Design and Analysis of a Compact Slotted Microstrip Patch Antenna for 5g Nr Mm Wave Frequency Band

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Abstract— *5G wireless communication brings us high speed data transfer between the transmitter and receiver through wireless channel. Date rate of the system will be increased when using mm wave frequency band. Although the increases in the data rate with the increases in the operating frequency leads to path loss. The antenna plays an important role in the mm wave communication; it should be compact enough to fit with other electronic circuits. The device compactness also one of the major problems while implementing the 5G mm wave communication. In this paper, a compact slotted microstrip patch antenna has been designed using Arlon Diclad 880 substrate materials, having a dielectric constant of 2.2. This substrate material is manufactured with woven fiberglass reinforced PTFE laminates which is suitable for high frequency applications. Also, it possess excellent chemical resistant, less moisture absorption and dimensionally stable. The simulated microstrip patch antenna comprises the overall size of 5×4.5×0.127 mm (without slot) and 3.5×4×0.127 mm (with slot). The simulated results show that the microstrip patch antenna has a return loss of -40.7 dB (without slot) and -40 dB (with slot respectively). Further, a 5x20 array will be developed for the massive MIMO applications.*

Index Terms— *Slotted microstrip patch antenna, 28 GHz frequency band, Compact size, 5G Wireless Communications.*

INTRODUCTION

The rapid increases in the usage of cellular devices, the increased data traffic, high speed data transfer and quality of services [11] leads to the introduction of the next generation wireless communication. 5G the next generation wireless communication will satisfy the huge data traffic and connect even more wireless devices with increased data rate [15]. The upcoming technologies and devices such as IoT communication, video streaming, live broadcasting, home automations, IP Cameras etc. that are directly connected to the internet through wireless channel. So, the next generation wireless communication should fulfill the availability and connectivity of devices with increased data rate. The high speed connectivity requires enormous bandwidth. This can be obtained with the increases in the operating frequency of the available and as well as upcoming devices. The FCC 5G spectrum are characterized into three band they are Low Band (<1GHz), Mid Band (1-6GHz) and High Band (6-100GHz mm wave communication) [13] in order to move the available and upcoming devices from 1 to 5 GHz frequency band. The devices like GPS, Wi-Fi, Bluetooth, up to 4th generation wireless communications use less than 6 GHz frequency band, this available 1 to 5 GHz frequency bands [16] getting crowded day by day and leads to interference and achieving the high data and high speed communication is not possible when using this frequency band. So, The FCC new radio frequency spectrum is useful for the 5G wireless communications. Particularly, the 28 GHz frequency bands are popular in the new radio frequency band of FCC. As this frequency band has been considered as high frequency mm band, this band can provided higher data rate to fulfill the requirements of the upcoming devices. Though, the mm wave frequency band has some advantages but it has some drawbacks too. The path loss is one of the major problems in the mm wave wireless communications [14]. To overcome these problems, a high directional antenna is required and it should be compact in size. The antenna should be easily installed alongside other electronic components of wireless devices. The antenna plays an important role in the wireless communication, without these radiating elements; the wireless communication is not possible. So, the designed antenna should be capable of handling the high data rate and should possess extremely low losses when particularly for the 5G communication because the quality of services are important aspects of the end user devices. Future devices are much more compact to handle, the antenna should be designed accordingly. Most probably the compact wireless devices uses microstrip patch antenna as a radiating elements. The microstrip patch antenna consists of radiating patch, substrate and the ground plane.

RELATED WORKS

In the existing work [1], a microstrip patch antenna was designed in the operating frequency of 28 GHz; the size of the antenna was 4.5×5.5×0.4 mm. Though the size meets the specification but the return loss is not appreciable, the return loss was -17.4dB. In the related works [2], the size of the antenna was 6.28 ×7.235×0.5 mm and, obtained return loss of -13.48 dB and the bandwidth of 847 MHz. Further [4], the microstrip patch antenna was designed with the size of 6.20×8.40×1.57 mm. Though, this work has excellent bandwidth but poor VSWR and the increased thickness of an antenna. From the analysis, it is clearly viewed that compensating one parameter will degrade the two or more parameters such as gain will be decreased if the size of an antenna reduced and the bandwidth of an antenna will be increased by increasing the substrate thickness of a microstrip patch antenna. Selecting substrates is also an important task when designing an antenna. The substrates should have extremely low dielectric loss and reduced thickness to design a compact microstrip patch antenna. The most challenging task is the size reduction of an antenna and the tradeoff should be taken to compensate other parameters such as bandwidth, gain and return loss. This paper focuses on the size reduction of a microstrip patch antenna. The antenna was designed and simulated using Arlon Diclad 880 substrate material having a dielectric constant of 2.2 and loss tangent of 0.0009. The size of the designed antenna 5×4.5×0.254 mm, which is extremely compact to fit with other electronic components. The Arlon Diclad 880 substrate material was made up of woven reinforced PTFE laminates this will provide a greater dimensional stability than non-woven reinforced PTFE laminates, it has excellent chemical resistance and electrical properties are highly uniform across frequency and water absorption percentage was 0.02.

DESIGN METHODOLOGY

A. Microstrip patch antenna

Generally, a microstrip patch antenna is called low profile antenna. It consists of a radiating patch and the top, ground plane at the bottom and the substrate material is lies between these planes. The conducting material or radiating patch may be a gold, silver or copper. Copper was used as a radiating patch in this research, when compared to silver and gold, a copper is a low profile. The substrate material was Arlon Diclad 880 has a dielectric constant of 2.2.

B. Design equations

Before going into the design, the microstrip patch antenna should meet the design considerations [12] such as dielectric substrate height should lies between $0.003\lambda \leq h \leq \lambda$, where λ is the free space wavelength. The permittivity of the substrate should lies between $2.2 \leq \varepsilon_r \leq 12$.

The following equations help to calculate the width and length of the patch.

$$W = \frac{C}{2F}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

To calculate the length of the patch, an effective dielectric constant of the substrate and ΔL should be known.

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\sqrt{1+\frac{12h}{W}} \quad (2)$$

$$\Delta L = 0.412h\,\frac{(\varepsilon_{reff}+0.8)(\frac{W}{h}+0.264)}{(\varepsilon_{reff}-0.258)(\frac{W}{h}+0.8)} \quad (3)$$

$$L = \frac{\lambda_s}{2} - 2\Delta L \quad (4)$$

$$\lambda_s = \frac{\lambda}{\sqrt{\varepsilon_{reff}}} \quad (5)$$

Where W = Width of the patch material

L = Length of the patch material

h = Height of the substrate material

ε_r = Dielectric Constant of the substrate material

ε_{reff} = Effective dielectric constant of the substrate material

ΔL = Variable length of the patch material

C = Velocity of light in free space

F = Resonant Frequency

λ_s = Wavelength of the substrate material

λ = Wavelength of the operating frequency

The below equations gives the dimensions of the substrate material:

$$Ls = L+6h \quad (6)$$

$$Ws = W+6h \quad (7)$$

Where Ls = Length of the substrate material,

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Ws = Width of the substrate material,

L = Length of the patch material and

H = Height of the substrate material.

A. Feeding structure

Choosing an appropriate feeding will enhance the performance of an antenna. In feeding, contact and non-contact methods exist. In contact feeding such as coaxial and microstrip line feeding are most popular whereas in non-contacting feeding, aperture coupled and proximity coupled feeding techniques are available in the existing system. This research mainly focuses on size reduction. So, a direct feeding technique is used in the design. In existing model, a quarter wave transformer matching network was used for the feeding but it is not compact as it increases the length of the antenna for perfect matching. So, an inset feeding is preferred in this research as it reduces the size of the microstrip patch antenna design.

Antenna Design Parameters

B. Antenna Design 1

The proposed microstrip antenna is operating under 28 GHz frequency band. The theoretical calculation and optimized values of the proposed microstrip patch antenna were listed in the table I and table II.

Table I. Calculated Dimension of the Proposed Antenna

Parameters	Dimensions (mm)
Ground plane length (Lg)	4.9931
Ground plane Width (Wg)	5.7591
Patch length (L)	3.469
Patch Width (W)	4.235
Substrate length (Ls)	4.9931
Substrate Width (Ws)	5.7591
Feed line width (Wf)	0.39

Table II. Optimized Dimension of the Proposed Antenna

Parameters	Dimensions (mm)
Ground plane length (Lg)	5
Ground plane Width (Wg)	4.5
Patch length (L)	3.5
Patch Width (W)	4.2351
Substrate length (Ls)	5
Substrate width (Ws)	4.5
Feed line Insertion (Fi)	0.94
Feed line width (Wf)	0.3913

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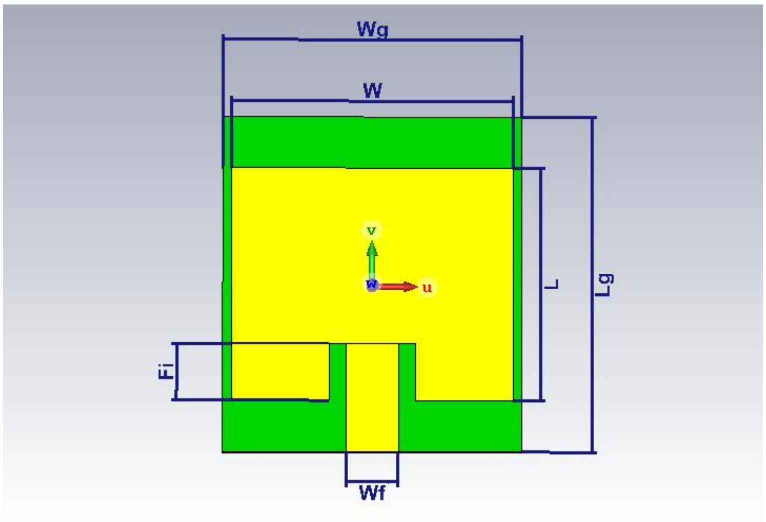

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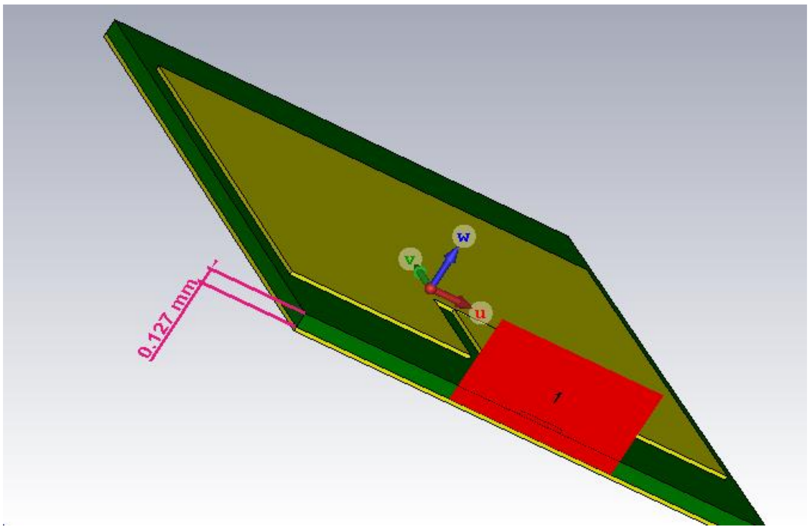

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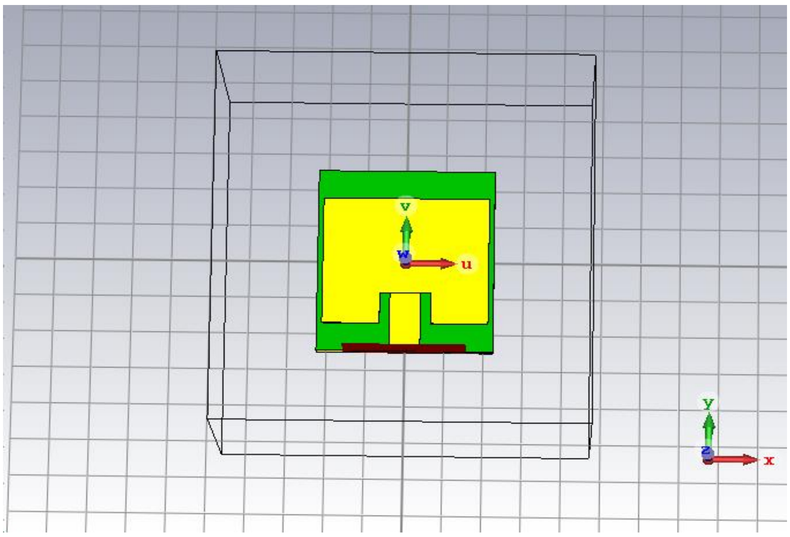

(c)

Fig. 1 Configuration of proposed antenna (a) Geometry of the proposed antenna (b) 3D view (c) Simulation environment

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The Figure 1 (a) shows the proposed microstrip patch antenna which consists of overall geometry, figure 1(b) shows the 3 Dimensional view and figure 1 (c) shows the Simulation environment of a proposed antenna. This will easily help to identify the dimensional that were displayed in the table I. The proposed antenna was designed and simulated using CST Studio suite 2019 Simulation tools.

Table III. Calculated Dimension of the Proposed slotted Antenna

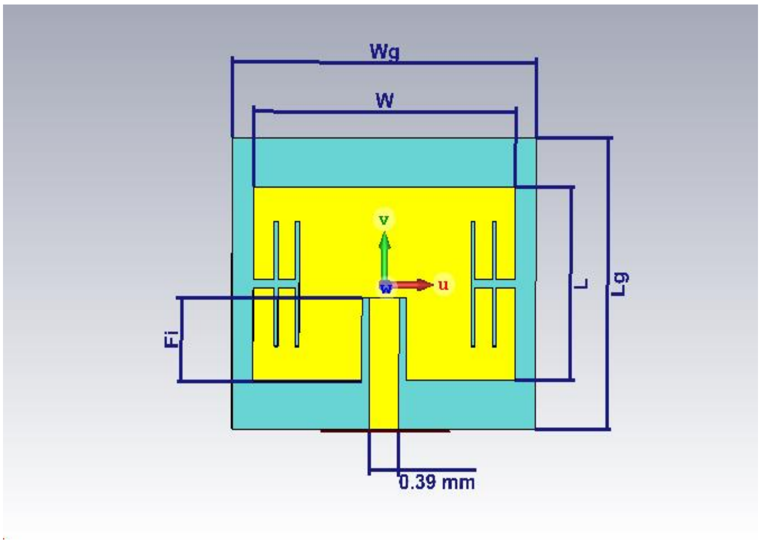
Parameters	Dimensions (mm)
Ground plane length (Lg)	4.9931
Ground plane Width (Wg)	5.7591
Patch length (L)	3.469
Patch Width (W)	4.235
Substrate length (Ls)	4.9931
Substrate Width (Ws)	5.7591
Feed line width (Wf)	0.39

Table IV. Optimized Dimension of the Proposed slotted Antenna

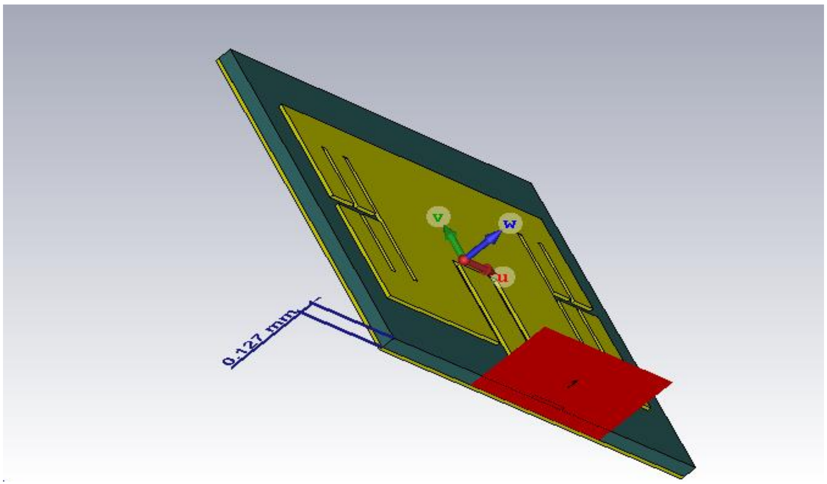
Parameters	Dimensions (mm)
Ground plane length (Lg)	3.5
Ground plane Width (Wg)	4
Patch length (L)	2.35
Patch Width (W)	3.45
Substrate length (Ls)	3.5
Substrate width (Ws)	4
Feed line Insertion (Fi)	1
Feed line width (Wf)	0.3913

A. Antenna Design 2

The proposed slotted microstrip antenna is operating under 28 GHz frequency band. The theoretical calculation and optimized values of the proposed microstrip patch antenna were listed in the table III and table IV.The Figure 2 (a) shows the proposed microstrip patch antenna which consists of overall geometry, figure 2 (b) shows the 3 Dimensional view and figure 2 (c) shows the Simulation environment of a proposed antenna. This will easily help to identify the dimensional that were displayed in the table I. The proposed antenna was designed and simulated using CST Studio suite 2019 Simulation tools.



(a)



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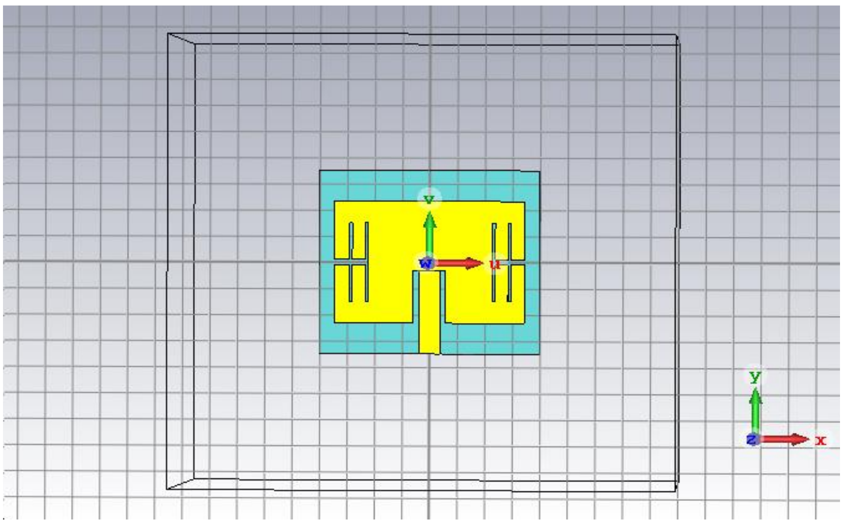

(c)

Fig. 2 Configuration of proposed slotted antenna (a) Geometry of the proposed slotted antenna (b) 3D view (c) Simulation environment

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Simulated Results and Discussions

B. Return loss

The return loss is one of the important parameters while designing a microstrip patch antenna. The accepted value of return loss should be less than -10 dB, which means 90 percent of the incident power will be accepted by the antenna to radiate and 10 percent of the power will be reflected back due to some discontinuity or miss matches in the design. The proposed antenna has a very good return loss of -40.7 dB without slot and 40 dB with slot respectively. The figure 3 (a) shows the return loss plot of the proposed antenna and figure 3 (b) shows the return loss plot of the proposed slotted microstrip antenna.

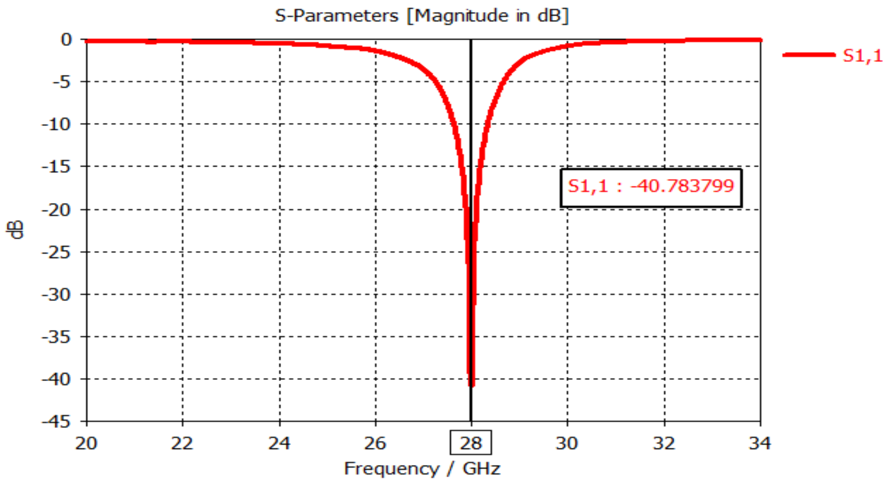

Fig. 3 (a) Return loss plot of the proposed antenna

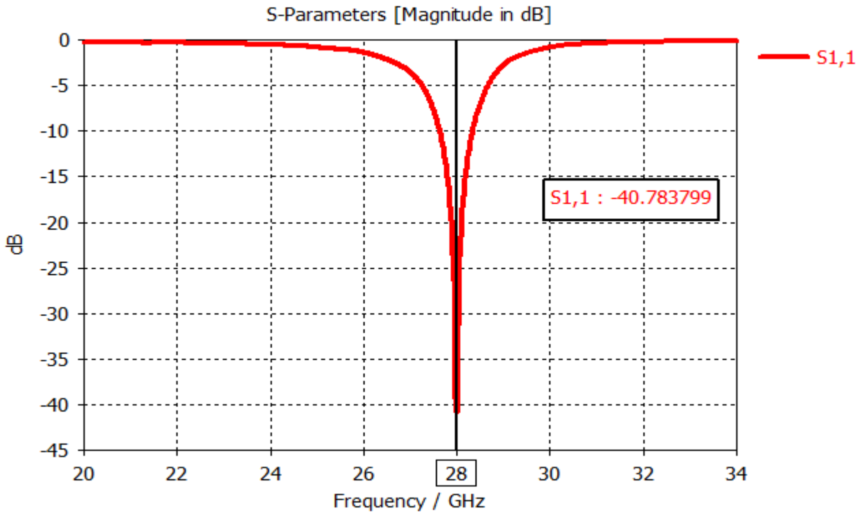

Fig. 3 (b) Return loss plot of the proposed Slotted antenna

C. VSWR Plot

The Voltage standing wave ratio and the return loss will measure the reflected signal during transmission where VSWR measures the ratio of voltage applied to the reflected voltage. The proposed antenna has a better VSWR value of 1.0184428 at resonance

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frequency of 28 GHz 27.94 GHz without slot and 1.0200072 at resonance frequency of 28 GHz 27.94 GHz with slot respectively. The figure 4 (a) shows the VSWR plot of the proposed antenna design and figure 4 (b) shows the VSWR plot of the proposed slotted antenna

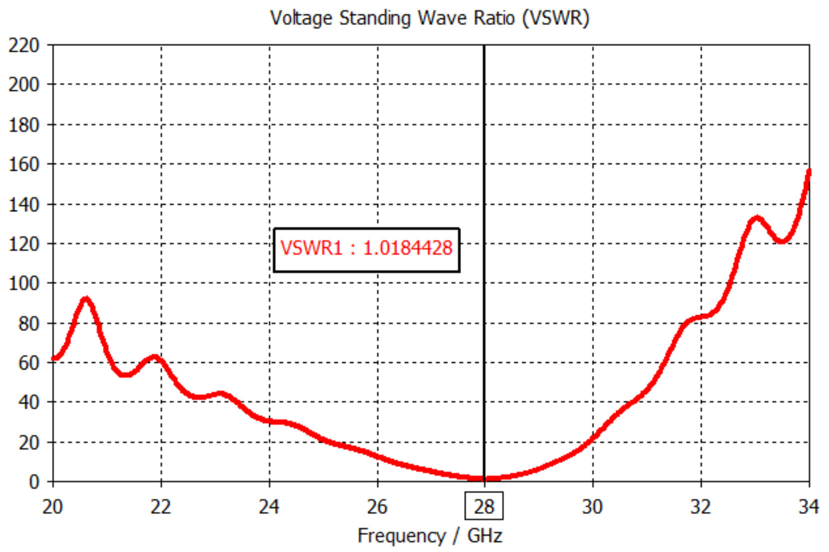

Fig. 4 (a) Voltage Standing Wave Ratio of the proposed antenna

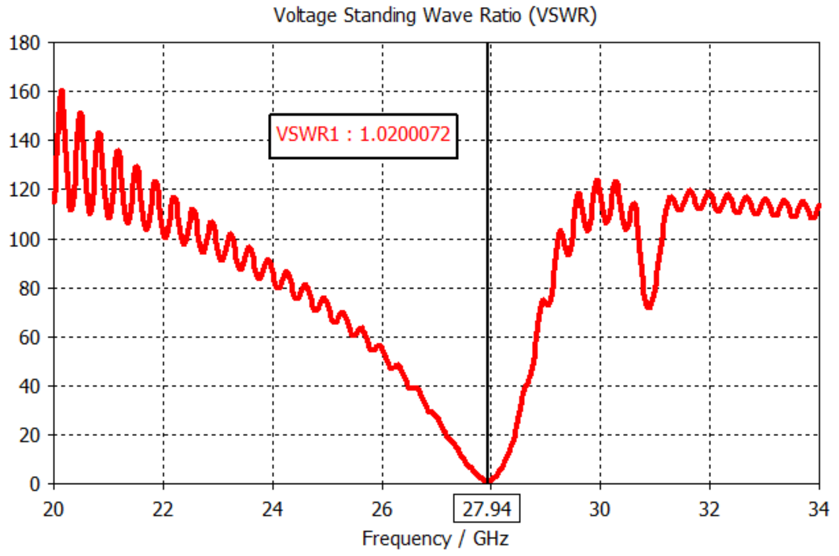

Fig. 4 (b) Voltage Standing Wave Ratio of the proposed slotted antenna

D. Bandwidth

Bandwidth is also one of the important antenna parameter. It shows the range of frequency over which the designed antenna can properly radiate or receive the electromagnetic energy. The bandwidth of the microstrip patch antenna is typically expresses in terms of VSWR. The VSWR is selected as the parameter for the bandwidth identification and thus this bandwidth is called the impedance bandwidth. Figure 5 (a) shows that the proposed microstrip patch antenna has the 10dB impedance bandwidth ranging from 27.6 to 28.3 GHz and Figure 5 (b)

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shows that the proposed slotted microstrip patch antenna has the 10 dB impedance bandwidth ranging from 27.8 to 28.025 GHz.

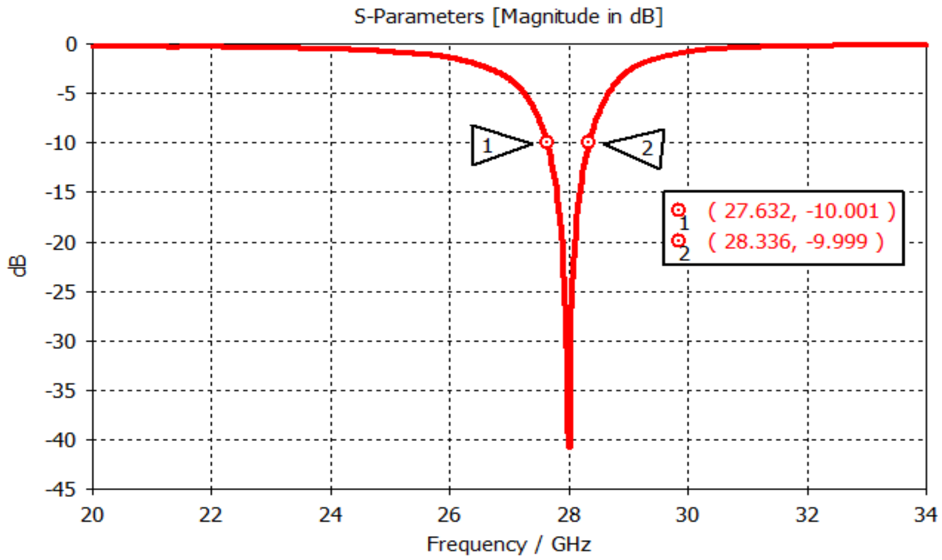

Fig. 5 (a) Bandwidth plot of the proposed antenna

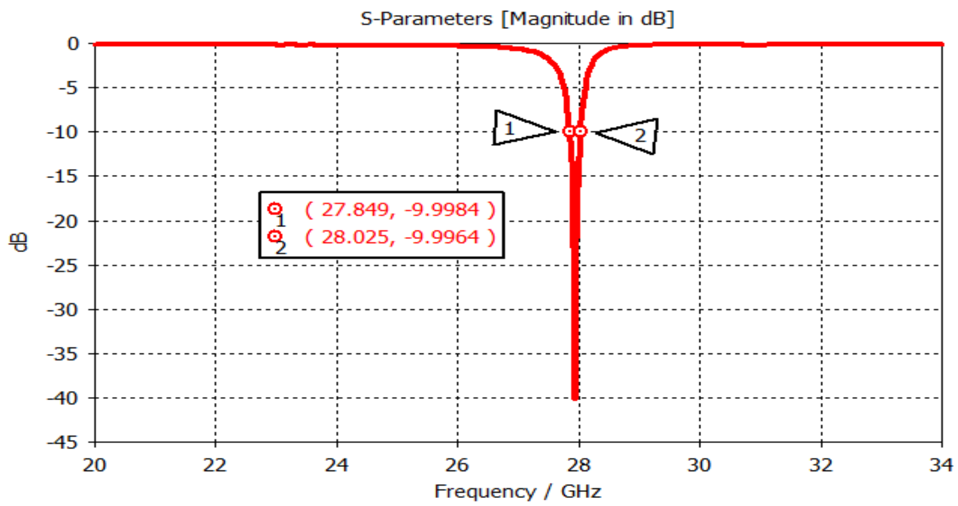

Fig. 5 (b) Bandwidth plot of the proposed slotted antenna

E. Gain

The antenna gain radiation pattern shows that the antenna radiate more or less in any direction. Typically, is the overall performance of an antenna, which is the combination of antenna directivity and efficiency. The figure 6 shows the 2D and 3D gain radiation pattern of the proposed microstrip patch antenna, it has a gain of 6.156 dBi and the Half Power Beam Width of 84.4° along with the side lobe level of -16.1 dB and the figure 7 shows the 2D and 3D gain radiation pattern of the proposed microstrip patch antenna, it has a gain of 1.812 dBi and the Half Power Beam Width of 97.7° along with the side lobe level of -6 dB respectively.

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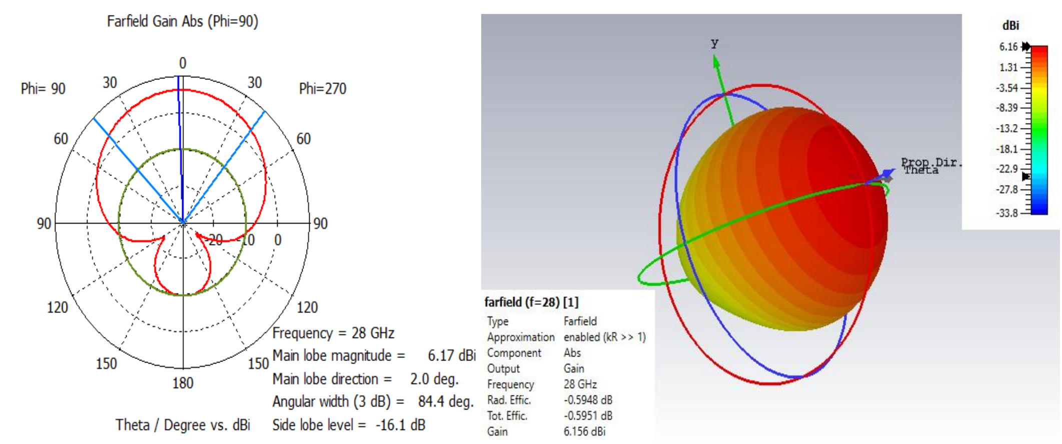
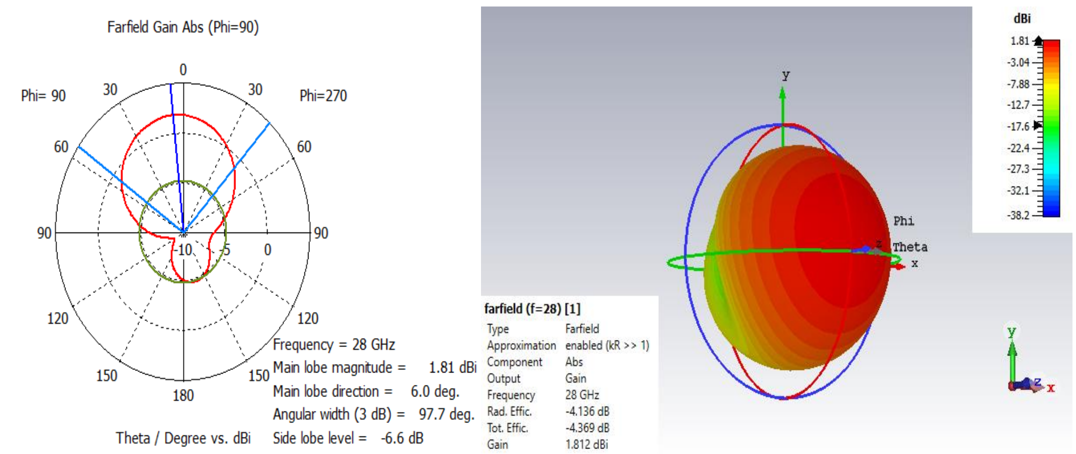


(a) (b)

Fig. 6 (a) 2D gain polar plot of the proposed antenna (b) 3D gain radiation pattern of the proposed antenna



(a) (b)

Fig. 7 (a) 2D gain polar plot of the proposed slotted antenna (b) 3D gain radiation pattern of the proposed slotted antenna

F. Directivity

Directivity is also one of the important antenna parameters. It is a measure of how the directional of an antenna is to be. The capacity of an antenna to focus its power or beam in a particular direction or receives the electromagnetic energy. The figure 8 shows the 2D and 3D gain radiation pattern of the proposed microstrip patch antenna, it has a gain of 6.751 dBi and the Half Power Beam Width of 84.4° along with the side lobe level of -16.1 dB and figure 9 shows the 2D and 3D gain radiation pattern of the proposed microstrip patch antenna, it has a gain of 5.948 dBi and the Half Power Beam Width of 97.7° along with the side lobe level of -6.6 dB.

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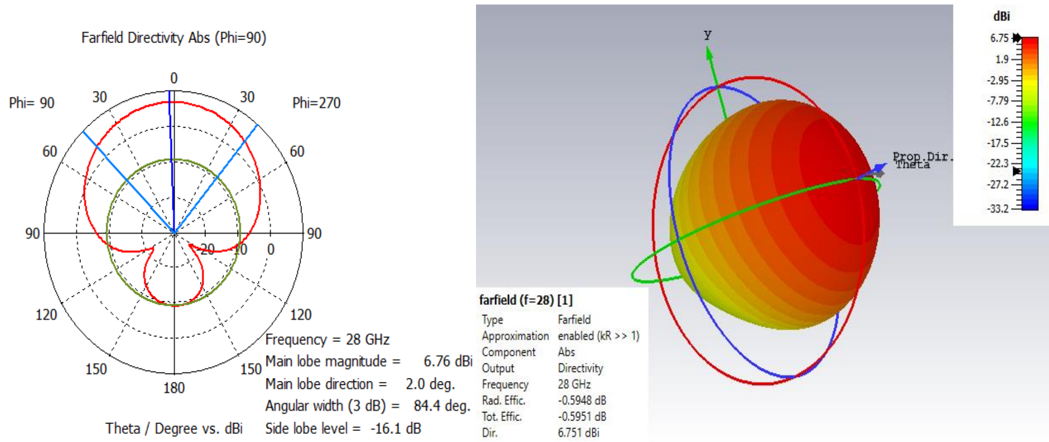
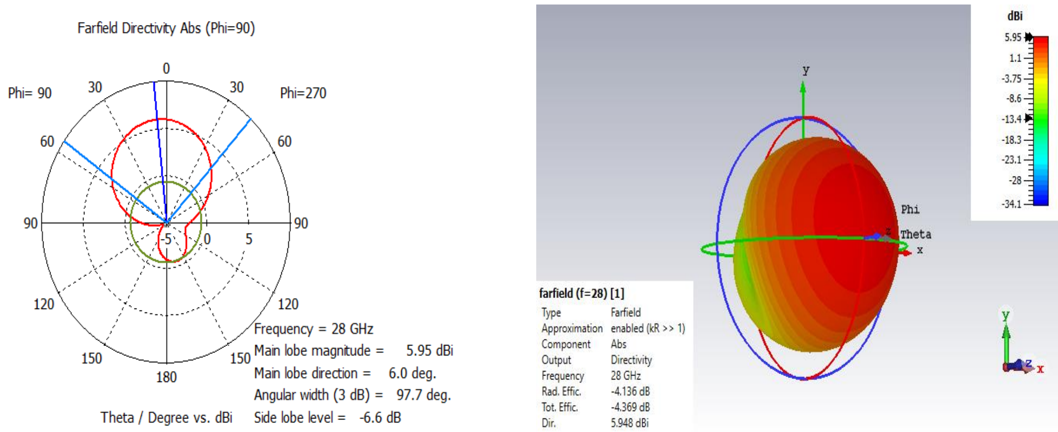


(a) (b)

Fig. 8 (a) 2D Directivity polar plot of the proposed antenna (b) 3D Directivity radiation pattern of the proposed antenna



(a) (b)

Fig. 9 (a) 2D Directivity polar plot of the proposed slotted antenna (b) 3D Directivity radiation pattern of the proposed slotted antenna

G. Surface current

The figure 10 (a) shows the surface current of the proposed microstrip patch antenna and figure (b) 10 shows the surface current of the proposed slotted microstrip patch antenna.

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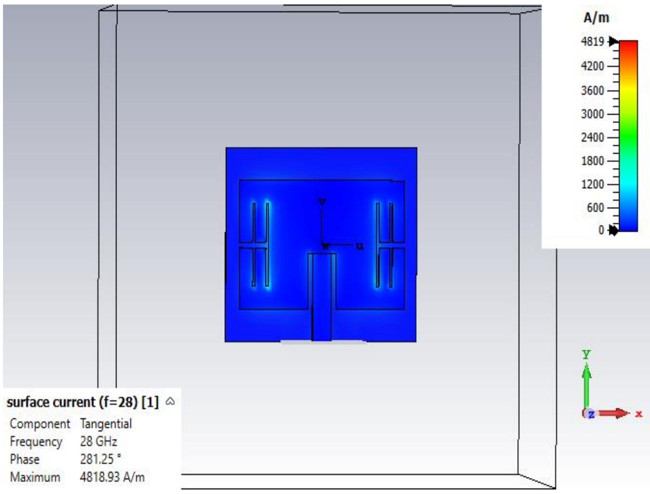

Fig. 10 (a) Surface Current Distribution of the proposed antenna

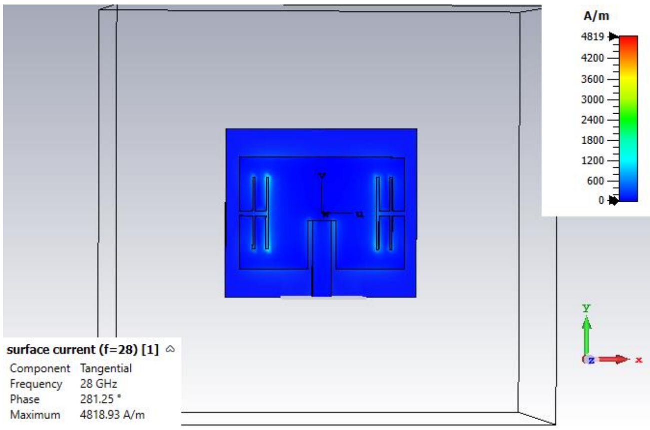

Fig. 10 (b) Surface Current Distribution of the proposed slotted antenna

H. Smith Chart

The figure 11 shows the impedance and the admittance smith chart of the proposed microstrip antenna and figure 12 shows the impedance and the admittance smith chart of the proposed slotted microstrip antenna

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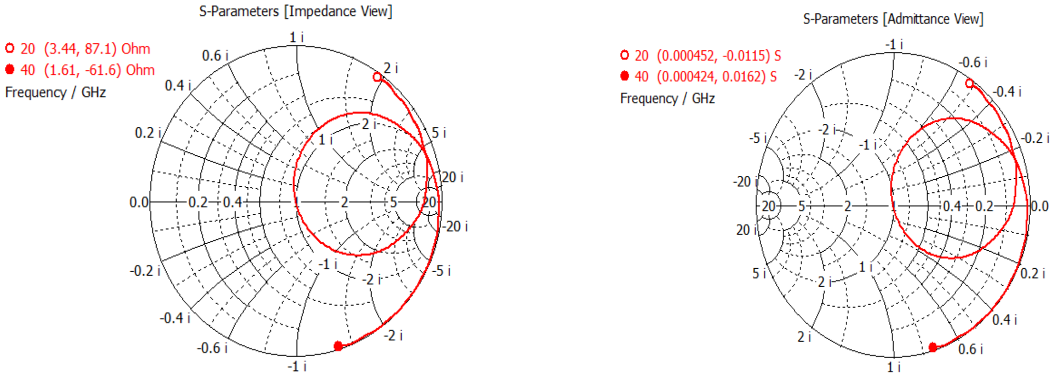
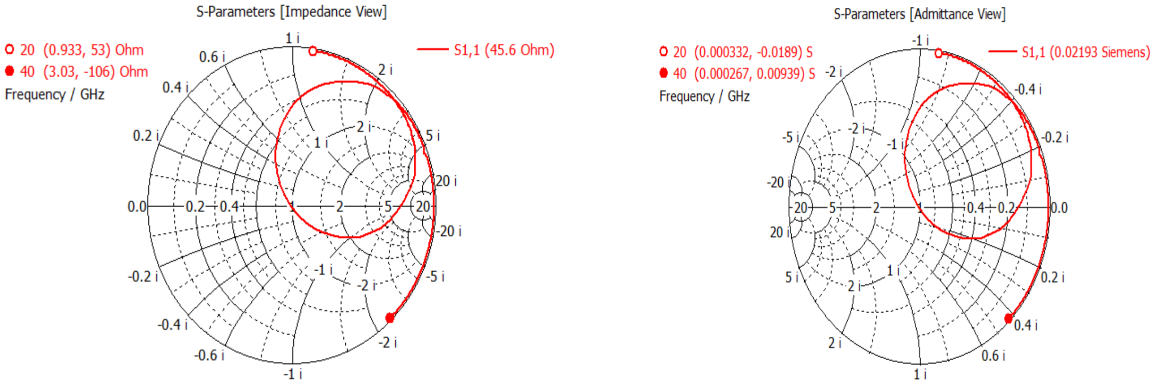


(a) (b)

Fig. 11 (a) Impedance chart of the proposed antenna (b) Admittance chart of the proposed antenna



(a) (b)

Fig. 12 (a) Impedance chart of the slotted antenna (b) Admittance chart of the slotted antenna

RESULT COMPARISONS

The table III and IV shows the overall simulated results of the proposed microstrip patch antenna and the comparison of the proposed antenna with the published result. This comparisons shows that the proposed microstrip patch antenna has overall dimension of 5×4.5×0.254 mm, which is suitable for the future generation compact wireless devices.

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Table V Overall simulated results

Parameter	Without slot	With slot
Dimensions (mm)	5×4.5×0.127	3.5×4×0.127
Resonant frequency (GHz)	28	27.94
Return loss (dB)	-40.7	-40
VSWR	1.0184428	1.0200072
Bandwidth (GHz)	0.7	0.5
Gain (dBi)	6.156	1.812
Directivity (dBi)	6.751	5.948

Table VI Comparison of the proposed antenna with the published work

Published antenna	Dimensions(mm)	Return loss (dB)	Gain (dBi)	Bandwidth (GHz)
[1]	4.5×5.5×0.4	-17.4	6.72	1.1
[2]	6.285×7.235×0.5	-13.48	6.63	0.847
[3]	8.5×8.5×0.325	-54.4	7.55	1.062
[4]	6.20×8.40×1.57	-22.5	5.06	5.57
[5]	7×7×0.8	-27.79	6.59	2.62
[6]	7×7×0.8	-39.3	6.37	2.48
[7]	14.71×7.9×0.254	-12.59	6.69	0.582
[8]	10×8×1.6	-40.14	5.29	14.674
[9]	8.5×8.5×0.244	-38.86	7.587	1.046
[10]	7.14×8.52×0.12	-36.179	6.72	0.463
This work Without slot	**5×4.5×0.127**	**-40.7**	**6.156**	**0.7**
This work with slot	**3.5×4×0.127**	**-40**	**1.812**	**0.5**

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CONCLUSION

This research work mainly focuses on the design of compact microstrip patch antenna for future generation wireless communications. To reduce the size of an antenna, a trade off should be made with other parameters such as impedance bandwidth, the gain of an antenna and the directivity. The size of an antenna will be reduced by increasing the substrate thickness, it will increase the impedance bandwidth but it will decrease the antenna gain and directivity. Also the volume of an antenna should be considered. This work gives the overall compact size of overall dimension of 5×4.5×0.127 mm (without slot) and 3.5×4×0.127 mm (with slot), which is suitable for the future generation compact wireless devices and IoT applications. Further, an array of an antenna will be developed for the 5G MIMO (Multiple Input and Multiple Output), Beamforming and Small cell technologies. The 5G wireless communication widely depends on the MIMO antennas.

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