A Super High Gain L-Slotted Microstrip Patch Antenna For 5G Mobile Systems Operating at 26 and 28 GHz

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Abstract-Microstrip patch antennas have been widely investigated and used in modern mobile communication technologies including 5G. Previous works in the area demonstrated that such antennas can be designed to operate in the low, mid, and high bands of 5G networks. This paper focuses on high-band millimeter-wave 5G mobile applications. In particular, the proposed microstrip patch antenna was designed to operate at 26 and 28GHz, which are the first introduced and widely used frequency bands of the 5G. This study aims to enhance the gain and other radiation characteristics of the antenna by adding a combination of different slot shapes to a single rectangular patch that is commonly used in other 5G antennas. The results show that an extremely high gain is achieved by inserting two symmetric L-slots and a middle-placed square slot. The dimensions of the slots were simulated and optimized using the CST Studio Suite simulator. A comparative study was also conducted showing that the proposed antenna features higher gain and directivity and provides very good VSWR and efficiency along with a reasonably large enough bandwidth at the two resonance frequencies considered.

Keywords-5G mobile communications; antennas; gain; microstrip; patch; slot

I. INTRODUCTION

Low profile, low cost, small size, easy fabrication, and the conformity of microstrip patch antennas have led to their wide adoption in mobile communication systems including mobile phones, Radio Frequency Identification (RFID), Global Positioning System (GPS), and many more applications [1-2]. Such antennas also have been recently found very effective in 5G wireless communication devices [3-4]. The millimeter-wave (mmWave) band represents a major part of 5G networks. The new mmWave bands allocated for 5G connectivity lie between 24.25–27.5, 27.5–29.5, 37–40, and 64–71GHz [5]. In particular, the first introduced 26 and 28GHz frequency bands are the two most important operating bands for mmWaves used in 5G, as defined by the Federal Communication Commission (FCC) [6-7]. For example, South Korea, US, and Japan considered the 28GHz band for their first 5G deployments, while Europe and China considered the 26GHz band [8]. The availability of mmWave spectrum, especially at 26 and 28GHz, has attracted the interest of various radio technologies, including mobile communication. Therefore, these particular frequencies have attracted considerable attention from many researchers working in 5G [7-11]. On the other hand, many researchers focused on improving the radiation characteristics of microstrip patch antennas for 5G applications. A major issue in microstrip antennas is their narrow bandwidth, which can be improved using various methods such as slotted patch, thick substrates, low effective permittivity substrates, incorporating multiple resonances, and optimizing impedance matching [12-13]. Moreover, the main disadvantages of using mmWaves can be the high path loss, the susceptibility to atmospheric and rain absorption, shadowing by materials or human body, etc., which can all be mitigated by using antennas with high gain and large bandwidth [14]. Nevertheless, the narrow bandwidth is not a major issue in 5G as in wireless applications operating at lower frequency bands, instead the achievement of high gain stands as the main challenge, provided that the bandwidth is not severely compromised. The primary goal of this study is to improve the microstrip patch antenna gain for 5G applications working at 26 and 28GHz bands (Ka-band). A summary of the key related works in this area follows.

In [15], a compact planar inset-fed microstrip antenna was designed at 28GHz and provided 6.83dBi gain. In [4], a triple-band antenna, using low relative permittivity and low thickness substrate, was designed to operate at 24.4, 28, and 38GHz. The gains achieved at these frequencies were 6.65, 7.02, and 5.05dBi respectively. In [16], a dual-band Coplanar Waveguide (CPW) slot directive antenna was designed to operate at 28 and 38GHz for 5G. The maximum gains achieved for the two bands were 6.6 and 5.6dBi respectively. In [17], a broadband elliptical-shaped slot antenna was designed to cover the 5G band from 20 up to 40GHz, having a maximum gain of 5dBi. In [18], a dual-band Planar Inverted-F Antenna (PIFA) with a CPW feeding line was designed. This antenna achieved a bandwidth of 3.34 and 1.395GHz and a gain of 3.75 and 5.06dBi in the 28 and 38GHz bands respectively. In [19], a combined structure was developed, using a microstrip patch

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radiator and a waveguide aperture, to provide a wide beam and high gain in a particular tilt direction. The maximum achieved gain was 7.41dBi at 28GHz. In [20] a slotted microstrip patch antenna was designed to operate at 28GHz for 5G applications. The design was based on the use of two slots of different shapes placed in the middle of the patch and connected through a narrow short strip. This compact antenna design provided a 6.37dBi gain. In [21], a dual-band (28 and 45GHz) elliptical-slotted circular patch antenna was designed for 5G communications and provided the maximum gain of 7.6dBi at 28GHz. In [22], Defected Ground Structure (DGS) and stub slot configuration were used to design a dual-band (28 and 45GHz) microstrip patch antenna with wide bandwidth and high gain (8.31dBi). Further studies that attempted to optimize microstrip patch antennas to operate at 28GHz for 5G communications were presented in [23-24], while the gains they obtained were 7.43 and 9.82dBi respectively. Furthermore, many studies focused on the use of microstrip patch arrays to enhance beamforming and directivity, and hence gain, of microstrip patch antennas for 5G applications. In [10], a novel antenna array design, based on using a square patch, an edge-plated air-filled cavity, and an hourglass-shaped aperture-coupled feed, was developed for the global 26 and 28GHz 5G bands. The presented 1×4 antenna array provided a peak gain of 10.1±0.7dBi. Many studies considered the design of array-based microstrip patch antennas for the 26GHz [25-29] and 28GHz [14, 30-36] 5G bands. Among these studies, the maximum gains achieved were 16.4dBi [25] and 19dBi [12] for the 26 and 28GHz bands respectively, which are considered very high. However, in terms of simplicity, such designs might not be the right choice in many cases, since the integration of patch arrays substantially increases the design complexity and the overall size of the antenna.

This study aims to design a dual-band single patch microstrip antenna operating at both the 26 and 28GHz mmWave bands of 5G. The slotted patch method is used in an attempt to improve the antenna gain significantly, as well as return loss (reflection coefficient), Voltage Standing Wave Ratio (VSWR), directivity, and efficiency while maintaining a sufficiently large bandwidth in the two 5G bands considered.

II. ANTENNA DESIGN

Considering that patch antennas are widely used in other shapes [37], the proposed antenna was based on a rectangular patch that has two symmetric back-to-back L-shaped slots and a single square slot placed between them. The antenna was built on a rectangular Rogers RT5880 substrate of 20mm length, 16.5mm width, and 0.508mm thickness. The relative dielectric permittivity ε_r was 2.2, and the loss tangent tan δ was 0.0009. Further details on the RT Duroid 5880 substrate can be found in [38]. Among the various feeding techniques available for microstrip patch antennas, the inset feed was selected to achieve a good impedance matching between the feed line and the patch. The dimensions of the patch were 9.9×9.7mm^2, fed by a 50Ω microstrip line of 0.7mm width and 4.75mm length. Table I provides the optimized dimensions of the proposed antenna depicted in Figure 1. The values from L_{L1} up to W_S in the table represent the optimized dimensions obtained from a parametric study performed using the sweep option available in the CST Studio Suite simulator.

TABLE I. OPTIMIZED DIMENSIONS OF THE SLOTTED PATCH OF THE PROPOSED ANTENNA

Dimension	L_P	W_P	L_{L1}	L_{L2}	W_{L1}	W_{L2}	L_S	W_S
Value (mm)	9.7	9.9	5.3	1	1.5	0.5	3.95	4.25

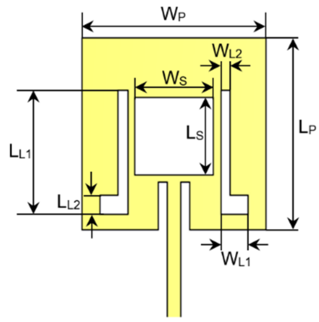

Fig. 1. Geometrical representation of the slotted patch element of the proposed microstrip antenna.

III. SIMULATION RESULTS

This section provides the simulation results of the designed antenna, using the CST simulation software. Table II shows the detailed results of the radiation parameters chosen in this study to analyze the performance of the developed microstrip patch antenna. These parameters are center frequency (how close it is to the selected band), reflection coefficient (S11), bandwidth, gain, directivity, VSWR, and efficiency. The parameters listed in the table are introduced below. The reflection coefficient is most commonly referred to as "return loss" and is calculated in dB as:

$$\text{Return Loss} = -20\log|\Gamma| \quad (1)$$

where Γ is the voltage reflection coefficient. As in all other microstrip antenna design studies, the bandwidth was measured at -10dB return loss.

The gain was measured in dBi (decibels-isotropic) as a reference to an ideal hypothetic isotropic antenna radiating (or receiving) energy equally in all directions. While the gain is the ratio of the radiation intensity in a given direction to the average of total input power, the antenna directivity, in contrast, is the ratio of the peak radiation intensity in a certain direction to the total radiated power [39]. The gain G is related to the directivity D by:

$$G = \eta D \quad (2)$$

where η is the efficiency factor lying between 0 and 1. For an ideal lossless antenna, η equals to 1 (i.e. 100%). The antenna efficiency is calculated as the ratio of the power radiated from the antenna to the power delivered to it. The higher the efficiency the more reliable and useful the antenna would be, particularly for 5G communications which require high speeds and reliable communication processes. The VSWR is a ratio between the maximum and the minimum voltage expressed by:

$$\text{VSWR} = \frac{V_{max}}{V_{min}} \quad (3)$$

VSWR measures the impedance mismatch between the feeding system and the antenna [38]. Its value must lie between 1 and 2, and the greater match is achieved as this value decreases towards 1. VSWR is calculated by [40]:

$$\text{VSWR} = \frac{1+|\Gamma|}{1-|\Gamma|} \quad (4)$$

where Γ is calculated as a function of the load (Z_L) and source impedance (Z_S) by [40]:

$$\Gamma = \frac{Z_L - Z_S}{Z_L + Z_S} \quad (5)$$

TABLE II. SIMULATION RESULTS OF THE PROPOSED ANTENNA AT 26 AND 28 GHZ

Frequency (GHz)	S11 (dB)	BW (GHz)	Relative BW (GHz)	Gain (dBi)	Directivity (dB)	VSWR	Efficiency
25.98	-24.14	0.55	2.12%	8.63	9	1.13	95.89%
28.2	-25.45	1.1	3.93%	11.26	11.8	1.11	95.42%

TABLE III. COMPARISONS OF ALL ANTENNAS AT THE 28 GHZ BAND

Design	Gain (dBi)	Center frequency (GHz)	Minimum S11 (dB)	BW (GHz)	Relative BW (GHz)	Directivity (dBi)	VSWR	Efficiency %	Other 5G bands (GHz)
Proposed	11.26	28.2	-25.45	1.1	3.93%	11.8	1.11	95.42%	25.98
[23]	9.82	28.1	-42	1.29	4.61%	-	1	99.99%	-
[21]	8.31	28	-54	5.13	18.32%	8.35	1	98%	38.5
[20]	7.6	28	-40	1.3	4.64%	7.68	1.01	85.6%	45
[18]	7.41	28	-35	1.5	5.35%	-	-	-	-
[3]	7.02	28.1	-19.3	0.9	3.21%	7.69	1.244	85.5%	24.4, 38
[14]	6.83	28.06	-18.25	1.1	3.93%	-	1.278	-	-
[19]	6.37	28	-40	2.48	8.86%	6.99	1.022	86.73%	-

The results show that the designed antenna provides high performance against all parameters considered in the study. For example, the reflection coefficients at the 26 and 28GHz frequency bands were equal to -24.14 and -25.45dB respectively. Such extremely low return loss values have a considerable impact on gain and directivity, which both scored very high values. On the other hand, the VSWR values in the two frequency bands are very close to 1, indicating a great match between the feeding system and the antenna. Moreover, the antenna efficiency exceeded 95% at both considered bands. Furthermore, the bandwidth of the proposed antenna in the two frequency bands is acceptable for 5G applications. Such moderate bandwidth values are outweighed by the super high gain achieved, which was the main objective of this study. As mentioned above, gain is of a higher priority than bandwidth in developing 5G antennas, given that the bandwidth is kept wide enough to cover 5G services. The high gain values achieved here by a single patch structure might be obtained by using array antenna structures, which in turn compromises the design simplicity and cost-effectiveness. The relative bandwidth in the table was calculated as the ratio of the bandwidth to the center frequency of the band in which the antenna operates (i.e. 26 or 28GHz in this case). A detailed comparison between the proposed antenna results and those achieved in other studies is provided in the next section. Figure 2 shows the S11 parameter in dB with respect to the operating frequency. The obtained center frequency and bandwidth are annotated on the graph for both considered operating bands. Figures 3 and 4 show the radiation pattern and the E-H plane of the proposed antenna at both resonance frequencies.

IV. COMPARISON OF THE PROPOSED ANTENNA WITH OTHER DESIGNS

Table III provides a detailed comparison between the proposed antenna and a set of other designs that used a single patch structure and a resonance frequency of 28GHz. It should be noted that all studies on the 26GHz band found in the literature were either based on antenna arrays or not designed for 5G applications (Ka-band), hence no comparison for 26GHz antenna designs is provided. The results are arranged in descending order according to the gain value. The best output value of each parameter is highlighted to facilitate the comparison between the various antenna designs.

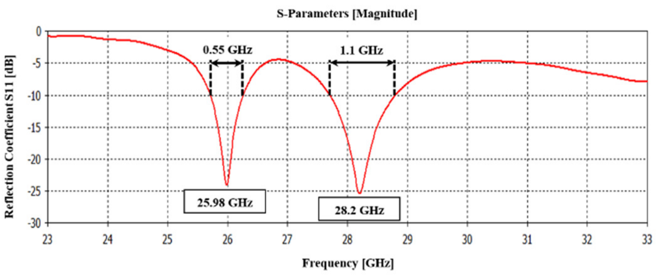

Fig. 2. S11 parameter as a function of frequency for the proposed antenna design.

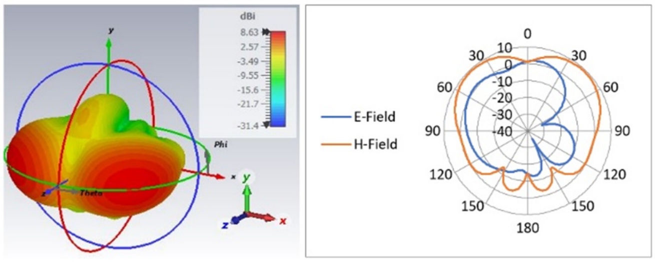

Fig. 3. The radiation pattern and E-H plane for the proposed antenna at 26GHz.

It can be observed that the proposed antenna provided the highest gain and directivity without compromising other parameters, except the bandwidth which was compensated by the very high gain and directivity. This indicates that the proposed microstrip patch antenna can be a strong candidate for 5G mobile communication devices, especially when simplicity, low cost, and small size are the key design requirements.

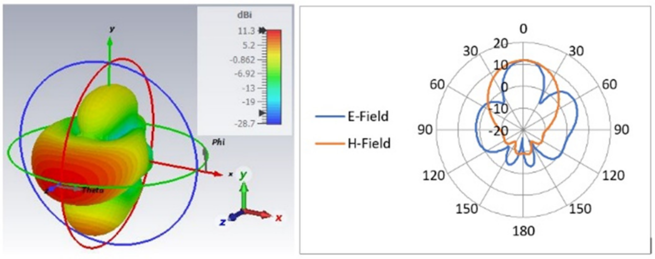

Fig. 4. The radiation pattern and E-H plane for the proposed antenna at 28GHz.

V. CONCLUSIONS

In response to the rising need for fast and reliable mobile communication devices, a rectangular slotted microstrip patch antenna was developed for high-band 5G applications. The main goal was to enhance the antenna gain along with other radiation characteristics. The proposed antenna was intentionally designed with a single patch for simplicity and aimed to resonate the antenna at the 26 and 28GHz 5G frequency bands simultaneously. The antenna consisting of double symmetric L-slots and a single square slot placed in the middle provided very good radiation characteristics, especially the peak gain. The antenna gains for the two resonance frequencies were 8.63 and 11.26dBi respectively, which were significantly higher than those achieved in the reviewed literature. The corresponding directivity values for the two considered bands were 9 and 11.8dB, and the minimum reflection coefficients obtained were equal to -24.14 and -25.45dB respectively. The latter values are far below the -10dB return loss at which the bandwidth is usually measured. The bandwidths of the two bands at -10dB return loss were equal to 0.55GHz (2.12% fractional bandwidth) and 1.1GHz (3.93% fractional bandwidth) respectively, with a total bandwidth of 1.65GHz covering the 5G spectrum lying between 25 and 29GHz. Furthermore, for the 26GHz band, the VSWR and efficiency were 1.13 and 95.89% respectively, while for the 28GHz band, the VSWR and efficiency were 1.11 and 95.42% respectively. These results proved to be satisfactory when compared to other designs. Based on these results and the small dimensions, light weight, and relatively simple design, the proposed microstrip patch antenna can be a suitable choice for the development of 5G mobile communication devices. In the future, we can investigate various combinations of other slot shapes or antenna array structures to further improve the radiation characteristics, particularly bandwidth.

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