A Dual-Band and Low-Cost Microstrip Patch Antenna for 5G Mobile Communications

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Abstract **─** This paper investigates the numerical and experimental analysis of a low-cost and dual-band microstrip patch antenna for the fifth generation (5G) mobile communications. The numerical analysis of the proposed antenna is performed using the computational electromagnetic simulator (CEMS) software which is based on the finite-difference time-domain (FDTD) and CST software which is based on the finite integration technique (FIT). The performance of the proposed antenna designed and fabricated on a low-cost FR-4 substrate is verified with the simulated and measured results. The antenna operates at dual frequency bands which are 24 and 28 GHz. The antenna maximum gain values are 3.20 dBi and 3.99 dBi in the *x-y* plane at 24 and 28 GHz, respectively. The proposed antenna provides almost omni-directional patterns suitable for 5G mobile communication devices.

Index Terms **─** 5G antenna, dual-band antenna, low-cost antenna.

I. INTRODUCTION

The developments in the mobile communications industry have been increasing day by day due to the increasing use of wireless and mobile devices. Therefore, mobile communication technology [1] developed from the first generation (1G) to the fourth generation (4G) has become unable to meet the demands of the user today. The fifth generation (5G) technology [2], which can provide higher data rate, wider bandwidth, larger capacity, and lower latency than 4G, has been developed to meet user demands. Thus, low-cost, lightweight, and low-profile antennas which have high performance over a wide bandwidth and are operated at licensed frequency bands are needed for 5G mobile communications. The 5G frequency bands [3-4] above 6 GHz announced by the Federal Communication Commision (FCC) [5] are licensed in the USA as 24.25-24.45 GHz, 24.75-25.25 GHz, 27.5-28.35 GHz, 37-37.6 GHz, and 37-38.6 GHz.

Some of the major differences between the 5G mobile communication technology and all previous technologies are to use the antennas operating at higher frequencies where it is easier to obtain wider bandwidth and to use efficient and high-performance antennas. Therefore, antenna design is one of the most important parts of 5G communication technology. The most common antenna type is the microstrip patch antenna, which is widely used due to its low-cost, small size, and light weight.

The antenna design for 5G communication brings new challenges to researchers. One of the challenges in antenna design for 5G mobile technology is the fabrication of small size antenna on a low-cost substrate such as FR-4, because it is too lossy especially at high frequencies. However, FR-4 is a common PCB fabrication material, the most cost effective, easy to find, and maintaining robust mechanical as well electrical characteristics. Therefore, this substrate provides significant cost saving to manufacturing companies for antennas. At higher frequency, it makes difficult to

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design the antenna because of its reduced size, inaccuracy in the connector modelling, soldering issue between the connector pin and feeding line, and other inaccuracy of the fabrication capabilities.

In the literature, many microstrip antennas operating at 5G frequencies above 6 GHz [6–15] are proposed and characterized by their compactness, small geometric dimensions, antenna bandwidth, and gain. Most of these were not fabricated, not measured, just designed on a substrate having a low dielectric constant, ultra-low loss tangent, and high cost. However, the antenna proposed in this paper is designed and fabricated on a low-cost and lossy FR-4 substrate. Although the antenna is fabricated on a low cost and lossy substrate, the gain patterns and their maximum values of the antenna are at least as suitable as the antennas in the literature for 5G mobile communications.

II. ANTENNA DESING PARAMETERS

The geometry of the proposed antenna is shown in Fig. 1 and its dimensions are given in Table 1. The antenna is designed and printed on both sides of a low-cost FR-4 substrate with a relative permittivity of 4.4, thickness of 1.6 mm, and loss tangent of 0.025. The overall size of the antenna is 25 mm × 20 mm × 1.6 mm. There are two radiating patches on the front side of the substrate and a partial ground plane on the back side of the substrate. The numerical analysis of the antenna is performed using the computational electromagnetic simulator (CEMS) software [16] which is based on the finite-difference time-domain (FDTD) method [17] and on CST software [18] to verify their simulation consistency before fabrication and testing. The fabricated prototype of the antenna is shown in Fig. 2. The configuration of the simulation platform is Intel® Core™ i7-4790 CPU, 32 GB Random-Access Memory (RAM), and NVIDA RTX 2070 Super GPU operating on Windows 10 system.

Table 1: Dimension of the proposed antenna

	F_1	F_2	F_3	F_4	P_1	P_2	G
Length (mm)	5	2	1	1.2	4.7	2.3	13.2
Width (mm)	2	0.8	0.4	0.4	7.4	3	25

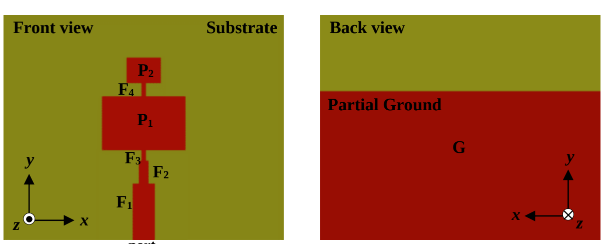

Fig. 1. Front and back views of the proposed antenna.

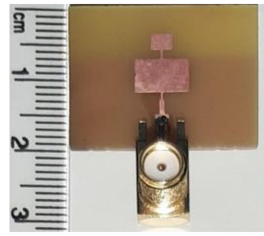

Fig. 2. Fabricated prototype of the proposed antenna.

A. CEMS simulation parameters

In CEMS simulation the problem space is composed of cubic cells and the choice of the cell size determines the accuracy of the solutions. In order to satisfy the numerical stability [17], the cell size should be less than $\lambda_{min}/20$, where λ_{min} is the wavelength of the highest frequency in the problem space. Therefore, in this work, the cell size of the problem in all directions is set to 0.1 mm which is less than $\lambda_{min}/20$. The problem space is terminated by 10 layers of convolutional perfectly matched layer [19] with 15 cell layers of air buffer. The total number of cells in the problem space is 4,950,000. The simulation shows reasonable convergence after 8000 time-steps with the GPU computing capability of almost 2 billion cells per second (MCPS) execution. The resulting total simulation time of this antenna is 19.8 seconds in CEMS running on the GPU specified in Section II.

B. CST simulation parameters

Commercial electromagnetic software CST is used to verify the accuracy of the simulation based on CEMS package. To keep consistency as much as possible, time-domain solver is also selected in CST, while unlike the FDTD method applied by CEMS, FIT is processed as the simulation method in CST. As for the working space, there are 365,040 total adaptive cells, in which the cell sizes are $\lambda_{min}/15$ for the maximum and $\lambda_{min}/20$ for the minimum. It should be pointed out that CST simulation of this antenna is computed on CPU due to the GPU limitation in CST educational license. All the other settings and the dimensions are kept the same as those in CEMS and the total simulation time was 163 seconds. The performance of this design based on CST and CEMS will be illustrated in the following section.

III. NUMERICAL AND EXPERIMENTAL RESULTS

A. Input reflection coefficient and radiation pattern

The simulated and measured input reflection coefficients (S_{11}) of the dual-band antenna are shown in Fig. 3 with good agreement at operation frequencies of 24 and 28 GHz. There are some acceptable differences between the measured and simulated results. The reasons of these differences might be due to poor soldering for the SMA connector, fabrication tolerance, losses on the SMA connector and coaxial cable, etc. The simulated gain patterns on the three plane cuts (*x-y*, *x-z*, and *y-z*) of the antenna at 24 and 28 GHz are shown in Fig. 4. The gain patterns in the *x-y* and *x-z* planes of the antenna are almost omni-directional. The omni-directionality of the antenna in the *x-y* plane at 24 and 28 GHz is 68.6% and 45%, respectively, for a gain difference of 6 dBi. The omni-directionality of the antenna in the *x-z* plane at 24 and 28 GHz is 81.9% and 85.8%, respectively. The performance parameters of the simulated and measured antenna are given in Table 2.

B. Effect of patches and ground plane

The antenna is composed of two patches: the smaller one (P_2) and the larger one (P_1). In order to show the effects of the sizes of the two radiating patches and the ground plane on the antenna performance, the proposed dual-band patch antenna is optimized in three different scenarios. First only P_1 is optimized (Case 1); then P_1 and P_2 are the optimization parameters with full ground plane (Case 2) and finally only P_2 is optimized (Case 3). The geometries of the three cases are presented in Fig. 5. Figure 6 shows the S_{11} of the antennas obtained using CEMS for these cases. The performance parameters of the antennas for the three cases are given in Table 3. The simulated results show that the proposed antenna provides good impedance matching, bandwidth, and better or comparable gain over the resonance frequencies of 24 and 28 GHz compared to other cases.

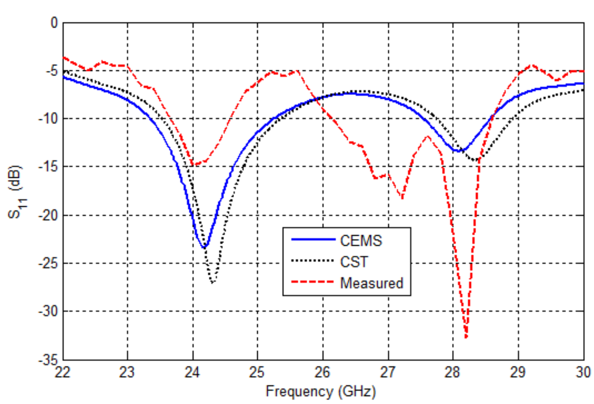

Fig. 3. Simulated and measured S_{11} of the antenna.

Table 2: Performance parameters of the proposed antenna

	Resonance Freq. (GHz)	S_{11} (dB)	Freq. Range (GHz)	Bandwidth (MHz)	Gain (dBi)
CEMS	24.16	-23.4	23.36-25.26	1900	3.20
	28.1	-13.4	27.56-28.57	1010	3.99
CST	24.31	-27.12	23.54-25.36	1820	3.53
	28.34	-14.33	27.75-28.91	1160	3.86
Measured	24	-14.86	23.7-24.6	900	-
	28.2	-32.72	26.2-28.5	2300	-

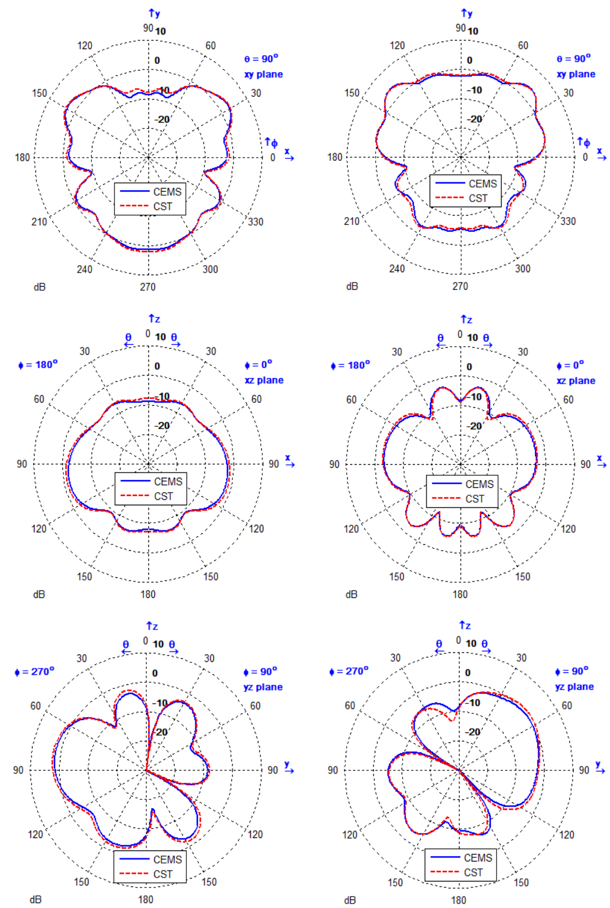

Fig. 4. Gain patterns of the antenna on the three plane cuts at (a) 24 GHz and (b) 28 GHz.

Table 3: Performance parameters of different configurations of the antennas

	Resonance Freq. (GHz)	S_{11} (dB)	Freq. Range (GHz)	Bandwidth (MHz)	Gain (dBi)
Case 1	24.12	-27.97	23.36-25.20	1840	2.11
	28.06	-11.61	27.50-28.46	960	4.02
Case 2	23.98	-19.27	23.10-24.86	1760	2.49
	27.20	-14.71	26.52-27.96	1440	2.85
Case 3	21.36	-20.72	20.22-23.24	3020	0.66
	26.26	-15.24	25.64-26.84	1200	0.74

C. Substrate thickness effects

By increasing and decreasing the thickness (h) of the FR-4 substrate, the antenna performance is investigated. The S_{11} of the antennas on the thickness of 0.8, 1.6, and 2.4 mm FR-4 substrate is shown in Fig. 7. The performance parameters of the simulated antennas are given in Table 4. The results in the table show that the thickness of substrate has a significant impact on the resonance frequencies, bandwidth, and gain. The antenna on the 0.8 mm substrate has a wider bandwidth than the proposed antenna, but its maximum gain values are lower than the proposed antenna. In addition, it is seen from Fig. 7 that the antenna on the 2.4 mm substrate has an S_{11} value above -10 dB in the specified frequency bands.

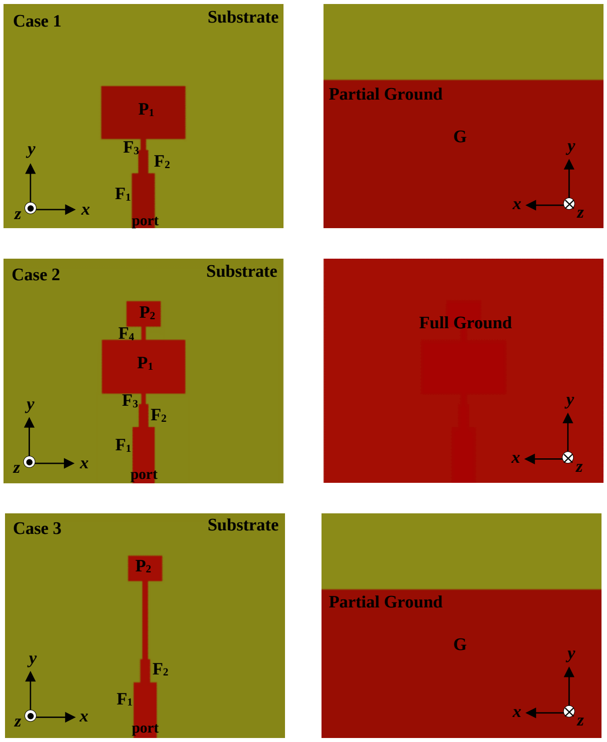

Fig. 5. Geometry of the antennas for three different cases.

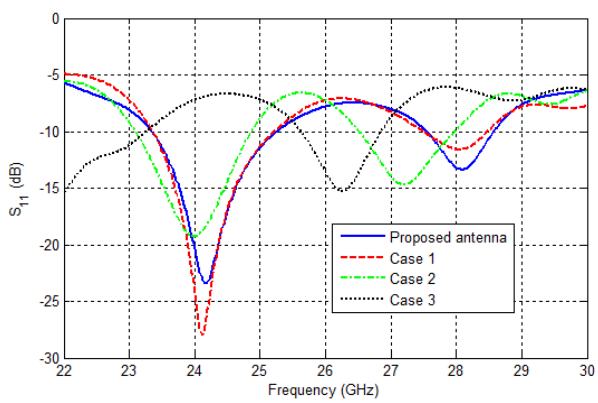

Fig. 6. Simulated S_{11} of the antennas for three different cases.

Table 4: Performance parameters of the antenna on different thickness of substrate

Thickness (mm)	Resonance Freq. (GHz)	S_{11} (dB)	Freq. Range (GHz)	Bandwidth (MHz)	Gain (dBi)
0.8	23.94	-17.76	22.54-25.74	3200	2.48
	27.22	-21.37	25.74-28.18	2440	0.55
1.6	24.16	-23.4	23.36-25.26	1900	3.20
	28.1	-13.4	27.56-28.57	1010	3.99

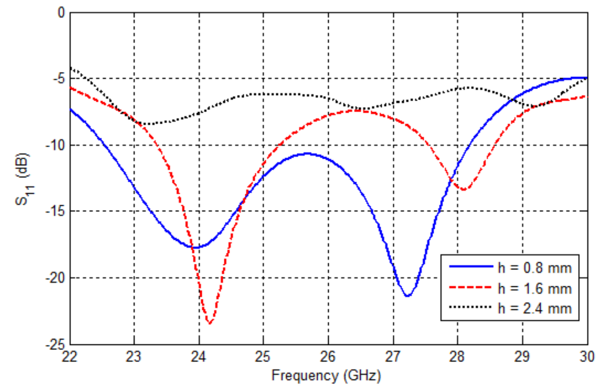

Fig. 7. Simulated S_{11} of the proposed antenna on the thickness of 0.8, 1.6, and 2.4 mm FR-4 substrate.

VI. CONCLUSION

Numerical and experimental analysis of the proposed microstrip patch antenna on a low-cost FR-4 substrate are presented for 5G mobile communications. The numerical analysis of the antenna is performed using CEMS software which is based on FDTD method and on CST software. The simulated and measured input reflection coefficients of the antenna are in good agreement at 24 and 28 GHz. The maximum gain values are 3.20 dBi and 3.99 dBi at 24 and 28 GHz, respectively. The proposed antenna has good performance in a small form factor which makes it a good candidate for 5G handheld devices.

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