Performance Enhancement of Microstrip Patch Antenna Based on Frequency Selective Surface Substrate for 5G Communication Applications

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Abstract—Besides the evolution of wireless communications and their across-the-board utilise due to the many advantages they provide, on other hand, microstrip antennas have been popular since ancient years. These antennas are characterized by ease of design, low cost and small size, in addition to their ability to integrate and embed with most portable applications. Despite the many benefits mentioned, these antennas suffer from many disadvantages of poor gain, narrow bandwidth, and low efficiency. In this article, a rectangular Microstrip antenna (MPA) is designed, simulated, and analysed based on the finite internal technique that is supported by the Computer Simulation Technology (CST) antenna simulation software for the 5G applications of the 28 GHz band. In order to improve the proposed MPA performance, the Frequency Selective surfaces (FSSs) are introduced. Whereas the proposed MPA is situated between two FSSs superstrates, the upper one acts as a passive bandpass filter and the lower acts as a passive bandstop filter reflecting the leakage radiation from the ground plane of the MPA.

Index Terms—Wireless communications, 5G, FSS, CST, MPA

I. INTRODUCTION

In recent years the wireless communication is especially significant and attractive for researchers' interests. Whereas, the wireless technology has evolved into an essential element of our daily life, in addition to voice communications. The wireless communication is the free-space transition of data or information from one point in a certain area to a different one without the need for the utilisation of a guided medium (e.g., wires). Through Radio Frequency (RF) and microwave, data can be sent without the utilise of the conductors. Over a well-defined channel, the information or data can be transported among different appliances over spaces varying from a few metres to the hundreds of the kilometres [1], [2].

More practically, the term “wireless” indicates the communication that carries place without the need for the wires utilisation. For wireless communications, the antennas play a vital role in the transmitter and the receiver for the purposed of completing the transmission manner when utilising wireless communication to send information such as voice or general purposes data. The antenna is can be defined as a device or transducer that is able to connect the RF energy from one area to another by using the air as a transmission media. Electromagnetic waves usually are utilised as a carrier for the transmitting of data through a channel among the transmitters and the receptors in wireless communication [3].

In the last three decades ago, there has been noticed considerable advancement in the area of the wireless communication besides the move from First-Generation (1G) toward the Fifth-Generation (4G). The principal objective of this study can be summarised as the study of the requirements that can be satisfying the ambitions of the users to acquire a higher bandwidth and lower latency. The 5G can offer high data rates, raised the Quality of Service (QoS), minimised latency, high range, high reliability, and services that are can be affordable for the unrestricted. In a general manner, there are three fundamental types for the services that are provided by the 5G technology which are the extreme mobile broadband, the massive machine type communication, and finally, the ultra-reliable low latency communication. In general, and according to many of the previous studies the basis of the 5G network is the utilising of the higher frequencies that are able to provide a large bandwidth contributing to a higher data rate, low latency, and increase in the number of the connected appliances [4]-[7].

The evolution of the mobile generation began with the 1G, which appeared as a primary generation in the 1970s. Following the 1G mobile network, the 2G network appeared in the 1990s, followed by 3G in 2001, and 4G in 2010. Currently, the following goal is to implement the 5G network, which has already begun in some countries around the world since 2020, as illustrated in Figure 1. In this generation, higher frequency bands are utilised to contribute higher rates of data while maintaining the required spectral efficiency. In contrast, is expected to achieve an actual gigabit bitrate in the millimetre-wave (mm-wave) regime. Various frequency bands have been allocated for 5G standards, including the well-known 28 and 38 GHz (O2 band) as well as 164–200 GHz (H2O band) as the license-free spectrum [8]-[11].

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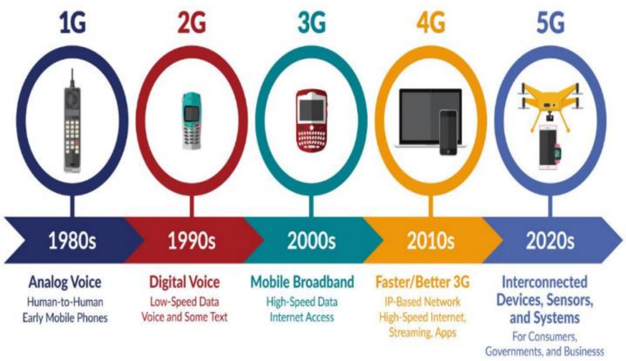

Fig. 1. Wireless communications evolution [12].

At the higher spectrum is devoid of implementations, the sub-band of 6 GHz is densely packed with them. The mm-wave spectrum is critical for weather conditions, but it is affected by atmospheric attenuation. Because the wavelength in the mm-wave has shrunk, such sensitivity can reduce signal power, reducing the experience of the utilising of the 5G technology. A pivotal segment of the wireless communication system in the mentioned range is the design of a small-sized antenna, which should be capable to supply good gain and reasonable efficiency [13], [14].

This paper's sections are organized as follows: Section 2 exemplifies the proposed methodology for designing this work. Section 3 provides a general and concise introduction to the structure as well as the characteristics of Microstrip Patch Antennas (MPAs). Section 4 Presents the principal procedure for designing and simulating the regular Microstrip Patch antenna (MPA) from the rectangular shape based on the Computer Simulation Technology (CST) antenna simulation and analysis software. Section 5 presents the necessary procedure for the designing and analysing of the Frequency Selective Surface (FSS) and embedding it with the simulated MPA. Section 6 includes the exhibition and discussion of the acquired results for the proposed MPA with the FSS substrate. Finally, Section 6 summarised the conclusion from this work.

II. Methodology

Besides the numerous advantages that are characterised by the MPAs, they are suffered from many of the issues and the most important of them is the poor and the narrow bandwidth. Many of the approaches have been introduced to enhance the mentioned issues, the FSS is one of the pioneer solutions. The FSS can be interpreted as a systematic or periodic surface that has identical two-dimensional arrays of the individual elements printed on a separated substrate. The FSS is a passive filter either a bandpass permits the signal to pass through it (i.e., acts as a second antenna fed from the traditional antenna by the radiation) or bandstop reflects the leaked radiation from the ground plane up toward the radiated patch. In this work, a rectangular MPA is designed, simulated, and analysed for the applications of 5G of the 28GHz band. In order to improve the MPA performance, a passive bandpass FSS substrate is allocated and tuned to be above the proposed MPA, as demonstrated in Figure 2.

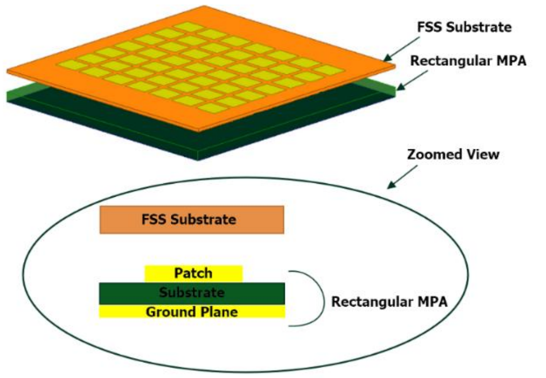

Fig. 2. General structure for the proposed work.

III. Microstrip Patch Antennas (MPAs)

Antennas are one of the considerable critical elements in wireless communications in general, as wireless communication cannot be established without them. The MPAs are one of the most important types of the antenna because of their lightweight, small size, ease of design, and low manufacturing cost. Practically, these antennas are made up of a radiated patch of one of the regular geometric shapes (for example, circular, rectangular, or square) that is placed on the face of the insulating material (named as the substrate), and the ground plane is printed from the bottom of this substrate, as illustrated in Fig. 3. The radiated patch and ground plane are typically made of a highly conductive material such as copper, gold, or other metals [15], [16].

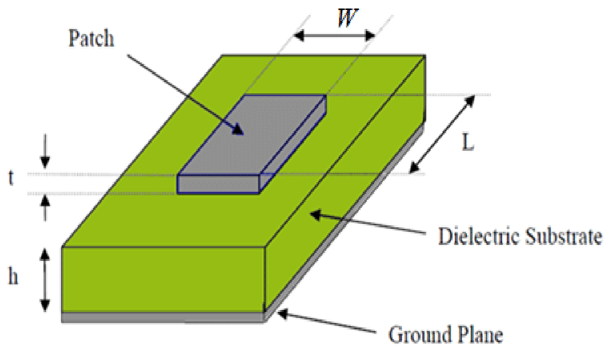

Fig. 3. Generic structure for the MPAs.

IV. MPA Design Procedure

The main point in the design of the MPA is to choose the primary parameters such as the specifications of the substrate, the operation frequency, and the input impedance which are specified in Table I.

TABLE I: SELECTED PARAMETERS FOR THE MPA DESIGN

Parameter Name	Description
Operation frequency (f_o)	28 GHz

Substrate type	Rogers RT5880
Thickness of substrate (h)	0.13 mm
Dielectric Constant (ε_r)	3
Input Impedance (R_{in})	50Ω

In order to ensure the best coupling and impedance matching the inset feeding line is used in this work. Whereas, the maximum value of the R_{in} is allocated at the patch edges and drops as nearing to the centre to be about zero. After completing the process of setting the primary parameters that we need to calculate the antenna dimensions, the MATLAB program is now used for the purpose of calculating these dimensions with the help of the equations listed below [17]-[19]:

$$W = \frac{3 \times 10^8}{2 f_o \sqrt{(\varepsilon_r + 1)0.5}} \tag{1}$$

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

$$\Delta L = 0.412h \frac{(\varepsilon_{reff} + 0.3)\left[\frac{W}{h} + 0.264\right]}{(\varepsilon_{reff} - 0.258)\left[\frac{W}{h} + 0.8\right]} \tag{3}$$

$$L = \frac{1}{2 f_o \sqrt{\varepsilon_{reff}}\sqrt{\mu\varepsilon}} - 2\Delta L \tag{4}$$

$$y_o = \frac{\cos^{-1}\left(\sqrt{\frac{Z_o}{R_{in}}}\right)}{\frac{\pi}{L}} \tag{5}$$

$$\mathrm{D} = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}} \tag{6}$$

$$W_{f_L} = \frac{2h}{\pi}\left\{\mathrm{D} - 1 - \ln(2\mathrm{D} - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left[\ln(\mathrm{D} - 1) + 0.39 - \left(\frac{0.61}{\varepsilon_r}\right)\right]\right\} \tag{7}$$

where, W is referring to the patch width, ε_{reff} is referring to the effective permittivity of the substrate, ΔL is referring to the extended in the patch length due to the fringing effect that is happen once feeding the MPA with the electric power, L is referring to the patch length, y_o is referring to the fed inset within the patch, and W_{f_L} is referring to the feed line width.

The next step, after calculating the rectangular MPA dimensions, is to start the simulation process through the utilizing of the Computer Simulation Technology (CST) simulation software, which provides the finite integration technique. Fig. 4 and Fig. 5, respectively, illustrates the simulated rectangular MPA within the CST environment, and the simulated MPA with its dimension's description.

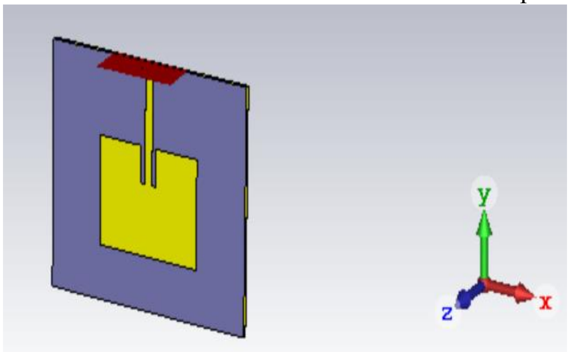

Fig. 4. Simulated rectangular MPA within CST.

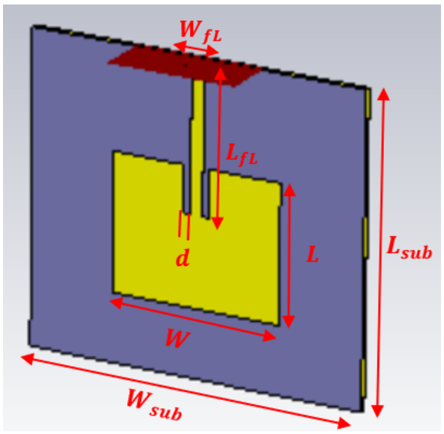

Fig. 5. Dimensions descriptions of the MPA.

After completing the simulation process within the CST environment, there is some shift in the MPA operation frequency. To solve the aforementioned problem, a parameter sweep should be used, which is accomplished by minimizing or maximizing the dimensions of the simulated MPA. After completing the simulation process within the CST environment, there is some shift in the MPA operation frequency. To solve the aforementioned problem, a parameter sweep should be used, which is accomplished by minimizing or maximizing the dimensions of the simulated MPA, as demonstrated in Table II.

TABLE II. PROPOSED MPA DIMENSIONS BEFORE AND AFTER PARAMETER SWEEP

Parameter	**Before sweep (mm)**	**After sweep (mm)**
Patch width (W)	3.7880	3.58
Patch length (L)	3.0501	3
Feed inset (y_o)	1.04	1.04
Feed width (W_{f_L})	0.3295	0.325
Feed length (L_{f_L})	3.3765	3.3765
Patch feed spacing (d)	0.15	0.15
Substrate width (W_{sub})	7.5761	7.16
Substrate length (L_{sub})	6.1002	6

V. FSS Substrate Design

For the purposes of optimizing the overall performance for the simulated MPA, the passive bandpass FSS substrate is proposed to add at the top of the MPA, the proposed FSS substrate segregated from the MPA by an air distance (i.e., air gap). It is worth noting that the use of the FSS substrate will improve the bandwidth and return losses as well as the gain. For applications of the 5G that are operated at the 28 GHz. The MPA configuration used here is directly associated with the FSS substrate to improve overall performance in a variety of MPA-related parameters. In this work, the square FSS type is designed based on Arlon AD 300 substrate with a thickness of 0.1mm and ε_r=2.75 to be operated at the f_o=28 GHz. Figure 6 illustrates the designed FSS single cell and Table III illustrates the dimensions of the proposed FSS unit cell that have been calculated based on the equations offered in [20].

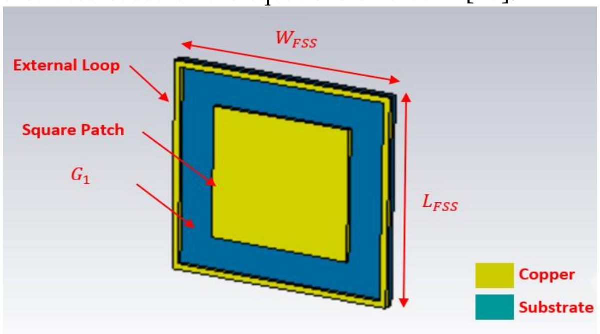

Fig. 6. Proposed FSS unit cell with its dimensions inside CST.

Table III. The Designed FSS Single Cell Dimensions

Parameter	Dimension (mm)
FSS width (W_{FSS})	3.40
FSS length (L_{FSS})	3.40
Square patch	2.140×2.140
External Loop	0.140×3.40
Gap between patch and external loop (G_1)	0.530

The proposed FSS design covers a good range which are from 27.2 to 28.78 GHz, with a return loss less -10 dB which contributes to make the transmission coefficient close to zero at the mentioned frequency range, as illustrated in Fig. 7.

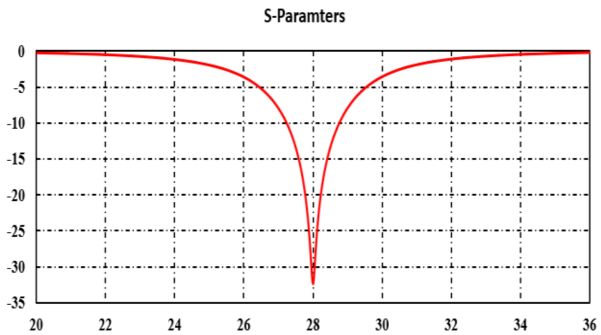

Fig. 7. Results of return loss for the proposed FSS unit cell.

Fig. 8 presents the configuration of the proposed MPA with the FSS substrate. In this work, the traditional rectangular MPA is used besides a passive bandpass FSS matrix, whereas, the FSS situated above the MPA at approximately 4.5 mm separation distance (i.e., air gap); whereas, this air gap is chosen based on the offered equations to the equations in [21]. By using this approach (i.e., FSS substrate), it can be observed that the directivity of the MPA increased as the reflection between the MPA and FSS increased.

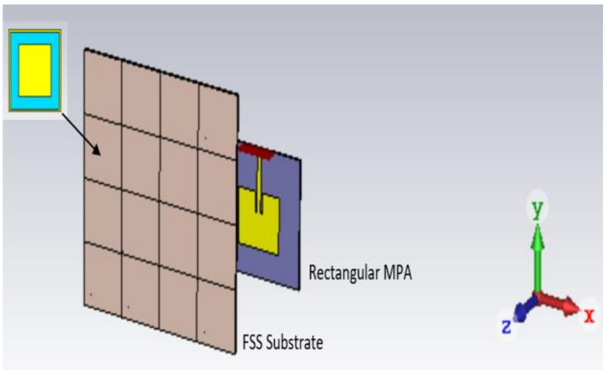

Fig. 8. Proposed MPA with FSS substrate

VI. Achieved Results and Discussion

In this part of the paper, the achieved results for the introduced antenna structure like as antenna return loss (S_{11}), antenna gain, and radiation pattern are presented as well as discussed. Before the parameter sweep procedure, it notices that the S_{11} of the simulated MPA is shifted toward the 29.21GHz. This shifting leading to make a mismatching at the required frequency (i.e., f_o=28 GHz). So that the mentioned problem is solved by applying the parameter sweep on the various of the MPA dimensions. After that the rectangular MPA operating frequency is reached to the required to the f_o=28 GHz as required. Fig. 9 illustrates the S_{11} results for the simulated antenna for the different cases, whereas it clearly observed that the S_{11} is enhanced after adding the FSS substrate.

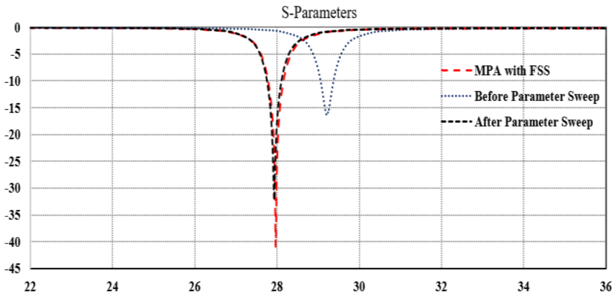

Fig. 9. The S_{11} result for the simulated antenna configuration.

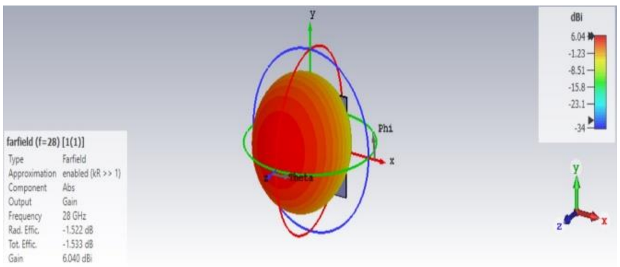

Fig. 10. Gain for the rectangular MPA.

In most cases, the MPA has a low gain problem, which researchers are attempting to improve through the use of various techniques. The reason for this is that the substrate specification affects this type of antenna. Fig. 10 and Fig. 11, respectively, illustrates the obtained gain results for the rectangular MPA before and after adding the FSS substrate.

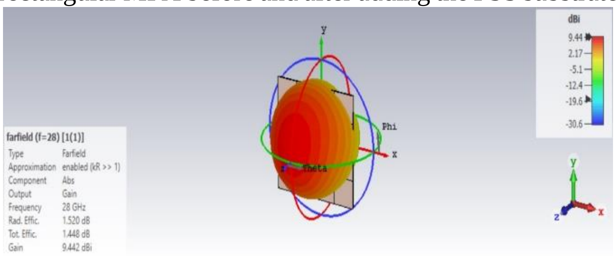

Fig. 11. Gain result for the rectangular MPA with FSS substrate.

An elementary major lobe with a moderate beam width can be utilized to describes the radiation pattern of the MPA. In utmost cases in the azimuth and elevation planes, the beamwidths are usually identical, contributing to a fairly circular beam. The beamwidths can be varied to generate or create a specific antenna design with higher or lower gain, dependent on the required implementations. Fig. 12 and Fig. 13, respectively, illustrates the beamwidth for the rectangular MPA and MPA with FSS substrate.

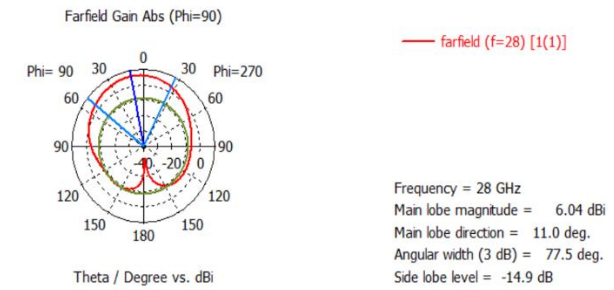

Fig.12. Obtained beamwidth result for the rectangular MPA.

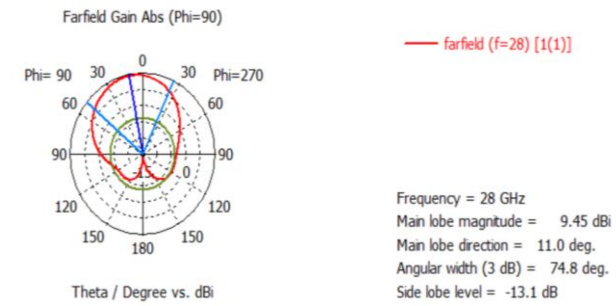

Fig. 13. Beamwidth result for the rectangular MPA with FSS substrate.

In order to compare the quality of the results obtained from the application of this approach, Table IV is developed, in which some previous work and approaches will be compared with the proposed work.

TABLE IV. RESULTS COMPARISON FOR THE PROPOSED WORK AND THE PREVIOUS STUDIES

Ref.	**Used Approach**	**S_{11} (dB)**	**BW (GHz)**	**Gain (dBi)**	**f_o (GHz)**
[22]	Rectangular MPA	-12.59	0.582	6.69	$f_o = 28$
[23]	Rectangular MPA with defected ground structure	-56.95	1.38	7.6	$f_o = 28$
[24]	Rectangular MPA array	-19.66	0.4	8.39	$f_o = 28$
This work	Rectangular MPA with FSS substrate	-40.5	0.51	9.44	$f_o = 28$

VII. CONCLUSION

The MPAs are distinguished by their small size, ease of design, low fabrication cost, ability to integrate with portable applications, and low cost. Despite these benefits, they have a number of drawbacks, the most significant of which are their limited bandwidth and low gain. In this work, a traditional rectangular MPA has been designed and simulated for the applications of 5G communications based 28GHz band by using the CST antenna simulation software. In order to optimise the overall performance for the designed MPA, the passive bandpass FSS substrate has been used and placed above the MPA with a distance of 4.5mm. By using the FSS substrate it is clear that the MPA performance was enhanced and the gain has increased by 3.4 dBi to be 9.44 dBi, on the other hand, a small limiting in the bandwidth has been observed due to the shifting of the resonant frequency toward the 28GHz as required.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

As a scientific team, we have previously chosen this topic according to the recent development in the field of wireless communications. The first author presented the proposed approach in this paper, which includes the design of an MPA intended to operate in the 28 GHz band of the fifth generation. Then the authors together chose an optimization approach based on the use of FSS. The first author has been introduced the basis of the proposed antenna and then prepared the initial version of the paper. Finally, the second author combine the research paper and made the submission via the journal online systm. As authors of this work, we declare that this is the final version of the paper.

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