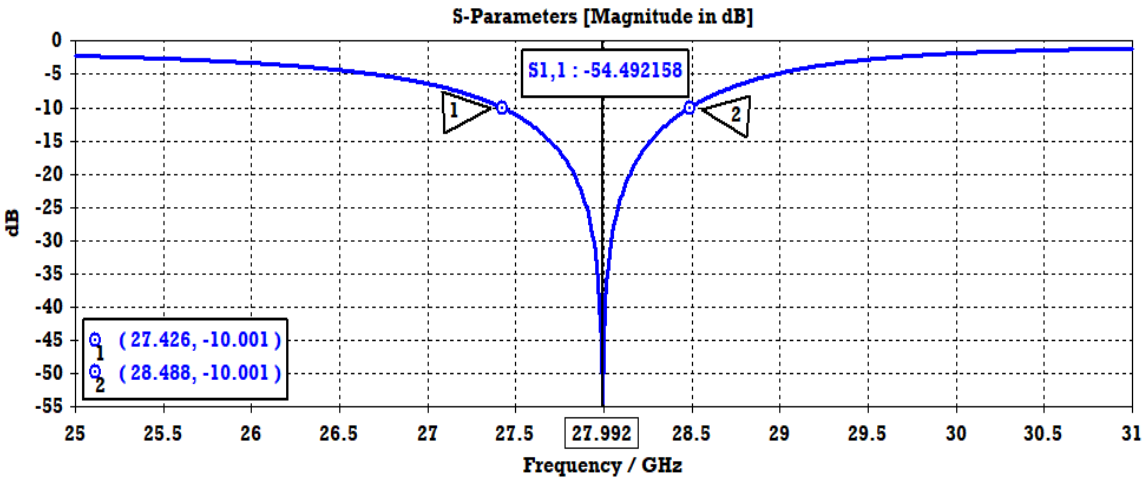


Figure 2. Return loss (S_{11}) versus frequency plot of the proposed rectangular MSPA

The input power delivered from the source cannot be radiated without loss due to incorrect compensations. Some of this power is reflected at the antenna, and it is returned to the transmitter, which is quantified by VSWR. The VSWR is described as a function of reflection coefficient, which expresses the power reflected from the antenna. The smaller the VSWR, the better the MSPA is matched to the feeder line and power distributed to the patch. Hence, for an ideal transmission line, the magnitude of VSWR is one, and for the practical scenarios, a magnitude of less than two is satisfactory as long as return loss is less than -10 dB [21]. Figure 3 shows that at 28 GHz, the VSWR of the studied antenna is 1.011 and very close to the ideal value. Within the -10 dB bandwidth, i.e., between 27.426 GHz and 28.488 GHz, the VSWR value of the proposed MSPA is less than two, which is within acceptable range.

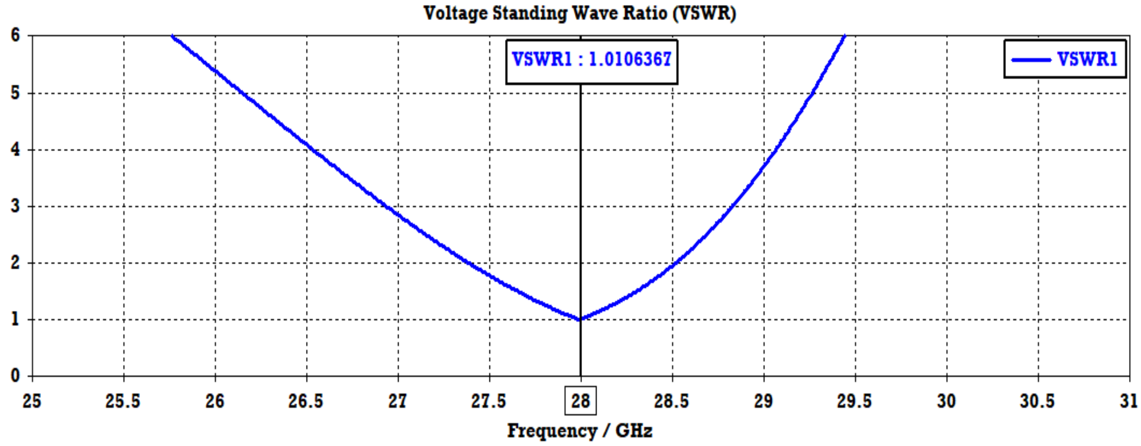
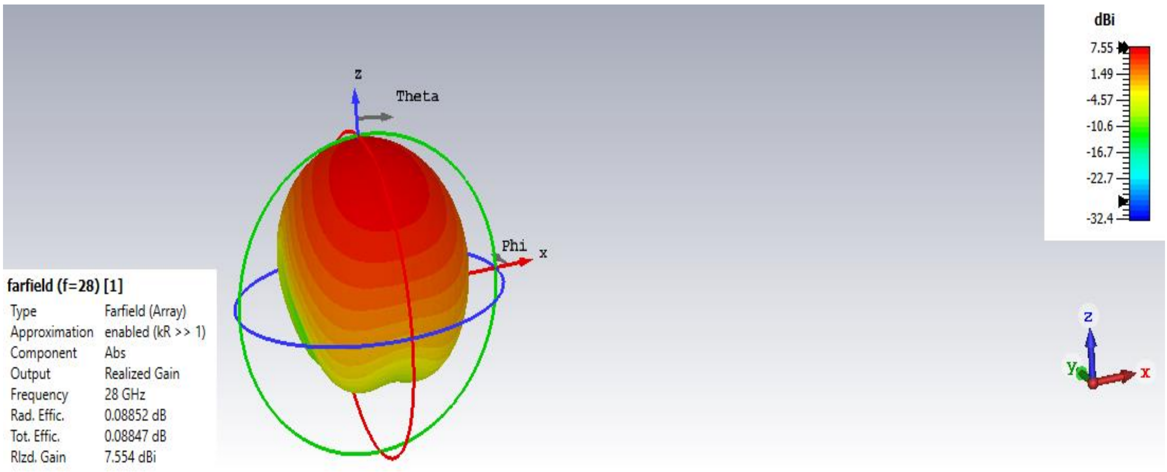


Figure 3. VSWR versus frequency plot of the proposed rectangular MSPA

Another parameter that characterizes radiation properties of an antenna structure and distinguishes one antenna from the other is the radiation pattern. It is the far-field plot of an antenna described in terms of spatial coordinates. It is specified using azimuth and elevation angles. Particularly, the plot shows the amount of radiated power from an antenna per unit solid angle. The radiation pattern plot can be visualized as a 3D graph or a 2D polar or Cartesian slice of the 3D graph. It is an important parameter as it shows the antenna's directivity and gain at various points in space [21]. Figure 4 indicates the 3D radiation graph of a proposed rectangular MSPA. From the figure, the beam-gain and radiation efficiency values of the proposed MSPA structure are found to be 7.554 dBi and 98 %, respectively. Also, the antenna's sidelobe level is -18.4 dB, as depicted in Figure 5.



farfield (f=28) [1]

Type	Farfield (Array)
Approximation	enabled (kR >> 1)
Component	Abs
Output	Realized Gain
Frequency	28 GHz
Rad. Effic.	0.08852 dB
Tot. Effic.	0.08847 dB
Rlzd. Gain	7.554 dBi

Figure 4. 3D Radiation graph of the proposed rectangular MSPA

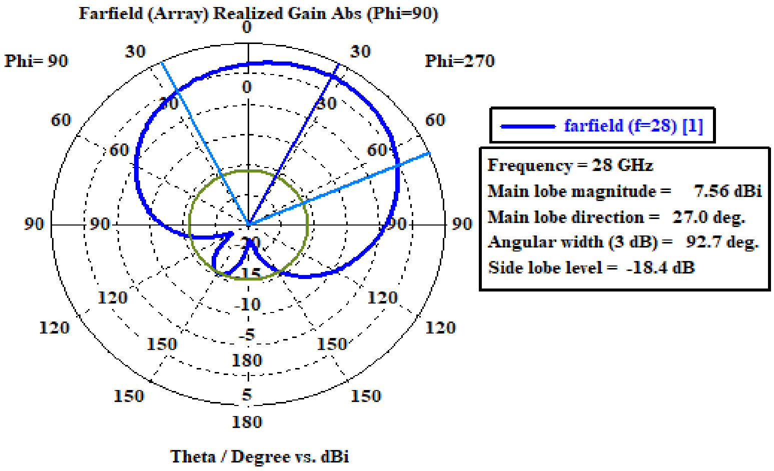


Figure 5. 2D radiation pattern of the proposed rectangular MSPA

The simulation outcomes of the proposed rectangular MSPA and other similar antennas reported in the scientific literature are tabulated in Table 2. Obviously, as the electromagnetic wave travels to different portions of the antenna, they encounter different impedance at each interface. However, in any case, at whatever point there is imperfect impedance matching at any of the interfaces, it causes a portion of the electromagnetic waves to return back to the source. Therefore, at the feeding network, perfect impedance matching is necessary to transfer considerable amount of power from the port to the feeder networks, which is connected to it. The proposed rectangular MSPA has been excited using the microstrip inset feed line.

At the interface of the feed-point and the patch edge, the impedance mismatch is significantly minimized by tuning the dimension of the inset-feed, patch width, and width of the microstrip transmission line. As a result, a huge amount of input power is transmitted to the feeding networks with very low return input power as a return loss. Therefore, from Table 2, it is clearly apparent that the studied antenna shows lower return loss as compared to the designs reported in [10, 12-20, 22, 23] and it gives lower VSWR than the structures introduced in [10, 13, 19, 20, 22, 23].

The dimension of the patch width determines the range of antenna bandwidth and radiation efficiency of the antenna. Then again, the chosen ground plane dimensions and substrate thickness plays a significant role in determining the performance characteristics of the antenna. Accordingly, in this study, both the ground plane dimension and the substrate thickness of the proposed rectangular MSPA are carefully designed and optimized. Extensive and meticulous tuning of the antenna parameters is indispensable for its performance improvement. Consequently, the surface wave, spurious feed radiation, and the reflection of the input power are considerably reduced. Besides, the input impedance mismatch of the MSPA is significantly reduced by using different impedance matching techniques and optimizing the patch width dimension. As a result, the proposed antenna has achieved better performance in terms of radiation efficiency, beam-gain, and sidelobe level. From Table 2, we note that the antenna radiation efficiency is higher than the designs reported in [10-13, 19, 22], the bandwidth is wider as compared to the antennas cited in [19, 20, 22]. In terms of beam gain, the rectangular MSPA in this paper outperforms the designs reported in [14, 20, 22]. Generally, the proposed single element rectangular MSPA gives an exceedingly competitive performance as compared to similar structure antennas reported in the scientific literature.

Table 2. Simulation results of the previous works and proposed antenna at 28 GHz

Ref.	S11 (dB)	Gain	VSWR	ηrad (%)	BW (GHz)
[10]	-20.03	5.23 dB	1.22	95.9	2.11
[11]	-56.95	7.6 dB	1.002	79.8	1.38
[12]	-39.37	6.37 dB	1.022	86.73	2.48
[13]	-17.834	-	1.299	92.65	-
[14]	-39.7	5.23 dBi	-	-	4.1
[19]	-13.48	6.63 dB	1.538	70.18	0.847
[20]	-14.151	6.06 dBi	1.488	-	0.8
[22]	-20.534	6.22 dBi	1.022	77.72	0.4
[23]	-22.2	6.85 dB	1.34	-	-
This work	-54.492	7.55 dBi	1.011	98	1.062

Where η_{rad} and BW denote radiation efficiency and bandwidth, respectively

4. CONCLUSION

In this paper, a 28 GHz broadband rectangular MSPA has been proposed for 5G wireless applications. The conducted simulations highlight that the proposed rectangular MSPA resonates at 27.992 GHz having a return loss of -54.49 dB. The achieved maximum beam-gain is 7.554 dBi, bandwidth is 1.062 GHz, VSWR is 1.011, the radiation efficiency is 98%, and the sidelobe level is -18.4 dB. As compared to other similar works, the proposed rectangular MSPA has achieved significantly higher performance in terms of bandwidth, beam-gain, return loss, and radiation efficiency. This improved performance has been achieved because of the reduced impedance mismatch between the microstrip feeder line interface and the patch edge using the inset-feed and quarter-wavelength impedance matching techniques. In addition to these impedance matching techniques, the antenna parameters (physical dimensions) are optimized by considering the performance trade-off between the parameters. The proposed rectangular MSPA has a compacted size; therefore, it is suitable for mobile devices with space constraints, and also, it can be considered a potential candidate to be used in an array of 5G communication systems.

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