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Substrate Analysis on the Design of Wide-Band Antenna for Sub-6 GHz 5G Communication

Bilal Tütüncü[1] · **Mahmut Kösem**[1]

Abstract

While copper is overwhelmingly used as the radiated part in microstrip antenna design studies, the choice of dielectric material offers a wide range of possibilities. At high frequencies, the effect of substrate permittivity on antenna performance is dramatically higher than low frequency microstrip antennas. For this purpose, in this study, a discussion on 4 different dielectric substrates to increase the overall efficiency of conventional sub-6 GHz 5G microstrip antenna is presented. A reference rectangular patch is modeled on FR4, Arlon AD300C, Rogers RO4003C and Mica substrates respectively. The radiating patch sizes are calculated and modeled for each dielectric substrate separately and then optimized for 5.65 GHz. Finally, gain and bandwidth analysis are performed with the help of CST Studio. Arlon AD300C, which is revealed to be the best in performance criteria analysis, is used for the proposed antenna fabrication and the simulated results are verified by bandwidth and gain measurements in a fully anechoic chamber. Finally, the advantages of the proposed antenna over some Sub-6 GHz 5G antennas with randomly selected substrates are confirmed by a comparative table.

Keywords 5G · Microstrip antenna · Dielectric material · Permittivity

1 Introduction

In the new world order -especially after COVID 19- where billions of wireless communication devices communicate simultaneously, the transition to 5G, which offers 100 times faster data speed than the current 4G, has been an indispensable necessity. However, efficient implementation of 5G technologies is only possible with efficient and compact antennas. In recent years, many different microstrip patch antenna (MPA) designs have been proposed for 5G communication. In all these studies, antenna performance criteria have been analyzed with various size parameters and many different antenna types are presented

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in the literature for future 5G communication [1–5]. For example, in [6], a MPA at 4 GHz center frequency is proposed with an impedance bandwidth of 58% from 2.84 to 5.17 GHz with a compact structure of 0.84 $\lambda_0 \times$ 0.68 $\lambda_0 \times$ 0.06 λ_0, (λ_0 is the free-space wavelength) with a stable radiation pattern. The presented 5G MPA has an average gain of 5 dBi, low back lobes, and low cross polarization. However, the main structure consists of two FR4 dielectric layers and the top layer consists of three vertical dielectric parts, and therefore this method negatively affects the antenna compactness. In [7], single and double bow-tie shaped MPAs with defected ground structures have been proposed for broadband wire-less applications including 5G with 12 dBi stable gain. The single bowtie antenna oper-ates in the 26.7–28.7 GHz frequency band, while the dual element bowtie antenna operates between 27.5 GHz and 28.3 GHz. However, the antenna presented in this method has a greater microstrip feed line than the radiating patch, this affects the impedance bandwidth negatively. A hexa-band, dual-polarization MPA for 5G communication is presented in [8] via fractal miniaturization techniques. The proposed antenna operates at 3.46, 8.28, 12.26, 17.21, 23.40, 26.01 frequencies (GHz) with Peak Gain (dB) of 6, 8.37, 9.65, 9, 7.84 and 9.34 respectively. Although the antenna operating frequency can be reached to the desired band with this method, the disadvantage of this method is design complexity. A metamate-rial lens layer loaded MPA is presented for 5G wireless communications in [9]. The trian-gular shaped superstrate metamaterial is loaded 12.5 mm above the proposed antenna to improve the gain and bandwidth at 10 GHz and 15 GHz operating frequencies. The pro-posed metamaterial layer enhanced the gain from 5.78 dB to 8.24 dB, and from 7.87 dB to 9.56 dB at 10 GHz and 15 GHz, respectively. Although this method provides a significant improvement in gain, it causes an increase in the antenna profile. From the literature review above, it is observed that the radiating patch, ground plate and top layer analyzes were per-formed to improve the antenna performance, but to the best of our knowledge, no analysis was made on the electrical properties of the substrate used for 5G MPAs. In the view of available bandwidth and radio wave propagation for 5G technology, the bands between 3 and 5 GHz have been promoted in many countries [10]. For example, 3.7–4.2 GHz and 3.1–3.55 GHz in USA, 3.3–3.6 GHz and 4.8–4.99 GHz in China and 3.4–3.8 GHz in Europe [11, 12]. In this study, FR4, Arlon AD300C, Rogers RO4003C and Mica dielectric materials are used respectively for a reference rectangular radiating patch which is designed for sub-6 GHz 5G communication. The scattering parameters and far-field radiation pat-terns are plotted separately for bandwidth and gain analysis. Modeling and simulations are performed with the CST STUDIO program and ARLON AD300C, which is revealed to be the most advantageous with performance analysis, is used in antenna production. The far-field radiation pattern measurements of the proposed antenna are carried out in a fully anechoic chamber and the bandwidth and return loss measurements are performed with a vector network analyzer. It is observed that the simulated and measured results are in a good agreement.

2 Sub-6 GHz Antenna Design

An MPA is a low profile antenna that is separated from the ground plane part of its radiat-ing patch by a dielectric substrate material. Fundamentally, the radiating patch has differ-ent sizes and shapes like circular, triangular, elliptical, rectangular etc. [13–17]. Since the aim of this study is not to analyze the performance based on shape, we started modeling by choosing the rectangular shape which is the most used in the literature. Four different

dielectric substrate parameters used in Eqs. 1–4 for the center frequency of 5.65 GHz, are given in Table 1. In the equations, f_c is the center frequency, c is the speed of light, ε_r is the dielectric coefficient of the dielectric material, ε_e is the effective dielectric coefficient, Δl is the feed line width and h is the substrate thickness [18, 19].

$$W = \frac{c}{2f_c}\left(\frac{\varepsilon_r + 1}{2}\right)^{-\frac{1}{2}} \tag{1}$$

$$L = \frac{c}{2f_c\sqrt{\varepsilon_e}} - 2\Delta l \tag{2}$$

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12h}{W}\right]^{-1/2} \tag{3}$$

$$\Delta l = 0.412h\frac{\left(\varepsilon_e + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_e - 0.258\right)\left(\frac{W}{h} + 0.8\right)} \tag{4}$$

The most popular feeding techniques used for patch antennas are coaxial probe, microstrip line, proximity coupling and aperture coupling techniques. The main advantage of microstrip feeding technique is that the feed can be etched onto the same substrate to provide a planar structure. Two-slit model is used for impedance matching because of the advantage of being able to match the impedance of the feed line to the patch without the need for any additional matching elements. Matching is easily achieved by proper control of the internal position of the slits. It provides ease of fabrication and simplicity in modeling [20]. In order to set the input impedance value of the microstrip line as 50 Ω, the width of the feed line "*f*" is calculated with the "calculate impedance" feature in the "Macros" menu of CST MWS. The length of the feed slit is calculated with the help of the following equation;

$$\begin{aligned} a = 10^{-4}\{&0.001699\varepsilon_r^7 + 0.13761\varepsilon_r^6 - 6.1783\varepsilon_r^5 + 93.187\varepsilon_r^4 \\ &- 682.69\varepsilon_r^3 + 2561.9\varepsilon_r^2 - 4043\varepsilon_r + 6697\} \end{aligned} \tag{5}$$

Here, even if the use of substrates of larger sizes increases the efficiency of the MPA, it may cause negative effects such as interference [14]. Therefore, we kept the dimensions of each 4 different substrates constant with an optimized scale, as seen in Table 1. For an accurate comparison, patch sizes are calculated and modeled for each dielectric substrate

Table 1 Substrate parameters used for the 5.65 GHz operating frequency

	FR4	Arlon AD300C	Rogers RO4003C	MİCA
Dielectric Constant (ε_r)	4.3	2.98	3.55	6
Substrate thickness (*h*)	1.2 mm	1.2 mm	1.2 mm	1.2 mm
Substrate width (Wa)	52.92 mm	52.92 mm	52.92 mm	52.92 mm
Substrate length (La)	55.56 mm	55.56 mm	55.56 mm	55.56 mm

Table 2 Optimized antenna patch parameters for 5.65 GHz center frequency

	FR4 (mm)	Arlon AD300C (mm)	Rogers RO4003C (mm)	MİCA (mm)
Microstrip Feed width (f)	2.46	2.94	2.64	2.21
Microstrip Feed length (fl)	12.13	13.23	11.85	11.36
Patch thickness	0.035	0.035	0.035	0.035
Patch width (W)	36.45	41.16	38.25	33.18
Patch length (L)	24.42	29.40	26.43	21.51
Feed-slit width (b)	0.39	0.5	0.41	0.35
Feed-slit length (a)	3.56	4	3.72	3.12

Fig. 1 Antenna model optimized for 5.65 GHz center frequency
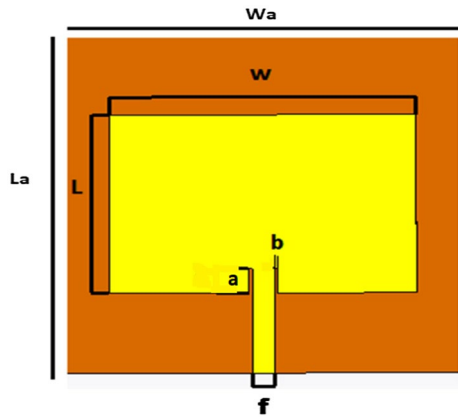
(with different permittivities) separately and then optimized for 5.65 GHz with the help of CST Studio. The magnitudes of these parameters obtained for each individual dielectric substrate are shown in Table 2. The antenna shape and size parameters are given in Fig. 1 (according to the selected values shown in Table 1).

3 Performance Analysis with Four Different Substrates

As is well known, each type of substrate used for MPA design studies has a different electrical permittivity. In this section, the effect of permittivity, which is a sensitive parameter in the efficiency of high frequency MPAs [21–23], on criteria such as bandwidth, gain and return loss is investigated. For this purpose, FR4, Arlon AD300C, Rogers RO4003C and Mica substrates are used and thus the optimal dielectric material for a 5G MPA at sub-6 GHz band is determined.

3.1 Bandwidth and Return Loss Analysis

The antenna is modeled according to the physical dimensions given in Table 2 obtained according to Table 1 for the 5.65 GHz center resonant frequency. For the performance analysis based on the dielectric coefficient, simulations are performed by changing only

the substrate materials. The frequency-based return loss curves of the MPA using FR4, Arlon AD300C, Rogers RO4003C and Mica with permittivities of 4.3, 2.98, 3.55 and 6, respectively, are given in Fig. 2.

As seen in Fig. 2a, when using FR-4 substrate with a dielectric coefficient of 4.3 and an electrical tangent loss of 0.025, the bandwidth is 90 MHz and the return loss is − 13.28 dB around.

the 5.65 GHz center frequency. The loss tangent of FR4 is higher than Arlon AD300C, Rogers RO4003C and Mica, so it is disadvantaged compared to others in terms of return loss. As a result, we can conclude that FR4 is preferable for lower frequencies than the others. In addition, as can be seen from Fig. 2c, Rogers RO4003C is the most disadvantaged in terms of bandwidth. Although Mica is close to Arlon AD300C in return loss, its bandwidth is half that of Arlon AD300C. Consequently, when the all curves are analyzed, it is seen that Arlon AD300C is the most advantageous in terms of both return loss and bandwidth.
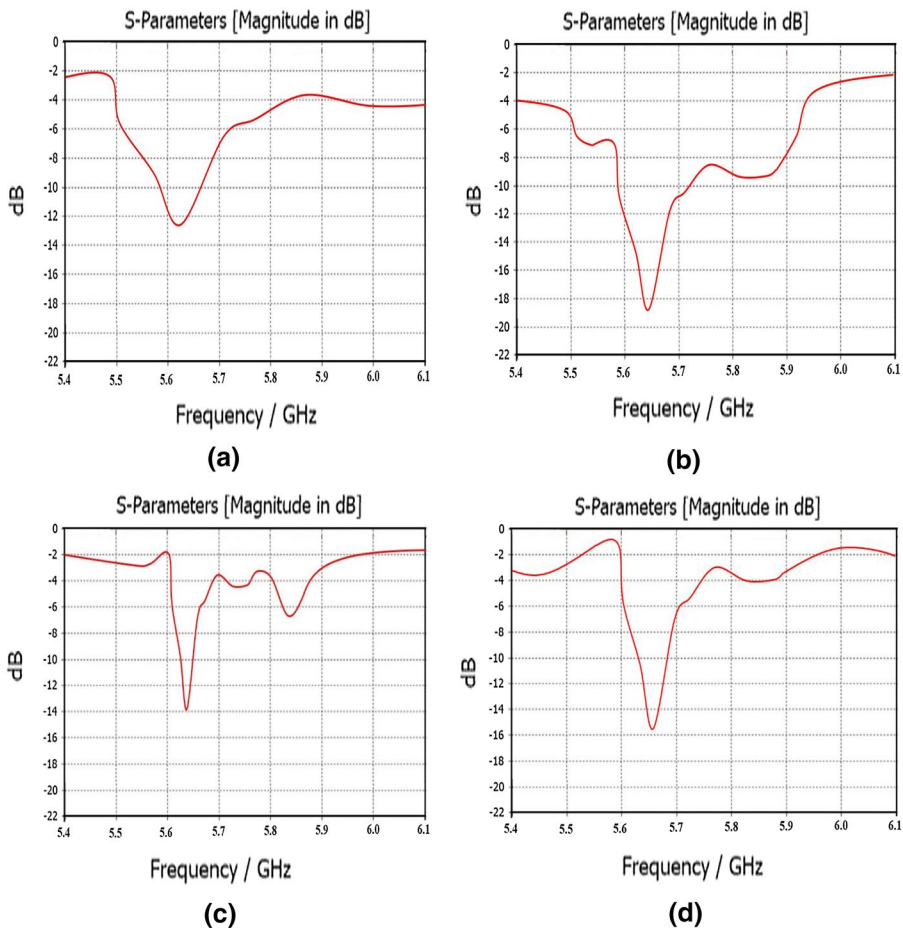

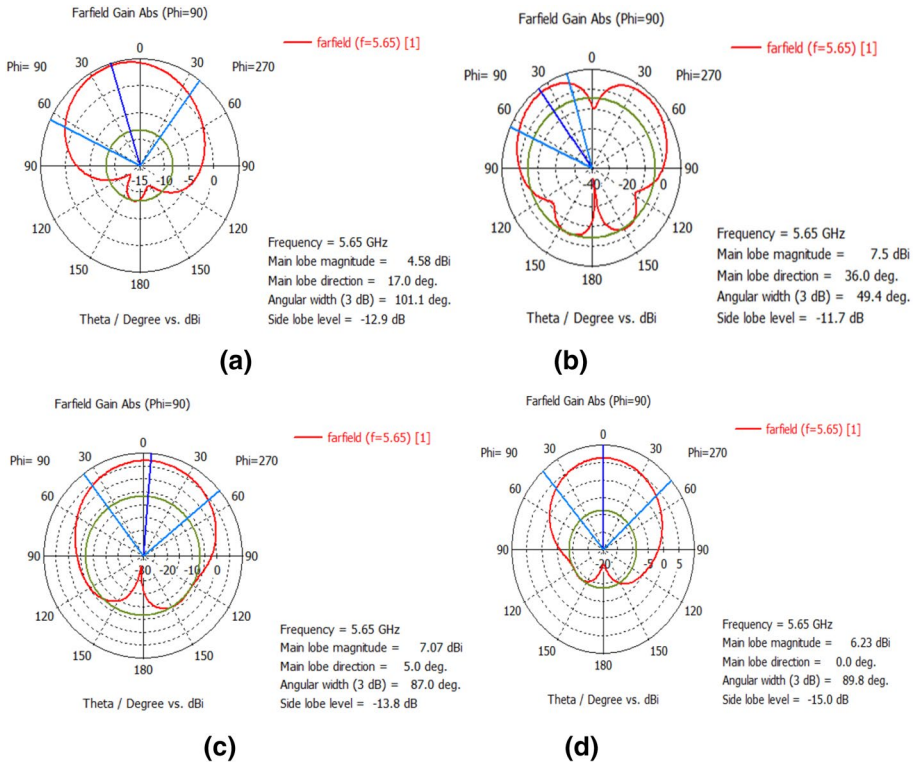**Fig. 2** Return Loss curves of the MPA with **a** FR4, **b** Arlon AD 300 C, **c** Rogers RO4003C, **d** Mica

Fig. 3 Radiation Patterns of the MPA at 5.65 GHz with **a** FR4, **b** Arlon AD 300 C, **c** Rogers RO4003C, **d** Mica

Table 3 Antenna performance simulation results according to 4 different substrates

Substrate	ε_r	tan (δ)	Band Width (< -10 dB)	Return Loss (at 5.65 GHz)	Gain (at 5.65 GHz)
FR-4	4.3	0.025	90 MHz	− 13.28 dB	4.89 dBi
Arlon AD300C	2.98	0.0023	120 MHz	− 19.44 dB	7.5 dBi
Rogers RO4003C	3.55	0.0027	30 MHz	− 13.96 dB	7.07 dBi
Mica	6	0.0003	60 MHz	− 15.65 dB	6.23 dBi

3.2 Gain Analysis

While bandwidth is about how much data is transmitted or received simultaneously, antenna gain is about the ratio of the data can be transmitted or received. Therefore, analysis of antenna gain as a performance criterion is as important as bandwidth analysis. In this section, antenna far-field radiation patterns are plotted separately for 4 different substrates according to the dimensions given in Table 2, as seen in Fig. 3.

The all results are summarized in Table 3 in order to select the most appropriate one in terms of performance criteria and to make fabrication and laboratory measurements.

As seen in Table 3, the lowest gain of 4.89 dBi is due to the high loss tangent (**tan (δ)**) of FR-4 compared to the others. It would be expected to show the highest gain since "Mica" has the lowest loss tangent, but Arlon has the highest gain since its dielectric coefficient is 2 times lower than that of Mica. In terms of gain, Rogers is closest to Arlon, but the bandwidth is at the lowest with Rogers. Considering all these situations, the most advantageous situation occurs when using Arlon AD300C in terms of both bandwidth, return loss and gain.

4 Fabrication and Measurement of Proposed 5G Antenna

In the previous section, the most suitable substrate for sub-6 GHz 5G antenna is selected among 4 different substrates with the help of CST simulation and it is revealed that Arlon AD300C is most suitable in terms of bandwidth and gain. To confirm the accuracy of this analysis and to verify the simulation results for the selected substrate, a prototype is fabricated. The bandwidth, return loss, and gain measurements of the prototype of the proposed antenna are performed at the Akdeniz University Industrial and Medical Applications Microwave Application and Research Center (EMUMAM) for 5.65 GHz center frequency. General test conditions are regulated primarily in the measurement processes. The measurements are carried out at a temperature of 25 °C and a humidity of 45%. In addition, the calibration system of the test equipment is a part of Akdeniz University EMUMAM's quality management system and it is documented in traceability to national measurement standards that realize the unit of measurement according to the International System of Units (SI). Measurements are carried out in a fully anechoic chamber. A horn antenna operating in the 1000–18,000 MHz range was used as a reference antenna in the measurement setup. A Rohde-Schwarz signal generator is used as the signal source, and an Agilent spectrum analyzer is used as a receiver.

The proposed prototype antenna is placed on an autonomous table that can rotate 360° and is 1 m away from the reference antenna. The photograph and the schematic representation of the measurement setup are given in Fig. 4. The far field radiation pattern of the proposed antenna is given in Fig. 5. The maximum gain point is marked on the graph.

Bandwidth and Return Loss (S11) measurements are performed with a vector network analyzer. Tests are carried out in the 4.5–7 GHz frequency range. Measurement setup and the results are given in Fig. 6. The minimum point is marked on the chart.

5 Results and Discussion

When using Arlon AD300 C substrate, the main lobe angle is 36˚ and the maximum gain is 7.5 dBi due to the simulation results, while it is 34.8° and 7.15 dBi, respectively, according to the measurement results. The minimums of return loss are obtained at 5.65 GHz according to both simulation and measurement results and are observed as −20.72 dB and −19.44 dB, respectively. Simulated and measured results of the bandwidth, minimum S11 and gain are given in Table 4 comparatively. Although the simulation and measurement results are in good agreement with each other, slight differences are due to fabrication error.

This study and some similar previously reported sub-6 GHz 5G antenna studies are tabulated in Table 5 with a detailed comparison.
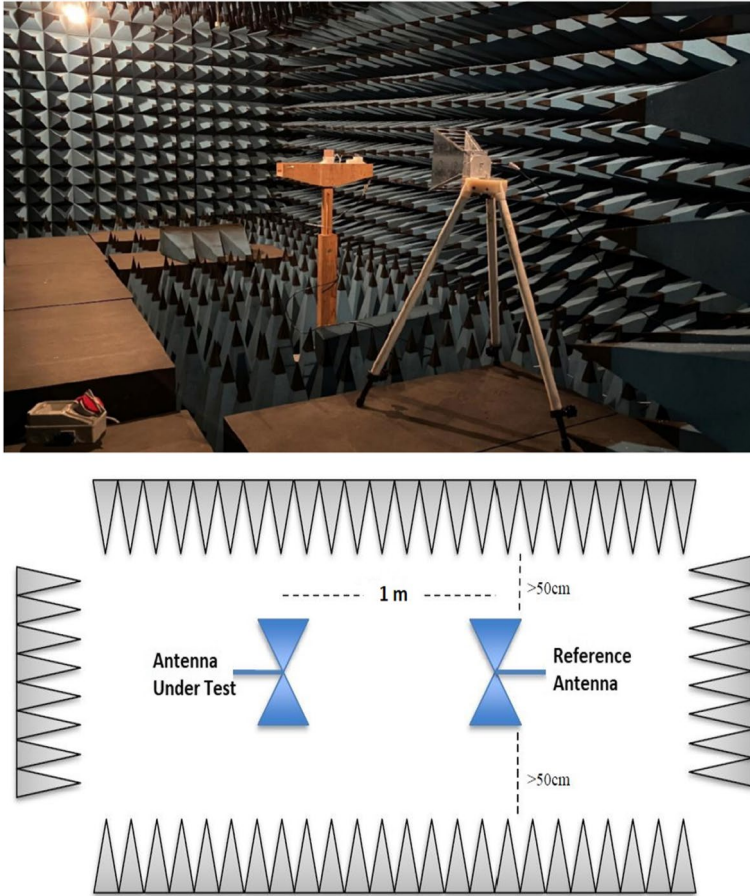
Fig. 4 The photograph and the schematic of the measurement setup

As seen in Table 5, the proposed antenna is the most advantageous in terms of gain. The closest gain is in Ref. 21, however, it is the most disadvantageous in terms of antenna profile. Although the Ref. 22 has the highest bandwidth, its gain is 62% lower than our proposed antenna. Ref. 23 seems more advantageous than the proposed antenna in terms of bandwidth. However, since it has two layers, the antenna profile is high and the gain is 30% lower than the proposed antenna. Although Ref. 20 and Ref. 24 seem more advantageous than the proposed antenna in terms of antenna profile, they are lower in terms of gain and bandwidth. As a result, the antenna presented in this study is higher than the others in terms of gain and is at an average level in terms of size and bandwidth.

Fig. 5 Far-Field Radiation Pattern of the proposed 5G Antenna at 5.65 GHZ
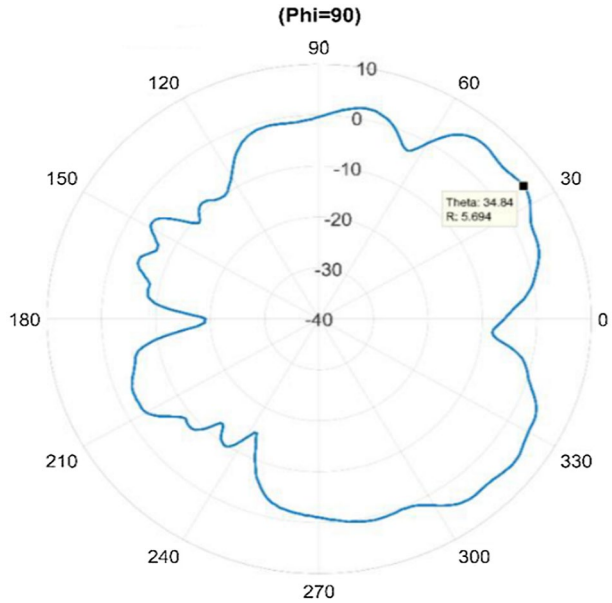
6 Conclusion

The dependence of performance criteria such as gain, efficiency and bandwidth of high frequency MPAs on the physical and electrical parameters of the dielectric substrate is much more sensitive than low frequency antennas. Hence, deciding a substrate with the most suitable permittivity for mm-wave antennas is very important in terms of antenna performance. To the best of our knowledge the appropriate substrate selection for 5G frequencies has not been investigated yet. In this study, a MPA for sub-6 GHz 5G communication is designed, simulated and performance analysis is performed according to substrate permittivity. The effects of the electrical characteristics of the proposed antenna substrate on antenna performance are investigated using 4 different dielectric materials. In order to obtain the optimum permittivity, the results are analyzed in terms of bandwidth, return loss and gain. Consequently, the highest performance of the proposed antenna for 5G communication at 5.65 MHz operating frequency is achieved with ArlonAD 300C substrate with 1.2 mm thickness, 7.15 dBi gain and 135 MHz bandwidth.
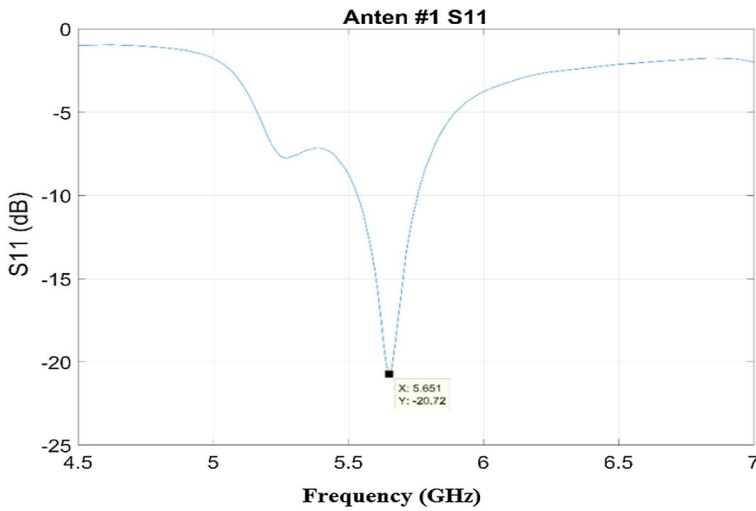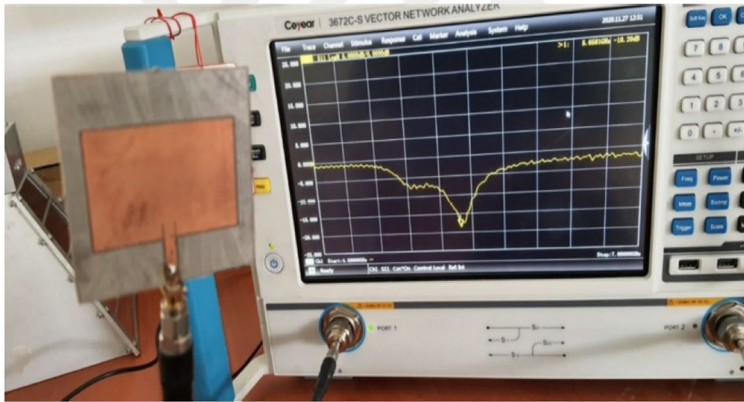
Fig. 6 Measurement setup and S11 curve of the proposed 5G antenna

Table 4 Simulation and measurement results of the proposed antenna with Arlon AD300 C

	Frequency (GHz)	Bandwidth (MHz)	Minimum S11 (dB)	Gain (dBi)
Simulation	5.65	120	− 19.44	7.50
Measurement	5.65	135	− 20.72	7.15

Table 5 Comparison with Similar Sub-6 GHz 5G Antennas

References	Freq	Substrate-$\mathcal{E}$	Ant. Size(mm)	Bandwidth	Gain
[24]	3.5 GHz	RT/duriod 5870 $\varepsilon = 2.33$	$27.5 \times 35.01 \times 1.57$	110 MHz	5.1 dBi
[25]	3.51 GHz	FR4 $\varepsilon = 4.4$	$60 \times 70 \times 1.6$	~100 MHz	6.77 dBi
[26]	5.55 GHz	FR4 $\varepsilon = 4.4$	$20 \times 30 \times 1.5$	2400 MHz	2.69 dBi
[27]	4.9 GHz	F4B-1/2 $\varepsilon = 2.6$	$45 \times 50 \times 5.1$	480 MHz	5.02 dBi
[28]	3.84 GHz	FR4 $\varepsilon = 4.4$	$30 \times 30 \times 1.6$	70 MHz	1.9 dBi
Proposed	5.65 GHz	Arlon AD300C $\varepsilon = 3.2$	$52.92 \times 55.56 \times 1.2$	135 MHZ	7.15 dBi

Data Availability The data that support the findings of this study are available from the author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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