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Abstract

Purpose: Continuous demand is for precise and compact systems that operate with 5G wireless technologies. The size and compactness of devices play a major role in developing communication systems, especially in 5G applications. One of the main components in 5G systems is the antenna system; it should be designed to meet 5G requirements. In this article, a microstrip antenna is designed with a resonant frequency of 12 GHz using an FR4 substrate with an overall size of 15x15x1.6 mm^3 for 5G applications.

Methodology: The patch is etched with an inverted-F slot with optimized dimensions of 0.5x2.5 mm^2 and 0.5x5.5 mm^2 to perform a resonant frequency of 6.2 GHz. The antenna is optimized to operate with 5.38 GHz with the same dimensions using double elliptical slots ring resonators (ESR) defective ground plane (DGND) with outer radii of (5 mm, and 4 mm) and inner of (4.25 mm, and 3.25 mm) with gap-space of 0.25 mm between them to perform a size reduction ratio of 82.558%.

Findings: This allows the antenna to operate with 5G applications such as WiFi and WiMAX. The antenna can be fabricated easily on an FR4 substrate with height, permittivity, and loss tangents of 1.6 mm, 4.3, and 0.02. It also can be implemented with metamaterial and studied/analyzed of the other antenna's performance for further size reduction.

Unique Contribution to Theory, Practice and Policy: The antenna configuration supports up to 82.558% size reduction. The proposed structure operates with return loss, gain, radiation efficiency, and bandwidth of -37 dB, 2.21 dB, 75.8%, and 122.2 MHz from (5.4417-5.3195) GHz respectively.

Keywords: *Inverted-F Patch Slot, Elliptical Slot Ring (ESR), Defective Ground Structure (DGS), 5G, WiFi/WiMAX*

INTRODUCTION

In recent years, it can be noted that the increase in the number of devices has led to data traffic around the world because of the need for security, large capacity, and high speed for wireless applications such as healthcare, IoT, smart cities, and automobile systems, etc. so the current technologies such as 3G, 4G, and WiFi/WiMAX, etc. it should improve the capacity and other features. To overcome these issues, the 5G/6G systems produce many characteristics such as low profile, low cost, high capacity, etc. (Saleh, Saeidi, Timmons, & Razzaz, 2024). The 5G system currently performs various benefits such as huge capacity, less latency, multiple connectivity, large reliability, high mobility, and wide coverage area (Chandra Paul et al., 2022). There are two well-known spectrums for the 5G systems, they are sub-6 GHz and mm-wave (Chakraborty, Rahman, Hossain, Nishiyama, & Toyoda, 2024; Chandra Paul et al., 2022). Certainly, the 5G technologies have a powerful impact on several applications to accept the lifestyle of recent residents (Paul et al., 2023).

The antenna requirements to operate in 5G applications are small size, support the single input single output (SISO), and multi input multi output (MIMO) techniques with a wide band or multiband, and operate for the frequency bands of the 5G such as sub 6 GHz, millimeter wave (mm-wave), etc. (S. Kumar, Dixit, Malekar, Raut, & Shevada, 2020).

One of the most basic requirements of the recent wireless communication systems is the microstrip antenna system. The features of the proposed antenna that meet the requirements of 5G applications are compact size, high gain, non-complicated structure, and simple design (Hanaoui & Rifi, 2019). However, limitations include a narrow frequency band in the microstrip antenna. There are many previous works have been proposed and implemented to enhance the features and performance of the microstrip antenna such as a defective ground plane or structure DGS in different structures such as rectangular slots (Chalasani, Boppana, & Kuruganti, 2020; Nadeem & Choi, 2018; Saxena, Sharma, & Deo Upadhayay, 2020; Ullah et al., 2020), circular ring slots (Ganesan & Iympalam, 2023; Gao, Hu, Wang, & Yang, 2018; A. Kumar, Mahto, Sinha, & Choubey, 2021), fractal geometries (Chandra Paul et al., 2022), and elliptical ring slots (Chakraborty et al., 2024; Hanaoui & Rifi, 2019; M. Kumar & Nath, 2020; Nasri, El Ghzaoui, & Fattah, 2024; Okas, Sharma, Das, & Gangwar, 2018; Sharma, Gunaram, Deegwal, & Mathur, 2022; Zhang, Ur Rahman, Cao, Gil, & khan, 2019).

Several features and benefits can be obtained by using DGS as it works to change the value of the inductance and capacitance of the transmission line, which leads to the antenna operating within multiple frequencies (Rappaport et al., 2013). It is also possible to benefit from DGS in improving the bandwidth in which the antenna operates (Chiang & Tam, 2008; Marotkar & Zade, 2016). DGS is also used to reduce the size of the antenna so that it is designed with small dimensions and operates at low frequencies as is the case in (Andrews, Narayanan, & Marazhchal Sunil, 2024; Hanae Elftouh, 2014; J. X. Liu, 2010) and the work proposed in this article. Improving the properties of cross-polarization through DGS (Tecpoyotl-Torres, Dimas, Castañeda-Sotelo, & Vargas-Bernal, 2013). It is usually used to improve the mutual coupling between the elements of the multi-input and multi-output system (Guha, Kumar, & Pal, 2009).

Related Works

The related works, which are mostly about the elliptical slot DGS and their proposed design, contributions, results, and applications, are selected.

In the article (Hanaoui & Rifi, 2019) they proposed a two-element rectangular microstrip patch with an elliptical slot antenna printed on an FR4 substrate with a center feeding technique to perform dual-band operation for 5G applications. The antenna operates on double bands with resonant frequencies of 3.43 GHz and 5.4 GHz and supports bandwidths of 400 MHz and 250 MHz respectively and a maximum gain of 8.77 dB.

The work of (Okas et al., 2018) they presented a circular monopole patch with an elliptical slot DGS printed on Rogers RT/duroid 5880 substrates to achieve super wideband usage (SWB). the proposed design is characterized by using an elliptical slot DGS and elliptical notch along with a tapered microstrip line to maintain supper wide bandwidth and by using an elliptical slot in the patch side to reduce the lower operating frequency from 1.07 GHz to 0.96 GHz and hence enhance the bandwidth to achieve frequency range of (0.96-10.9) GHz and bandwidth dimension ratio of 6975.22.

In (Zhang et al., 2019), They designed a triple-notch wideband antenna for SWB applications. The antenna structure consists of a radiating patch with an elliptical slot and a rectangular slot ring, feeding with a tapered microstrip feed line and an elliptical DGS printed on an F4B substrate. The antenna operates with a frequency range from (1.42-50) GHz, an impedance bandwidth of 189%, and a bandwidth dimension ratio of 4375.

The proposed work in (M. Kumar & Nath, 2020) provides a two-rotated perpendicular wide elliptical DGS antenna with microstrip line feed printed on FR4 substrate to perform circular polarization for various wireless applications. The antenna achieved an operating bandwidth of (4.94–12.72) GHz and an impedance bandwidth rate of 88.11%. The antenna supports radiation with left-hand circular polarization with an axial ratio bandwidth of (5.4–7.45) GHz, 31.91%. The antenna's bandwidth dimension ratio and peak gain are 1062 and 4.39 dBi respectively.

The presented work in (Chandra Paul et al., 2022) it proposed an antenna for 5G sub-6 GHz and WiMAX applications. The antenna comprises a plus-shaped patch with a middle rectangular slot and DGS printed on Rogers RT5880. The antenna works with a resonant frequency of 3.12 GHz, bandwidth from (2.67–5.23) GHz, a gain of 2.44 dB, a directivity of 2.53 dBi, and an efficiency of 98%. The antenna is designed and the impact of its parameter using CST (time-domain and frequency domain), high-frequency structure simulator (HFSS), and computational electromagnetics (FEKO).

In (Sharma et al., 2022), they proposed an elliptical ring patch with an elliptical slot and an elliptical DGS printed on an FR4 substrate with tapered microstrip line feed to perform a super wideband for 5G applications. The designed antenna offers a frequency range from (2.31-40) GHz, a bandwidth ratio of 34.63:1, an impedance bandwidth of 188.56%, a bandwidth dimension ratio BDR of 1732, and a maximum gain of 5.81 dBi.

The research article (Paul et al., 2023) presented a compact microstrip antenna with a slotted semicircular patch as a wrench shape and a slotted semicircular with slotted parasitic element DGS printed on Rogers RT 5880 substrate for 5G applications. The designed antenna operates with a maximum gain of 2.77 dB, a directivity of 3.7 dBi, an impedance bandwidth of 1.47 GHz, and a radiation efficiency of 92%. The antenna performance has been studied with three different electromagnetic software, CST, HFSS, and FEKO.

The proposed work in (Nasri et al., 2024), produces a 4-element MIMO antenna printed on RT 5880 substrate for 5G applications. The proposed design of the single element consists of a perforated rectangular patch with circular and rectangular patterns, and DGS of a perforated

GND plane to achieve the desired operation. The antenna is designed and simulated using two different electromagnetic tools, CST and HFSS. The antenna achieves resonant frequency at 38.7GHz, a wide bandwidth from (34.8-43.7) GHz, a peak gain of 10.24 dBi, isolation less than -20 dB, envelope correlation coefficient ECC less than 0.0002, diversity gain of 9.999, and minimal channel capacity loss less than 0.4.

The research article of (Chakraborty et al., 2024) presents a double band 4-element MIMO antenna based on a non-uniform elliptical ring slot DGS and L-shaped feed network to feature orthogonal circular polarization printed on an FR4 substrate for sub-6 GHz 5G applications. The designed structure performs a bandwidth form (3.55-3.8) GHz and from (4.6-4.8) GHz, with a simulated gain of 4 dBi and 5dBi respectively, ECC less than 0.04, and isolation less than -15 dB.

The research gap can be defined by this article using ESR for antenna size reduction as small as possible to make a compact antenna with simple design structure operate and meet the 5G applications requirements.

This article is organized as the introduction is presented in the first section, the second contains the previous works in this field, the proposed configuration and analysis are presented in section three, the results and discussions are provided in section four, and the last section produces the conclusions.

In this article, an ESR-DGND antenna is proposed, analyzed, and optimized parameter for size reduction to operate on 5G wireless applications. Contributions of this work can be summarized as:

1. Proposed an antenna design that works on 12 GHz with a parametric study on the substrate size using different substrates such as FR4.
2. Etching an inverted F-slot shape in the patch optimizes the optimum slot size and studies its effect on the operation.
3. Evaluate (ESR) in the GND plane and optimize the size of slots to compare their simulation results and their effect on the antenna operation.
4. Perform and evaluate the size reduction.

Proposed Antenna Design

The proposed structure in this article passes through several stages of the design procedure as shown in Figure 1. The antenna uses different substrates such as FR4 to maintain the optimum design and operation for 5G applications. The proposed antenna is printed on the FR4 substrate with a thickness of 1.6 mm, loss tangent of 0.02, and an overall size of 15x15x1.6 mm^3 and patch area of 7.5x8.5 mm^2. The patch dimensions (L_p and W_p) are designed using the formulas of equations (1) and (2) respectively (A. Jabber & H. Thaher, 2021; Balanis, 2016; Abdullah Ali Jabber & H. Thaher, 2020; Abdullah A. Jabber, Jassim, & Thaher, 2020; A. A. Jabber & Shadeed, 2022; Abdullah A. Jabber & Shadeed, 2023; Abdullah Ali Jabber & Raad H. Thaher, 2020; A. A. Jabber & R. H. Thaher, 2020) with a parametric study to maintain the optimum resonant frequency at 12 GHz as presented in Figure 2.

$$L_p = \frac{C_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}}\text{.....................(1)}$$

$$W_p = \frac{C_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r-1}}\text{.....................(2)}$$

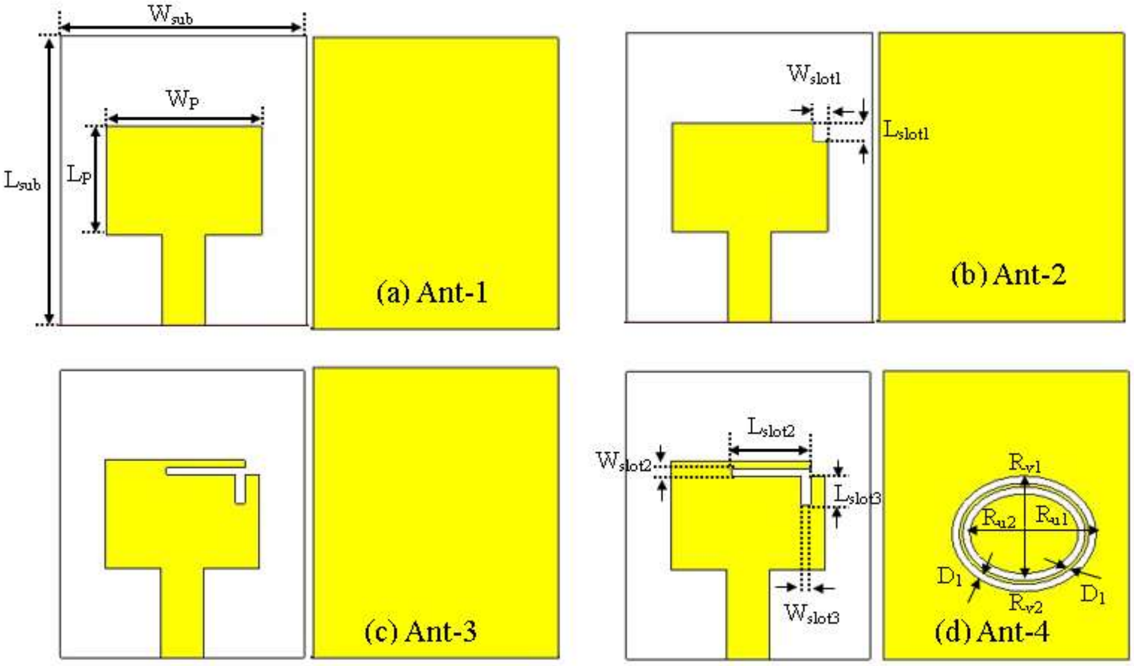


Figure 1: The Proposed Antenna Design Procedure with ESR DGND.

The ESR Design

To design an elliptical slot ring, it should take one wavelength of the operating frequency (fundamental) so that it is equal to the outer perimeter of the elliptical slot. The elliptical slot ring can be designed using equations (3) and (4) (Chakraborty et al., 2024).

$$C = \lambda = 2\pi\sqrt{\frac{a^2 + b^2}{2}} \text{……………………..(3)}$$

$$b = \sqrt{\frac{\lambda^2}{2\pi^2} - a^2} \quad ; \frac{\lambda^2}{2\pi^2} > a^2 \text{………..(4)}$$

Where (a) and (b) are the major and minor axes of the elliptical slot ring, (λ) is the wavelength at the desired frequency, and (C) is the outer perimeter of the elliptical ring slot. Note that these equations produce approximate values. The values of the outer elliptical slot ring (a) and (b) are calculated from equations (3) and (4) by calculating (λ = 26.89 mm) from the resonant frequency of 5.38 GHz, assuming (a = 5 mm) and calculating (b = 3.415 mm), then these values are optimized through parametric analysis to find the best values of (a = 5 mm, b = 4 mm). The same procedure is used for the inner elliptical slot ring values, where the values are calculated and optimized to (a = 4.25 mm, b = 3.25 mm).

The Parametric Analysis

The proposed configuration goes through several steps of design analysis and parameter optimization to perform the final structure and operating performance. Firstly, the antenna is designed and optimized substrate and patch parameters to resonate at 12 GHz as shown in Figure 2. The obtained return loss shows a high impedance matching with -50 dB.

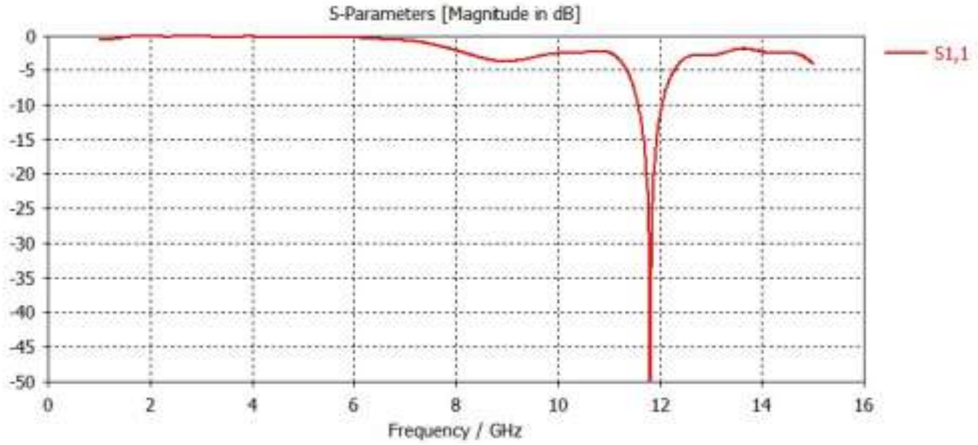
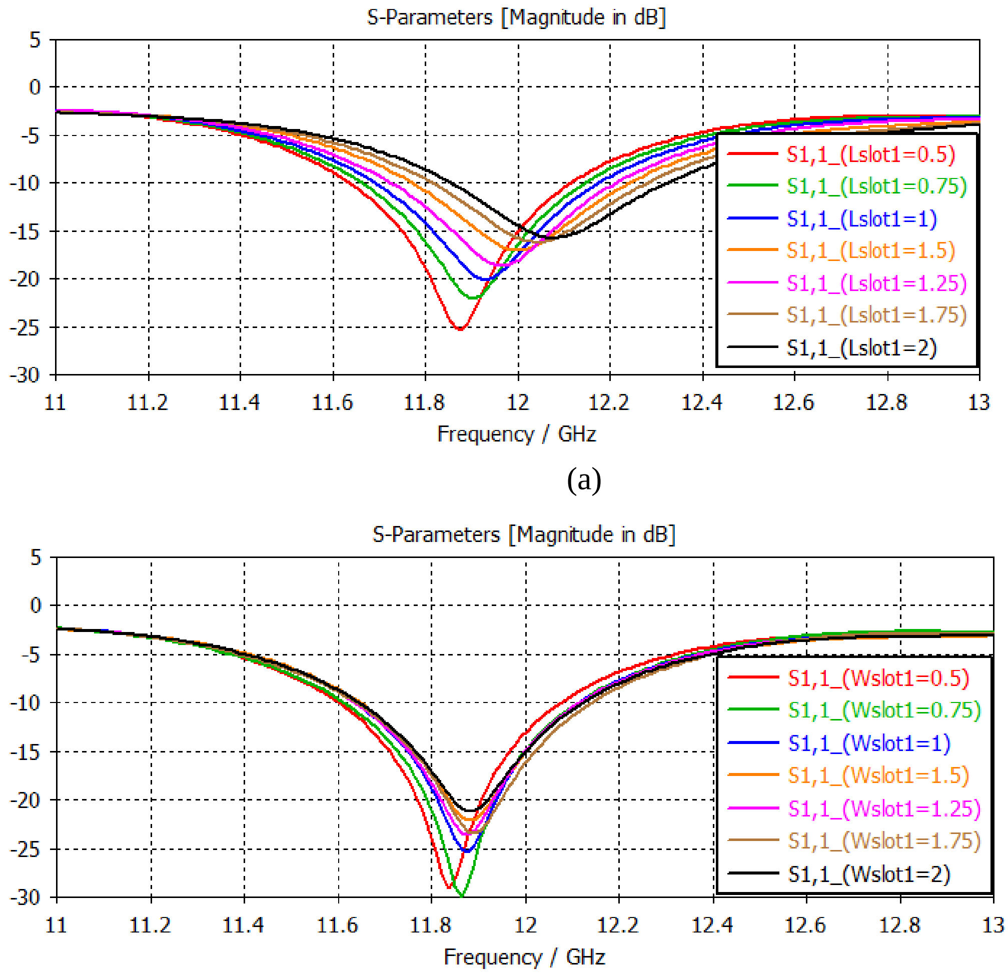


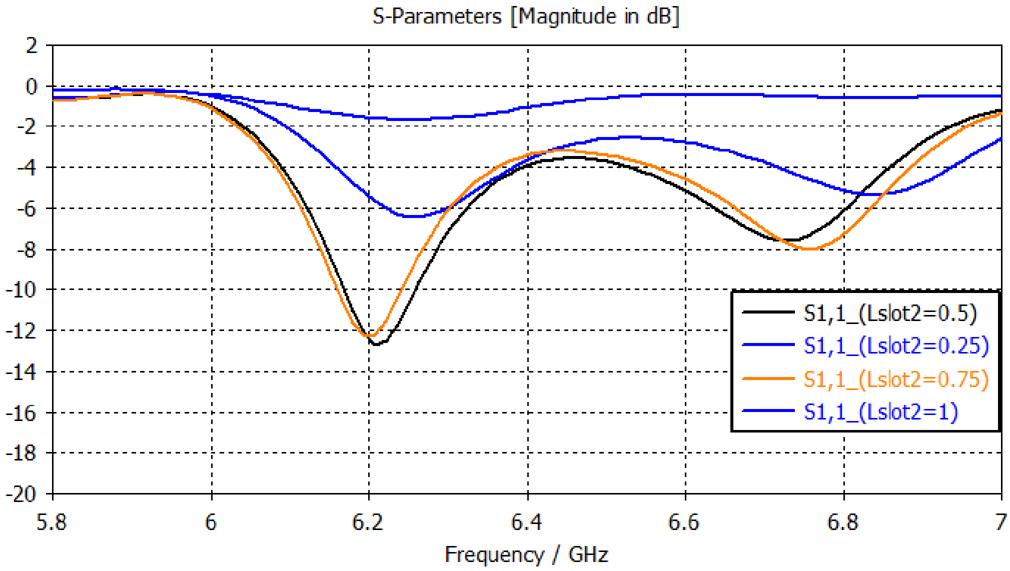
Figure 2: The Simulated S11 of the Proposed Design at 12 GHz.

The second step is to etch and optimize a small rectangular slit and an inverted-F slot on the upper right of the patch side with dimensions of 1x1 mm^2 0.5x2.5 mm^2 and 0.65x5.5 mm^2 respectively as presented in Figure 3 to achieve a resonant frequency of 6.2 GHz and S11 of -37 dB.

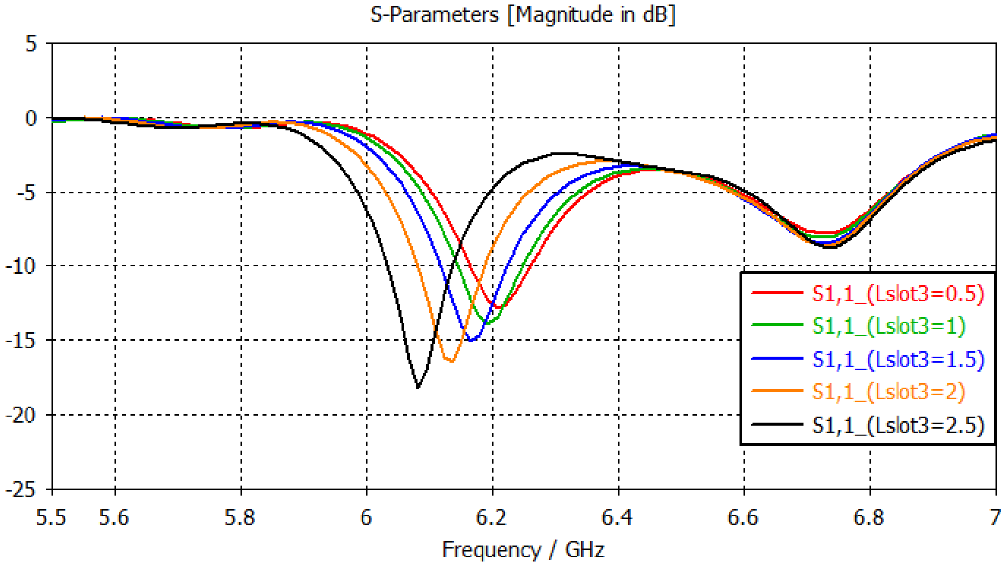


(a)

(b)



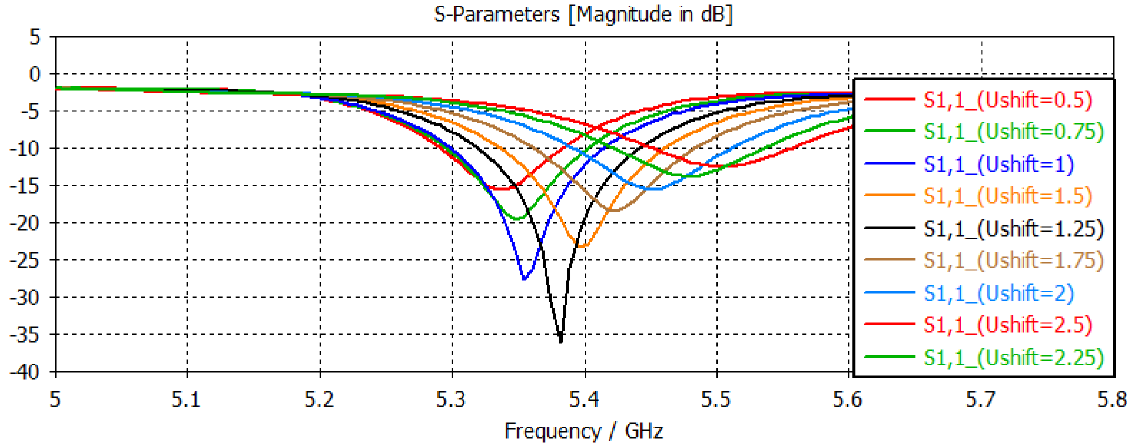
(c)



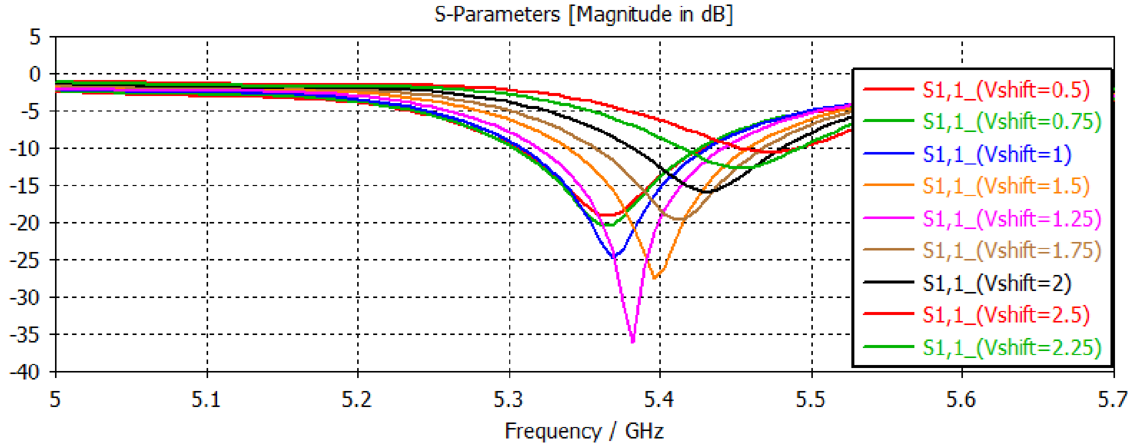
(d)

Figure 3: The Optimization of the Slot Parameter at the Patch Side, (a) L_{slot3} = 1mm, (b) W_{slot1} = 1 mm, (c) L_{slot2} =0.5 mm, (d) W_{slot3} = 2.5 mm

The final step is to produce a DGS using a dual ESR with a gap between them as shown in Figure 1-c. The proposed dual ESRs have outer and inner radii (R_{u1}, R_{v1}) and (R_{u2}, R_{v2}) of (5 mm, and 4 mm) (4.25 mm, and 3.25 mm) with gap-space between them of 0.25 mm respectively. These DGS slots are proposed and optimized through several parametric studies until they get a resonant frequency of 5.38 GHz as shown in Figure 4. Not only are the dimensions optimized, but the position of the ESR is optimized through vertical and horizontal shifting parameters, as shown in Figure 4.



(a)



(b)

Figure 4: The Optimization of Elliptical Slot Ring Using a Parametric Study, (a) Horizontal Shifting by (U_{shift} = 1.25 mm) and (b) Shifting by (V_{shift} = 1.25 mm)

The optimum parameters of the proposed configuration are summarized in Table 1.

Table 1: The optimum parameter of the proposed ESR-DGS antenna.

Parameter	Value (mm)	Parameter	Value (mm)
L_{sub}	15	L_{slot3}	2.5
W_{sub}	15	W_{slot3}	0.65
L_{gnd}	15	U_{shift}	1.25
W_{gbd}	15	L_{shift}	1.25
L_{slot1}	1	R_{u1}	5
W_{slot1}	1	R_{v1}	4
L_{slot2}	5.5	R_{u2}	4.25
W_{slot2}	0.5	R_{v2}	3.25
L_P	7.5	D_1	0.5
W_P	8.5	D_2	0.25
W_f	3	L_f	10
t	0.035	h	1.6

RESULTS AND DISCUSSIONS

The antenna has been designed using FR4 substrate as shown in Figure 1. The simulation results have been achieved using the CST package. The antenna results evaluate the antenna performance and operation to meet the requirements of wireless 5G applications. These results contain the return loss, gain and efficiency, directivity, radiation pattern, current distribution, electric field, and magnetic field.

The S-Parameter

The return loss has a magnitude of -37 dB, a single band, a resonant frequency of 5.38 GHz, and a bandwidth of (122.2 MHz) from (5.4417-5.3195) GHz. This band covers applications such as WiFi/WiMAX and IoT devices. As presented in Figure 5 the antenna operates with high impedance matching to maintain high performance. Also, the antenna achieves a voltage standing ratio (VSWR) of 1.1 which meets the metric of less than 2 for best antenna operation.

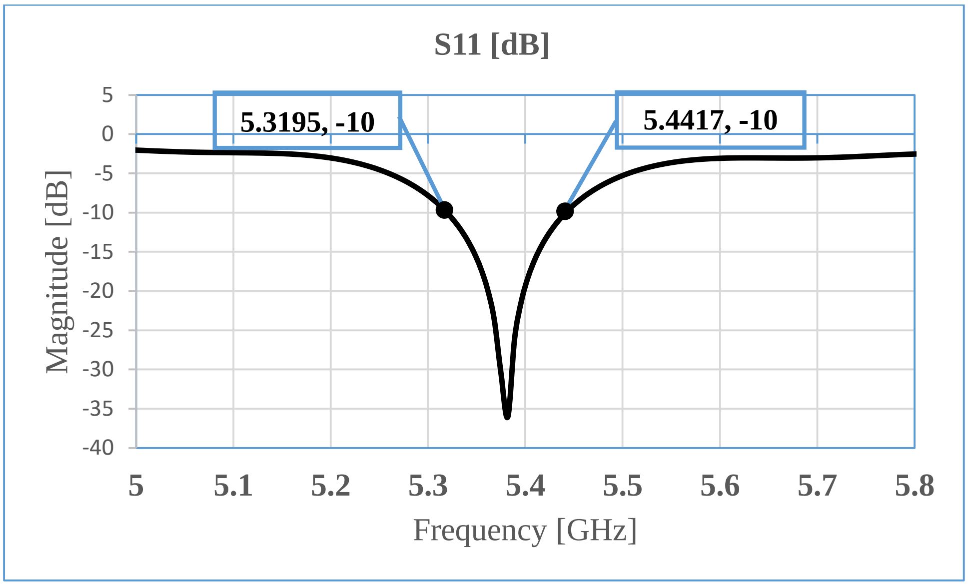


Figure 5: The S11 of the Final Antenna Structure with ESR.

The Gain and Directivity

The antenna gain is presented in Figure 6. The antenna operates with a simulated gain and directivity of 2.21 dB 5.46 dB at 5.38 GHz, making it suitable for 5G applications.

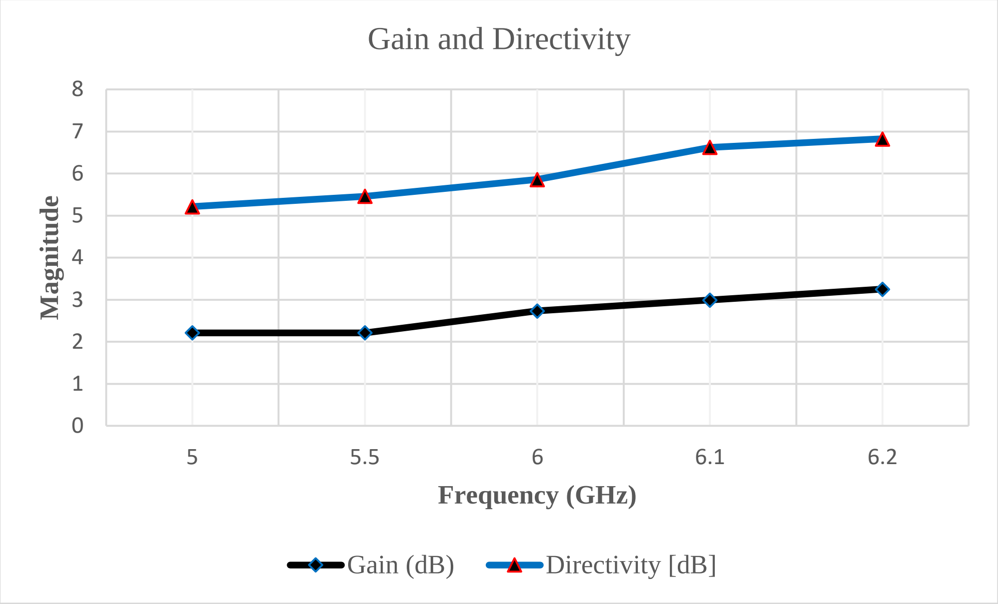


Figure 6: The Antenna Performance with Gain and Directivity

The Antenna Efficiency

The antenna operates with an efficiency of 75.8% at 5.38 GHz, and it increases with increasing frequency, as presented in Figure 7. The antenna's radiation performance, such as its efficiency, depends on converting the accepted radio frequency power at its terminals into wireless radiated power.

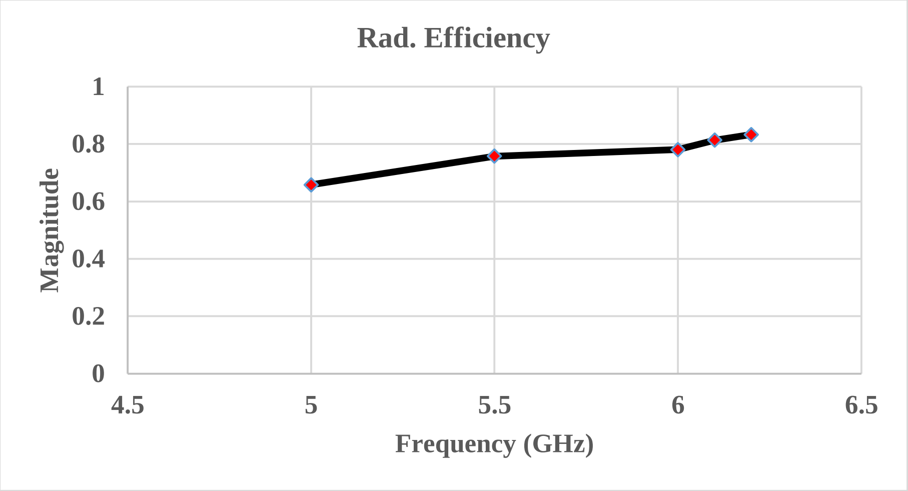
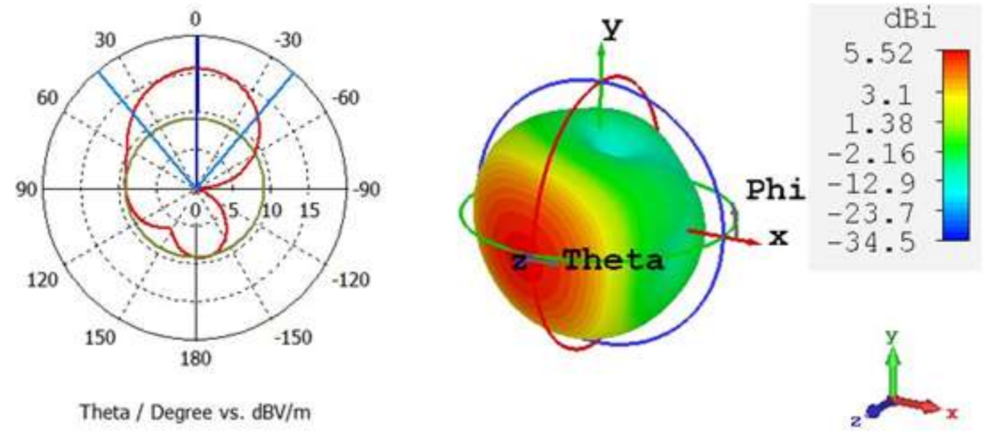


Figure 7: The Radiation Efficiency of the Proposed Antenna

The Radiation Pattern

Figure 8 shows the radiation pattern with 2D and 3D plots. The 2D radiation pattern is a dipole of the E-plane, while the H-plane is omnidirectional, as shown in Figure 8-a. The antenna has an accepted directionality and gain of 2.21 dB at 5.38 GHz.

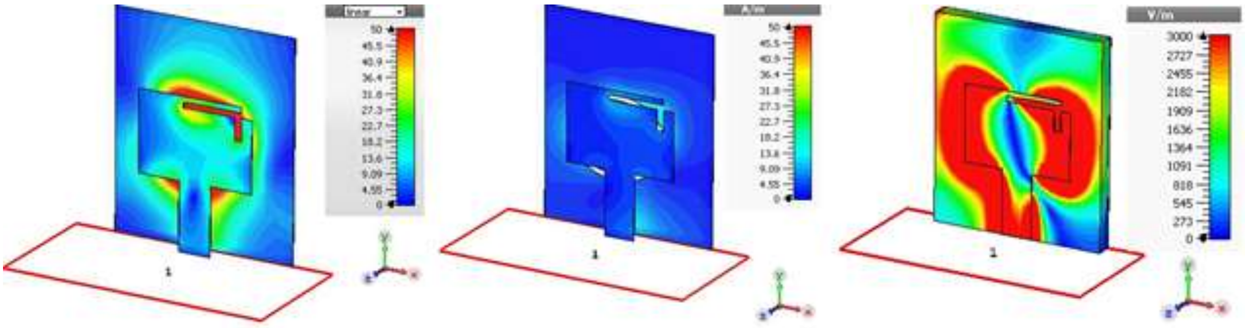


(a) (b)

Figure 8: The Antenna Radiation Pattern with a) 2D, and b) 3D.

The Electric Field, Magnetic Field, and Surface Current Distribution

The electric and magnetic fields are concentrated at the ESR and around the patch as presented in Figure (9-a, b). The surface current distribution is distributed as a double-side from the feedline to the around patch as presented in Figure (9-c).



(a) (b) (c)

Figure 9: The Antenna Performance with a) Electric Field, b) Magnetic Field, and c) Surface Current Distribution.

Size Reduction Calculation

1) 12 GHz antenna patch dimensions:

Area = L_p x W_p = 7.5 mm x 8.5 mm = 63.75 mm^2

2) 5.38 GHz antenna patch dimensions:

Area = L_p x W_p = 17 mm x 21.5 mm = 365.5 mm^2

Then the size reduction could be calculated using equation (5) as calculated in (Andrews et al., 2024):

$$Size\ reduction\ ratio = \frac{(5.5\ GHz\ patch\ area) - (12GHz\ patch\ area)}{(5.5\ GHz\ patch\ area)} * 100\% \ \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

$$= \frac{365.5 - 63.75}{365.5} * 100\% = 82.558\ \%$$

Table 2. The Comparison of the Performance of the Proposed Antenna with Previous Works

Refs.	Approach	Antenna Size (mm^3)	S11 (dB)	Gain (dB)	Efficiency (%)	Size Reduction Ratio (%)
(Chandra Paul et al., 2022)	Slot patch+ DGS	20x35x0.79	-52.06	2.44	98	-----
(Chakraborty et al., 2024)	non-uniform width ESR	64x34x0.8	-24	4 5	-----	-----
(Paul et al., 2023)	Reactangular+semi-circular slots	25x34.5x1.575	-34.24	2.77	92	-----
(Hanaoui & Rifi, 2019)	ESR	52×41×1.6	-18.27 -29.75	6.85 6.44	-----	-----
(Okas et al., 2018)	ESR+semi-ESR	52.25x42x1.575	3.5	-----	-----	-----
(Zhang et al., 2019)	Reactangular+ESR	34x57x 1	-32	7	-----	-----
(M. Kumar & Nath, 2020)	Two rotated ESR	18x17x1.6	-37	4.39	85	-----
(Sharma et al., 2022)	Two ESR	39x39x1.6	-40	5.81	------	-----
(Nasri et al., 2024)	Multi-Reactangular+CSRR	35x30x0.8	-50	10.24	-----	-----
(Hanae Elftouh, 2014)	Cross-shaped DGS	------	-28 -15.5	3.8, 2.8 3.74, 2.5	77 79	68
(J. X. Liu, 2010)	Two cells of DGS	22x23x1.6	-50	2.41	-----	50
(Andrews et al., 2024)	Slots+metamaterial-CSRR	12x12x1	-20.41	-3.7	24.1	92
Proposed work	Slots+ESR	15x15x1.6	-37	2.21	75.8	82.558

Conclusion

This work produces the design and simulation of antenna size reduction using an elliptical slot ring defected GND plane (ESR-DGND) and inverted-F slot on the patch side for 5G communication systems. The proposed antenna shows four steps for the final design. The antenna is designed for 12 GHz with an overall size of 15x15x1.6 mm^3 and finished to operate at 5.38 GHz at the same size. The simulation results show that the inverted-F slot performs a resonant frequency of 6.2 GHz while the ESR-DGND slot at the GND plane performs a 5.38 GHz resonant frequency. The proposed antenna achieved a size reduction ratio of 82.558% and other antenna performance to meet the 5G requirements. It can be noticed that antenna size reduction plays a significant role in compact wireless systems like 5G applications. The proposed antenna can be supported to achieve more compactness in size reduction by using metamaterial for high-speed 5G wireless communication systems.

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