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DGS Based CP Antenna for 5G Communication with Harmonic

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Defected ground structure (DGS), harmonic suppression, circular polarization (CP), truncate

Abstract

Higher harmonics in antennas contribute to negative effects on antenna performance such as interference, radiation pattern distortion, impedance mismatch and increased complexity in design, commonly occurring in RF communication systems caused by the non-uniformity of the antenna structure and the presence of parasitic elements. Therefore, a patch antenna operating at 3.65GHz for 5G mobile communication that incorporates techniques to suppress unwanted higher harmonics is presented. The antenna design employs a basic rectangular patch antenna with an inset feed technique to enhance the S11 parameters at the resonant frequency. Additionally, two dumbbell defected ground structures (DGS) are employed to minimize the higher modes of harmonic distortion. To transform the antenna into a circular polarized (CP) antenna, two truncated corners and a cross slot perpendicular to the middle of the patch are introduced. The proposed antenna is able to suppress unwanted harmonics at higher resonances, demonstrating its effectiveness in mitigating harmonic distortion.

1. Introduction

Unwanted harmonic signals result can cause significant performance degradation in wireless communication systems. When an antenna is excited with an electrical signal, it generates a radiated electromagnetic field that consists of a fundamental frequency, also known as the first harmonic, as well as higher harmonics. Higher harmonics in antennas refer to the additional frequencies that are integer multiples of the fundamental frequency. These higher harmonics can have both positive and negative effects on the performance of an antenna system. Unwanted higher harmonic can result in spectral regrowth, which can cause an interference with other communication systems and violate regulatory requirements. Higher harmonics also can distort the radiation pattern of an antenna, leading to undesirable changes in the directionality or coverage area of the antenna. This can result in reduced performance in certain directions, leading to decreased signal strength or coverage in certain areas. [1-2]. To address this issue, various techniques have been developed, including the use of circular polarization antennas, defected ground structures (DGS), and harmonic suppression techniques [3-5].

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Harmonic suppression techniques are used in RF communication systems to reduce unwanted harmonic signals. These techniques can be passive or active, and they can include filters, baluns, and impedance matching networks [6-8]. Passive harmonic suppression techniques are typically implemented as passive components in the RF circuitry, and they can provide effective harmonic suppression at low cost. Active harmonic suppression techniques, on the other hand, require additional circuitry and can be more expensive, but they can provide better harmonic suppression at higher frequencies [9].

Circular polarization antennas (CPAs) are used in wireless communication systems because they offer several advantages over linear polarization antennas. One of the primary advantages of CPAs is that they reduce the impact of multipath fading, which is a common problem in wireless communication systems. CPAs also offer better coverage and higher gain than linear polarization antennas, which can help to reduce the impact of unwanted harmonic signals. Moreover, CPAs can offer better polarization diversity, which can improve the overall system performance.

Research paper by N. Islam and M. Islam proposed a new design for a circularly polarized antenna with harmonic suppression characteristics using a fractal Koch curve patch antenna with a square slot to achieve dual-band circular polarization and high levels of harmonic suppression [10]. In 2020, a study by M. U. Rehman et al. investigated the use of CPAs in the design of a compact, high-gain, and wideband antenna [11]. The authors proposed a novel design that incorporated a circular patch with two diagonal slots to achieve circular polarization.

Another research paper by Y. Wei et al. proposed a new design of a circularly polarized antenna with harmonic suppression capability by implementing microstrip-fed circular patch antenna with a rectangular slot and a meandered ground plane to achieve circular polarization and harmonic suppression simultaneously [12].

Defected ground structures (DGS) are used in RF communication systems to improve antenna performance and reduce unwanted harmonic signals [13-14]. DGS are typically implemented as a patterned metal layer on the ground plane of a microstrip antenna, and they can provide improved impedance matching, increased bandwidth, and reduced surface wave radiation [15-16]. DGS can also be used to suppress unwanted harmonic signals by providing a filtering effect at the resonance frequency, as long as reduces the overall size of the antenna, which can be particularly useful in portable or mobile communication systems [17-19].

Harmonic distortion is a significant problem in wireless communication systems, and it can result in reduced performance and interference with other systems. Circular polarization antennas, defected ground structures, and harmonic suppression techniques are all useful tools for reducing unwanted harmonic signals and improving the performance of wireless communication systems. This paper proposed a design of patch antenna, in combination of discussed techniques to suppress the unwanted harmonics and achieve the desired level of performance, so that they can be particularly useful in high-power or high frequency applications.

2. Antenna Design with Higher Harmonic Suppression

A microstrip patch antenna is a type of antenna that is widely used in various applications because of its low profile, light weight, and ease of fabrication. The parameters involved in the dimensions of the antenna patch are defined as follows: *W* represents the width of the patch, *L* signifies its length, and *h* pertains to the height of the dielectric substrate. These dimensions are determined through specific mathematical formulations. The width, denoted as *W*, is computed using equation (1).

$$W = \frac{c}{2f\sqrt{\frac{(\varepsilon_{\mathrm{r}} + 1)}{2}}} \tag{1}$$

where c is the speed of light (3×10^{8} ms^{-1}), f is the resonance frequency of the desired antenna and ε_r is the dielectric constant of the substrate. L (length) can be expressed as equation (2) to (5).

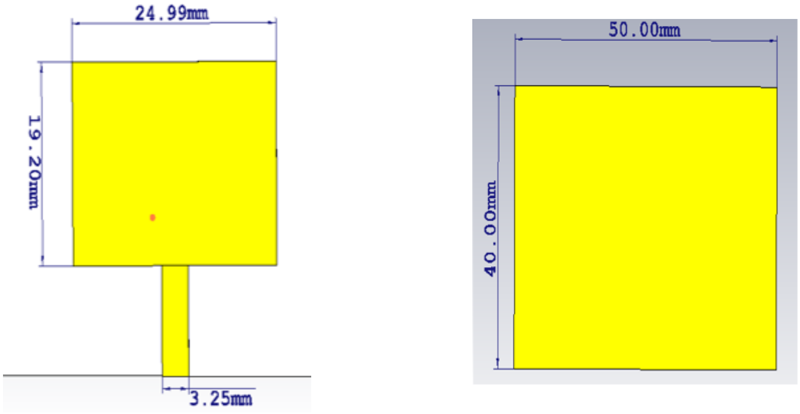
$$L = L_{eff} - \Delta \mathrm{L} \tag{2}$$

$$L_{eff} = \frac{c}{2f\sqrt{\varepsilon_{\mathrm{eff}}}} \tag{3}$$

$$\Delta L = 0.412\mathrm{h}\frac{(\varepsilon_{\mathrm{eff}} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{\mathrm{eff}} - 0.258)(\frac{W}{h} + 0.8)} \tag{4}$$

$$\varepsilon_r = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\left[1 + 12\frac{h}{W}\right]}^{-\frac{1}{2}} \tag{5}$$

In the design process, it is important to ensure that the antenna resonates at the desired frequency. However, in some cases, the antenna may have higher modes of harmonics at frequencies other than the desired resonance frequency. This can result in unwanted interference and reduced antenna performance. Fig. 1 is an illustration of the initial microstrip patch antenna designs, along with the parameters used in the design. The parameters in this design include the length, width, and substrate thickness of the patch, the feed position, and the ground plane size.



(a) **(b)**

Fig. 1 *Initial square patch antenna (a) top; (b) bottom view*

Fig. 2 shows the higher modes of harmonics of the initial microstrip patch antenna design at frequencies of 5.51GHz, 9.29GHz, and 10.459GHz. These harmonics are caused by the non-uniformity of the antenna structure and the presence of parasitic elements. To eliminate these harmonics, various techniques can be employed such as adjusting the antenna dimensions, changing the substrate material, or using filtering techniques. It is important to eliminate these harmonics to ensure proper antenna performance.

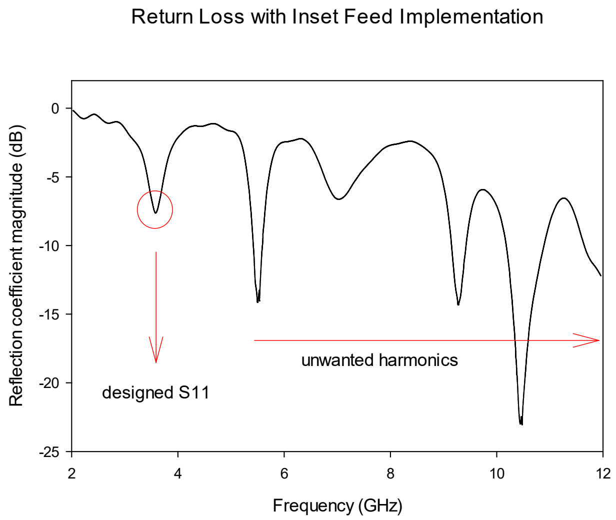
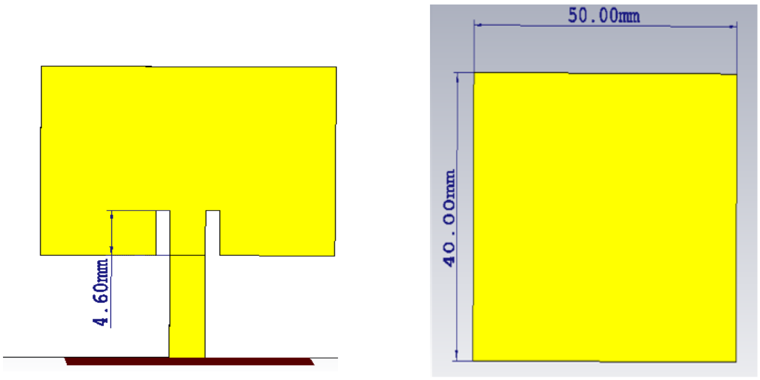


Fig. 2 *S_{11} of initial antenna design*

The application of an inset feed technique can enhance the antenna's bandwidth and S_{11} performance. This is attributed to the improvement in the antenna's impedance matching, which results in a better S_{11} response. A parametric investigation was conducted by varying the inset feed length from 5.1mm to 4.1mm, as illustrated in Fig. 3, to identify the optimal length that yields favorable S_{11} parameters. The S_{11} responses at each length were evaluated, and 4.6mm was determined to offer a superior return loss at the resonant frequency and reduced S_{11} for higher harmonic modes, as depicted in Fig. 4.



(a) **(b)**

Fig. 3 *Inset feed position*

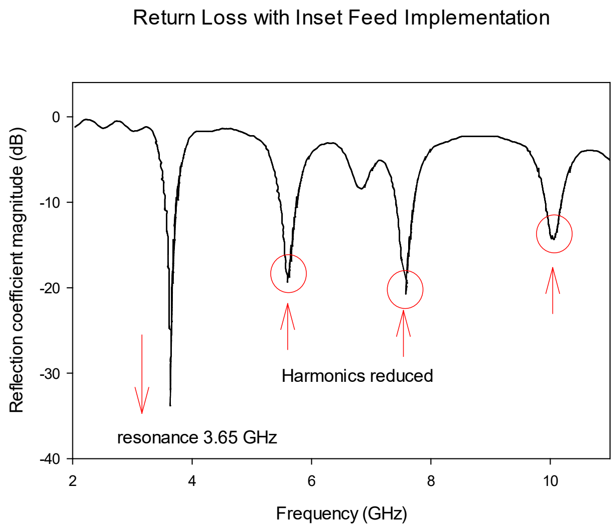
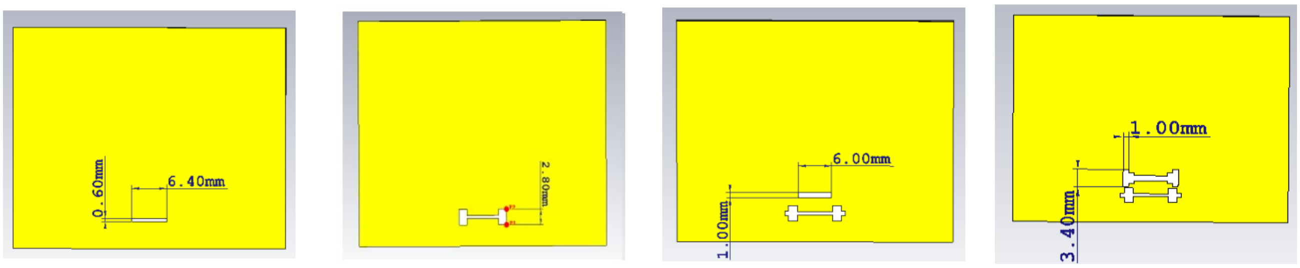


Fig. 4 *S_{11} of the antenna with inset feed*

To mitigate the occurrence of unwanted harmonics, a number of steps were taken to optimize the design of the Defected Ground Structure (DGS) implemented on the antenna in a systematic manner. The optimization process started with the use of the simplest square shape and was systematically transitioned to the dumbbell shape to achieve a superior antenna performance at 3.65 GHz, while suppressing the harmonics. Ultimately, referring to Fig. 5, the double unique dumbbell shape was selected as the final design with the best performance, harmonics suppressed, and an S_{11} of -27.65 dB.



(a) **(b)** **(c)** **(d)**

Fig. 3 *Optimization of DGS on antenna process from slot (a) to (d)*

Referring to Fig. 6, the undesired harmonics in a signal are reduced to a significant extent, measured as below -10dB. Despite the return loss at operating frequency reduce significantly to -27.52 dB, all unwanted harmonics at higher frequency successfully suppressed. However, the resonant frequency of the antenna was slightly shifted, resulting in it occurring at 3.52 GHz.

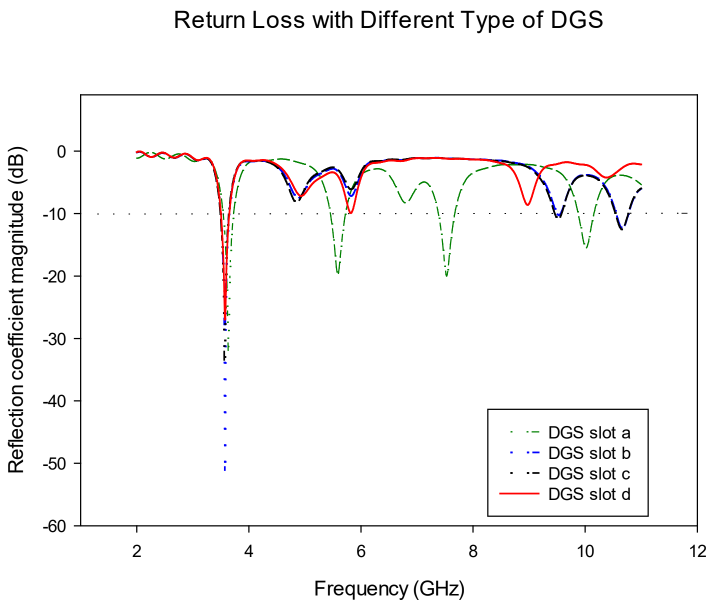


Fig. 4 *S_{11} for antenna with double dumbbell shape*

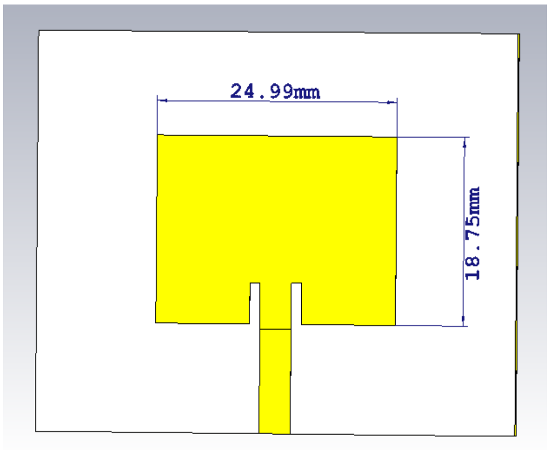


Fig. 5 *Optimum size for maximum return loss*

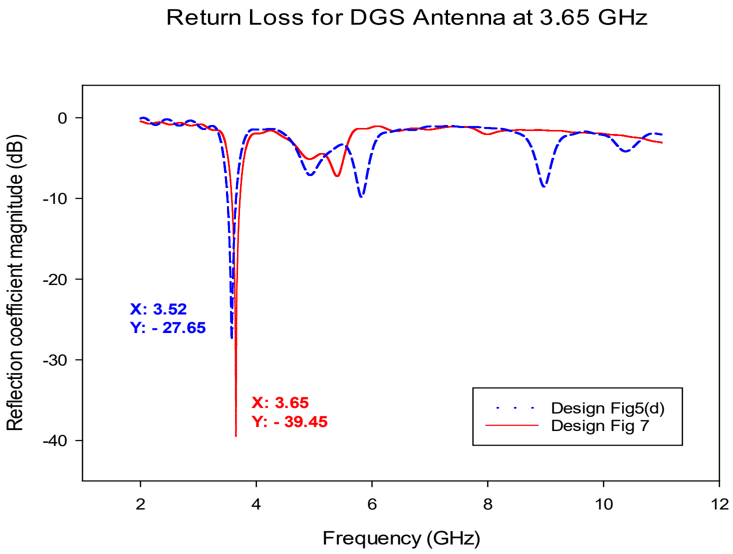


Fig. 6 *S_{11} for optimized antenna size*

To address this issue, a minor adjustment was made to the antenna size by reducing the length from 19.2 mm to 18.75 mm, which led to a resonant frequency of 3.65 GHz and an S_{11} of -39.45 dB, indicating very low reflection characteristics; see Fig. 7 and Fig. 8 respectively. The unwanted harmonics were successfully suppressed further, with their magnitudes reduced to -5 dB, -1 dB, and -2 dB at 5.5 GHz, 9.3 GHz, and 10.5 GHz, respectively.

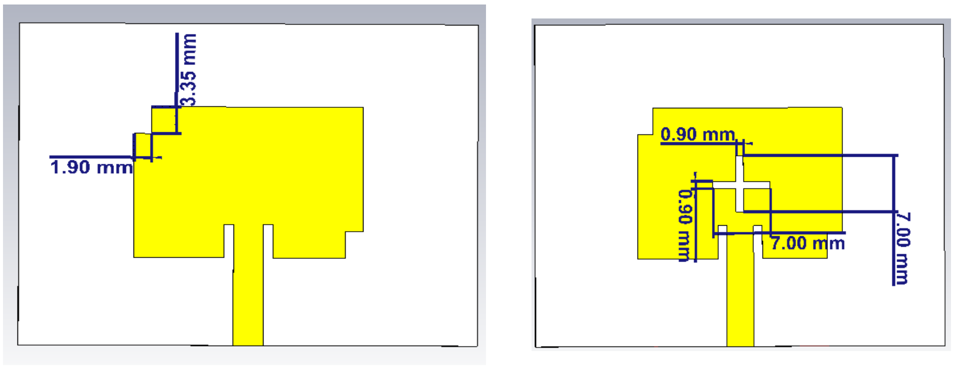
Overall, the systematic optimization of the DGS design significantly enhanced the antenna's performance, while successfully suppressing unwanted harmonics and achieving excellent return loss characteristics.

3. Circular Polarization

In mobile communication systems, the ability to transmit signals in all planes is critical for ensuring reliable and robust communication. Circular polarization (CP) is a technique that achieves this by radiating electromagnetic waves with a rotating electric field. This technique is especially useful for antennas used in mobile communication systems because it enables the antenna to receive and transmit signals in all directions.

To determine whether an antenna is a CP antenna, the axial ratio is measured. The axial ratio is a measure of how circularly polarized the antenna's radiation is. If the value of the axial ratio at a given frequency, such as 3.65GHz, is less than 3, the antenna is considered to be a CP antenna.

To enable a patch antenna to radiate circularly polarized (CP) signals, the patch needs to have several orthogonal slots. The first step in this process involves truncating two corners of the patch with dimensions of 1.90mm x 3.35mm, as illustrated in Fig. 9(a). Next, a cross-shaped slot is created in the middle of the patch using two rectangular slots with dimensions of 7mm x 0.9mm and 0.9mm x 7mm, respectively, as shown in Fig. 9(b). This slotting process modifies the patch's electromagnetic field, resulting in a more uniform distribution of the electric field, which leads to a reduction in the axial ratio.



(a) (b)

Fig. *7 (a) Truncate; and (b) Cross-shape slot position*

The axial ratio of the antenna, which is the ratio of the maximum to the minimum amplitude of the electric field in the antenna's radiation pattern, is reduced from 26.4 to 2.22 as shown in Fig. 10. This decrease in the axial ratio satisfies the requirement for a CP antenna, which mandates an axial ratio value below 3, making the patch antenna a viable option for circularly polarized applications.

The performance of the S_{11} parameter, which describes the amount of energy reflected by an antenna at a specific frequency, is affected by adjustments made to a CP (circularly polarized) antenna. However, despite these adjustments, the S_{11} parameter at 3.65 GHz remains within the required range with a value of -17.02 dB as presented in Fig. 11. Additionally, all harmonics which represent the unwanted frequency components that can interfere with signal transmission, have been effectively eliminated and remain below a threshold of -5 dB. These results indicate that the CP antenna has been optimized to operate at the desired frequency with minimal interference from harmonic signals.

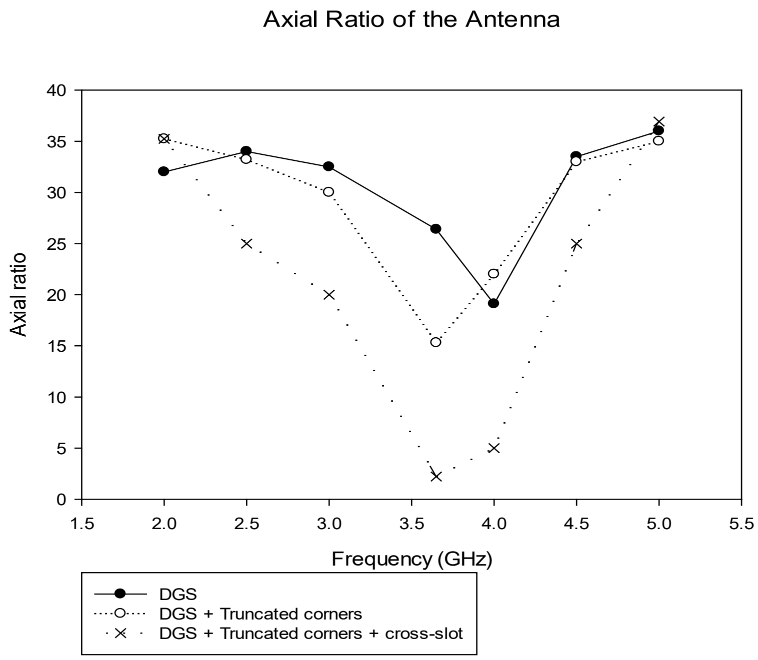


Fig. 8 *Axial ratio improvement*

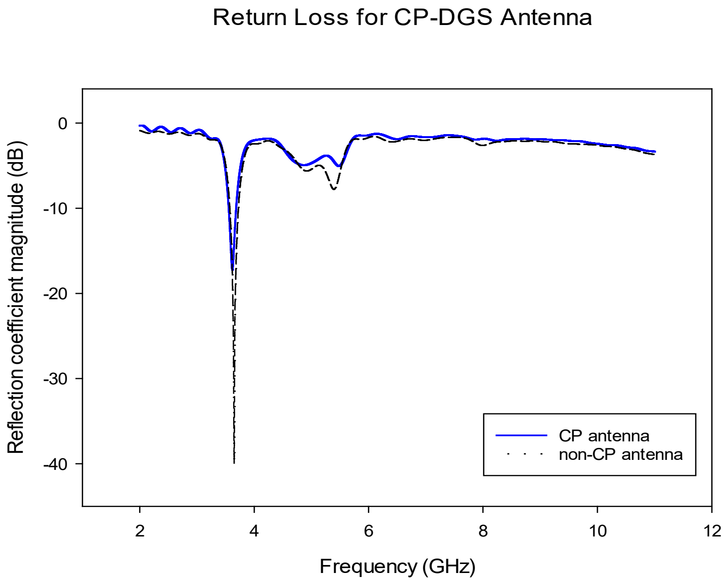


Fig. 9 *S_{11} of the CP antenna*

4. Result and Discussion

After the design of the antenna was completed, it was fabricated, as depicted in Fig. 12. The fabricated antenna was then taken to the lab for measurement using a network analyzer. The results of the measurements were recorded and analyzed to determine the antenna's performance characteristics.

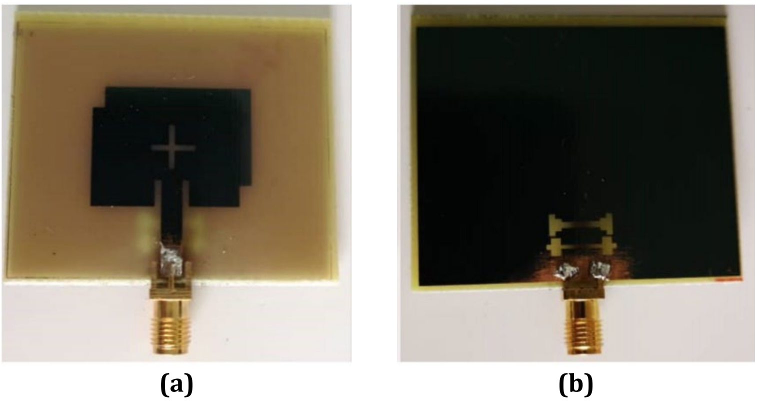
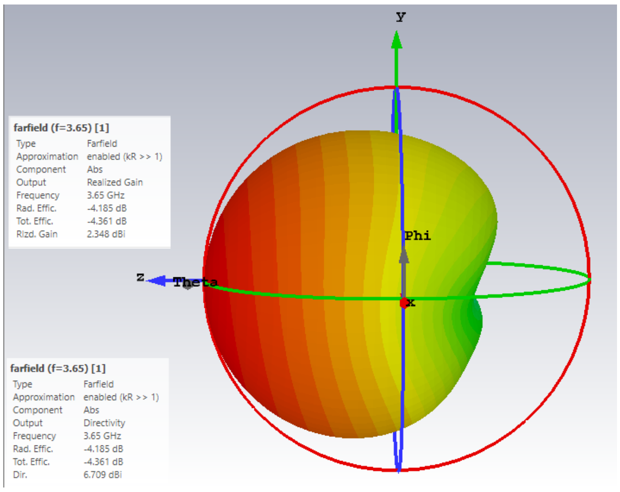

(a) (b)

Fig. 10 *Fabricated microstrip patch antenna (a) top view; and (b) bottom view*



farfield (f=3.65) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Realized Gain
Frequency	3.65 GHz
Rad. Effic.	-4.185 dB
Tot. Effic.	-4.361 dB
Rlzd. Gain	2.348 dBi

farfield (f=3.65) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Directivity
Frequency	3.65 GHz
Rad. Effic.	-4.185 dB
Tot. Effic.	-4.361 dB
Dir.	6.709 dBi

Fig. 11 *Radiation of the CP antenna*

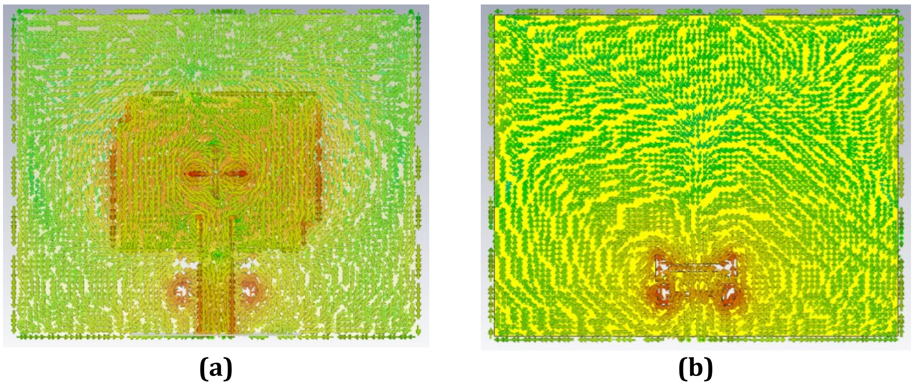
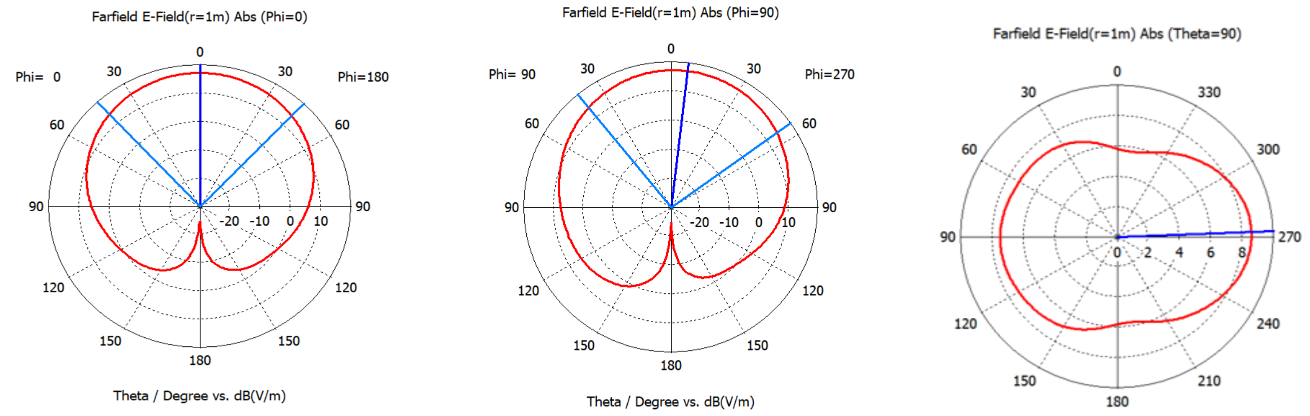

(a) (b)

Fig. 12 *Surface current distribution on the antenna for (a) patch antenna; (b) ground plane*

To determine the antenna's gain, which is a measure of its ability to radiate energy in a particular direction, the farfield monitor in CST was used for simulation. The simulation results indicated that the antenna had a gain of 2.348 dB, with a radiation efficiency of -4.185 dB (38%), a total efficiency of -4.361 dB (36.6%), and a directivity of 6.709 dBi, as shown in Fig. 13. Fig. 14(a) and (b) visualized the surface current distribution on the antenna. The current distribution on the antenna surface is affected by the frequency and the feeding technique of the antenna. High current density is appeared on the both patch antenna slot and DGS structure, which contributed to the harmonics suppression and CP capability of the antenna.

Furthermore, the radiation pattern of the antenna was studied by examining the energy radiated by the antenna at different angles. The radiation pattern was depicted in Fig. 15(a) to (c), which showed the radiation pattern at phi = 0°, 90°, and theta = 90°. The radiation pattern of the antenna indicated that it was a CP (Circularly Polarized) antenna, as it radiated energy equally in all directions. In other words, this antenna can be used to transmit signal in any direction, 360°.



(a) (b) (c)

Fig. 13 *Radiation pattern for circular polarized antenna at 3.65GHz for (a) Phi = 0° (b) Phi = 90° (c) Theta = 90°*

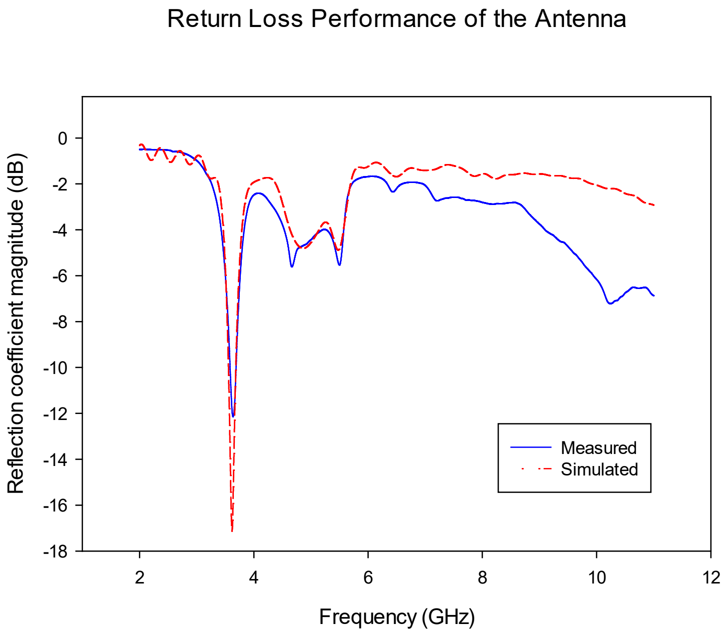


Fig. 14 *Comparison of return loss between simulation and measurement*

The evaluation of an antenna design is done by comparing the simulated and measured return loss. In this case, Fig. 16 shows the simulated and measured return loss for the proposed antenna design. The simulated return loss is -17.02 dB at resonant frequency, which means that only 2% of the signal is reflected back to the source. On the other hand, the measured return loss is -12.2 dB at resonant frequency, indicating that 6% of the signal is reflected back to the source. The measured return loss is slightly higher than the simulated return loss, which can be attributed to various factors.

One possible factor that contributes to the difference between the simulated and measured results is the soldering process. The tin element may have some effect that could affect the accuracy of the results. Another factor that could affect the accuracy of the measured results is the inaccurate etching process. The antenna design is fabricated using an etching process, and any inaccuracies in the etching process could result in a deviation from the simulated results. Additionally, the tolerance in the component used can also contribute to the difference between the simulated and measured results.

Despite these factors, the measured result is still acceptable, with a measured return loss of -12.2 dB, which is within an acceptable range. Furthermore, all harmonics do not exceed -10 dB, indicating that the antenna does not produce any significant interference with other nearby devices.

However, the gain measured is 17% lower than the simulation, with a gain of 2.34 dB for the simulation and 1.93 dB for the measurement. Gain is a measure of the antenna's ability to convert electrical power into radiated power. The lower gain could be due to the same factors that affect the return loss, such as soldering effect and inaccuracies in the etching process.

Overall, the evaluation of the proposed antenna design shows that the measured results are slightly different from the simulated results. However, the measured results are still within an acceptable range and do not produce any significant interference with other devices.

The polarization of an antenna can be determined by analyzing its axial ratio, which is the ratio of the amplitude of the major axis to the amplitude of the minor axis of the elliptical polarization. To determine the axial ratio, simulation results are typically used, and if the axial ratio is below 3 dB, it indicates that the antenna is circularly polarized (CP).

Fig. 17 shows the comparison of simulation and measurement results for the proposed antenna, and it can be seen that the axial ratio is below 3, indicating that the antenna has achieved the specifications for a CP antenna. Specifically, the proposed antenna has achieved an axial ratio of 2.93, which is within the acceptable range for CP antennas.

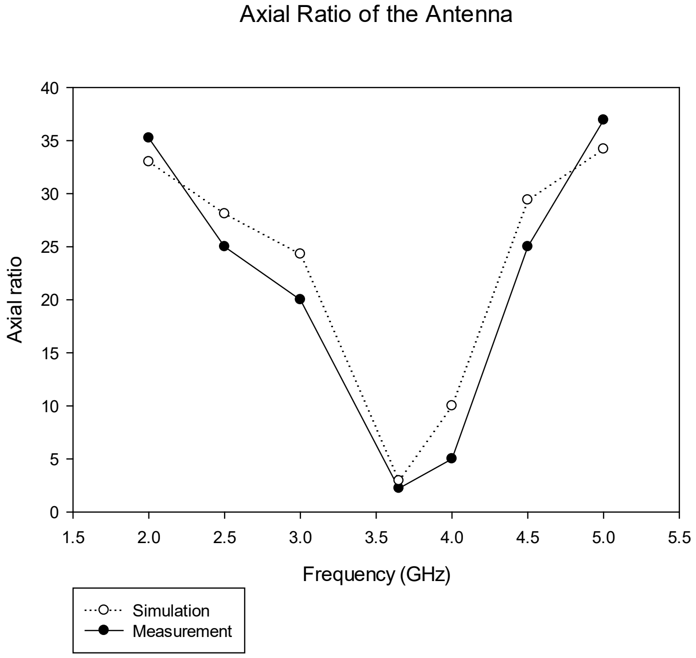


Fig. 15 ***Axial ratio of proposed antenna***

The radiation pattern of the antenna is determined in the far field region for the simulation. The radiation patterns were simulated at 3.65GHz when phi = 0°, phi = 90° and theta = 90° as shown in Fig. 16. When phi = 0°, it has a main lobe in the direction of 0°. For phi = 90° it also has a major lobe in the direction of 7°. For theta = 90°, it shows an omnidirectional radiation pattern. Tab. 1 shows the result of gain, directivity, and total efficiency of the proposed antenna. The enhancement achieved by DGS technique implementation is summarize in Tab. 2.

Table 1 *Summarization of CP antenna parameters between simulation and measurement*

	S_{11} (dB)	**Axial ratio**	**Gain (dB)**	**Directivity (dBi)**
Simulation	-17.02	2.22	2.348	6.709
Measurement	-12.2	2.93	1.932	-

Table 2 *Enhancement of DGS based CP antenna*

	S_{11} (dB)	**CP**	**Harmonic resonance (GHz)**
Initial Design	-7.1	X	3.5, 5.7. 9.2, 10.3
DGS implementation	-12.2	√	3.5 (unwanted harmonics suppressed)

5. Conclusion

A rectangular patch antenna has been designed and fabricated on an FR4 substrate, suitable for use in 5G and future 6G mobile communication systems. The design incorporates two dumbbell-shaped defected ground structures (DGS), two truncated corners, and a cross slot in the middle of the patch to suppress the higher order modes of harmonics and produce a circularly polarized (CP) radiation pattern. The simulation results show that the antenna has a resonant frequency of 3.65 GHz with a return loss of -17.02 dB, while the measured S11 parameter for the fabricated antenna is -12.2 dB. The gain of the antenna has also been analyzed, and the simulation result shows a gain of 2.348 dB, while the measured gain of the fabricated antenna is 1.932 dB. The CP performance of the antenna is excellent, with an axial ratio of 2.22 and 2.93 for simulation and measurement respectively at 3.65 GHz.

For future work, the gain of the designed antenna can be increased to enhance its performance for different applications. Additionally, the antenna can be fabricated using Rogers material, which has better performance in terms of gain, radiation pattern, return loss, and size as compared to FR4 substrate.

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