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Design of Compact Doughnut Slotted Microstrip Antenna using CSRR for 5G Applications

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Abstract: ***5G is a term covering various technologies, network and applications. It is a standardization for mobile communication and 5G uses different kinds of antennas, operates on different radio spectrum frequencies, connects many more devices to the internet, minimizes delays, and delivers ultra-fast speeds are an obvious and significant merit over 4G as well as all the previous generations that preceded it. Extremely fast 5G speeds means extremely high frequency, the millimeter wave frequency which can beam ultra-fast data to a lot more users, with high precision and little latency and due to enhancement in technologies, mm wave can be used in most of the new electronic components mainly, antennas. The challenging task is reducing the size of the antenna and achieving an equilibration between the size, gain, bandwidth, and efficiency. This project intent to design a compact doughnut slotted circular microstrip patch of size 7*7*0.8 mm resonates at 28GHz frequency designed on Rogers (RT3003) with dielectric constant(ε=3) and loss tangent (tan δ) of 0.001 with improved antenna performance in terms of return loss, bandwidth, efficiency, gain, and directivity using CSRR is proposed. Two different models of microstrip antennas is proposed with the variation in ground structure seems with and without CSRR technique and with multiple slot configuration are proposed. Bandwidth is the major parameter which increases the user occupancy by adding more number of slots the bandwidth can be enhanced and also applicable to reduce the effective area. And to achieve the compact size and to enhance the performances of the antenna, a novel technique CSRR is introduced in the ground structure which is used to reduce the dimensions of the patch antenna. So, in the proposed design size is reduced at the same time, the desirable performances also obtained which is applicable for 5G applications.***

Index Terms: Circular Microstrip patch Antenna, Compact Size, CSRR, Fifth Generation(5G), Millimeter Wave Frequency, 5G Applications.

I. INTRODUCTION

The fifth generation (5G) mobile communication system will be a new kind of network on a large-scale in forthcoming years, and it will bring us many merits such as high transmission rate and shorter latency over the present 4G system. Due to the compact volume of mobile terminals, however, to achieve better antenna performance characteristics for the antenna system in terms of return loss, directivity, gain, efficiency, VSWR becomes a major challenge. In the past, numerous studies many investigations pursued techniques that allow decreasing the size of electromagnetic radiators, without influencing negatively their electric parameters. The efficiency and the process of such techniques depend on the category of the antenna under study, but when the equipment includes one or more planar antennas, one may mention several procedures, and all of them have effect on the performance of the antenna and its parameters, like bandwidth, radiation efficiency, gain. The techniques use in the past studies like Meandering the radiators may minimize the coupling of the antenna along with the operating frequency and, also, the cross-polarization may be increased, arise by the cancelling currents from adjacent conductors. A similar complication happens when some fractal techniques are used (e.g. Hilbert curve dipole); more than that, shaping many iterations does not warrant a further size reduction, and the difficulty of design would be upheld only if a UWB performance is pursued and achieved[2]. The Slot loading and the presence of shorting pins, results in frequency-sensitive procedures, making them complex to analyze with simple lumped-element designs. In addition, the gain and the bandwidth may decrease by using these methods, and back plane leakage may high when inserting slots or other defected structures on the ground structure, although size reductions of more than 50% are obtained. The manipulation of metamaterial behaviour structures on the substrate or on the body of the antenna is becoming popular, but has several drawbacks, depending on the used topology; the split ring resonator (SRR) is considered a lossy structure with a narrow bandwidth, thus their applications on broadband antennas are limited[2]. However, many appliances of SRR structure, and its dual, is complementary SRR (CSRR) are found in recent survey for producing a multi-band operation of patch antennas design.

In this paper, a novel technique for size reductions is presented based on CSRR, looking for preserving the electric characteristics of the antenna, such as gain, radiation pattern, bandwidth, among others. Following sections shows the design procedure with reduced size patch antenna, implemented with CSRR.

A novel technique (CSRR) is introduced for reducing the dimensions of patch antennas. The technique complementary split ring resonators (CSRR) is for improving the slow-wave effect on the radiator, and enlarge its electrical length, which denotes the modified designed antenna gets a lower physical dimension than a conventional one. The future 5G technology will arise from various vendors and will be composed of solutions designed network to provide very fast download speeds and low latency. Its applications include economic growth, education, healthcare, transportation, power grid, smart cities, etc. The expected bands recommended (FCC) for 5G mobile communications are: 27.5–29.5, 42–45, 47–50.2, and 50.4–52.6 GHz [1]. Operating frequency is expected to be around Ka band (26.5–40GHz)[9]. The antenna with operating frequency of 28GHz will provide better results when compared to the other frequencies. Antenna designers showing more attention on microstrip patch antenna for its several advantages such as compact size, low profile, high reliability, low cost, etc[9]. With such benefits, microstrip patch antenna (MPA) has demerits too. Lower bandwidth is the major disadvantage. The circular patch antenna has the merit of their radiation pattern being symmetric. Other configurations are hard to analyze and require complex numerical computations. A microstrip antenna is justified by its Length, Width, Input impedance and Gain and radiation patterns. The various bandwidth enhancement of MPA is slot configuration, multiple radiating elements, parasitic patch, multiple feeding, and proximity couple. The applications of the slot antenna are used in broad range of applications from wireless and satellite communication system to medical system. Bandwidth is the major parameter which increases the user occupancy by adding more number of slots the bandwidth can be enhanced. This paper aims to propose a compact Doughnut slotted CMPA with good performances for 5G mobile communications operating at 28 GHz. To achieve this objective, two different models with multiple slot configuration and with CSRR etched ground structure are proposed. One is a conventional circular microstrip patch antenna with a multiple slotted antenna that obtained by modifying the first model to improve the gain, bandwidth, and antenna performance; and finally novel technique is introduced to reduce the patch dimension compared to conventional one and to enhance the performance of the proposed antenna system. CST tool issued to simulate and performance analysis of these antennas.

A. Problem Statement

In the past works, the microstrip antenna is designed and modified using different slot configurations and in some other cases modified by introducing different novel techniques in the design. The Antenna parameters such as return loss, VSWR, bandwidth, size, and gain are analyzed [5,6]. The existing antennas are of sizes 20 × 25 × 1.587mm [15] and 12 × 12.5×0.8mm [13]. The size is related to the gain and efficiency of the antenna. As the size of the antenna increases, the gain increases and the frequency decreases. It must be noted that improving particular characteristic of the antenna may result in the degradation of other performance characteristics. The major challenging task is to make an equity between the size of the antenna and other performance characteristics such as return loss, gain, bandwidth, and efficiency. For 5G mobile communication, a compact, high gain antenna is required. The proposed antenna intent to design a two different antenna structures such as first model modified by inserting multiple doughnut slotted configuration and in a second model a new CSRR etched ground structure is introduced of size 7*7*0.8 mm operating at 28 GHz is compared and analyzed which is considered to be suitable for 5G antenna design and the Rogers 3003 substrate of dielectric constant of 3, thickness of 0.8 mm and loss tangent of 0.01 is used in the design. By introducing doughnut slot in the design, the bandwidth gets enhanced than the existing design. The goal in the implementation of the CSRR into the patch antenna structure is to change the propagation conditions over the structure in such a way that the resonant frequency is shifted to a lower frequency, giving as a result a smaller antenna in comparison to a conventional one. The characteristics of the proposed patch antenna II are compared with that of a first model without CSRR at the ground plane. Both the structures of patch antennas are optimized using CST software.

II. DESIGN ANALYSIS OF CIRCULAR MICROSTRIP PATCH ANTENNA

A. Circular Microstrip Patch Antenna

For the circular patch design, the radial electrical fields of TM modes are given by the equation

$$E_{\rho} = E_{O} J_{N}(k_{nm} l)\cos[n(\beta - \beta_o)] \quad (1)$$

while k_m(x) is the Bessel function of the first kind of order m; and k_{nm} is the root of Jn (k_{nm}a) = 0
The resonant frequency of a circular patch antenna is approximately given by

$$f_{nm} = \frac{k_{nm} {*} c}{2\pi a_e \sqrt{\varepsilon_r}} \quad (2)$$

where c is the speed of light in free space; and ae is the effective radius that is given by

$$a_e = a\{1+(\frac{2h}{\pi a \varepsilon_r})[\ln(\frac{\pi a}{2h})+1.7726]\}^{0.5} \quad (3)$$

Therefore, the resonant frequency of (2) for the dominant TM_{110} should be expressed as

$$f_{110} = \frac{1.8412}{2\pi a_e \sqrt{\varepsilon_r}} c \quad (4)$$

A first-order approximation to the solution of (3) for the value a is to find ae using the equation (4) and to substitute it into (3) for ae and a in the logarithmic function. The circular patch of radius Rp calculated using the below equation

$$R_P = \frac{F}{\sqrt{\{1+\frac{2h}{\pi \varepsilon F[\ln(\frac{F\pi}{2h})+1.7726}\}}} \quad (5)$$

Where

$$F = \frac{8.791 * 10^9}{f_r \sqrt{\varepsilon}} \quad (6)$$

B. Substrate Length and Width

In general, substrate length *L* and width *W* are taken twice time larger than patch diameter (*2a*). So substrate length and width can be expressed as

L=2 × Patch Diameter = 2 × (2 R_P) (7)

W = 2 × Patch Diameter = 2 × (2 R_P) (8)

C. Microstrip Feed Line

The width and length of the microstrip feed line calculated by using the formula

$$\frac{\varepsilon_r - 1}{\varepsilon_r}[\ln[B+1]+0.39-\frac{0.6}{\varepsilon_r} \quad (9)$$

$$\frac{w}{h} > 2$$

$$\frac{w}{h} = \frac{8e^{A}}{e^{2A-2}} \text{ for } \frac{w}{h} < 2 \quad (10)$$

$$where\ A = \frac{Z_o}{60}\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}(0.23 + \frac{0.11}{\varepsilon_r} \ \&$$

$$B = \frac{377\pi}{2Z_o\sqrt{\varepsilon_r}} \quad (11)$$

then the length of feed line is given by

$$L_f = \frac{90\ xc}{w\sqrt{\varepsilon_{eff}}} \quad (12)$$

D. Quarter Wave Transformer

The quarter wave transformer is designed to achieve perfect impedance matching between the patch and the feed

E. Length of the Quarter Wave Transformer

$$\text{Length} = \frac{\lambda_g}{4} \quad (13)$$

Where λ_g is the guided wavelength, $\lambda_g = \frac{\lambda_o}{\varepsilon_r}$

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III. ANTENNA DESIGN AND RESULT ANALYSIS

The design of compact 7*7*0.8 circular microstrip patch antenna is on substrate Rogers RO3003 of dielectric constant (ε) 3, loss tangent 0.001 and substrate height (h) is 0.8mm. A circular patch of radius Rp using equation (5) is used to design an antenna resonating at 28GHz. The feed is at the bottom of the circular patch. A quarter-wave transformer provides matching to a transmission line for any load impedance. The impedance matching between the patch and the feed will be varying and to provide perfect matching the quarter-wave transformer is designed between the patch and the feed. In order to improve performance characteristics such as bandwidth and return loss of antenna, the design of patch antenna is modified by inserting doughnut slots and by introducing CSRR in the ground structure the performance get enhanced and also the patch size get reduced compared to the conventional one. Here, (Wg, Lg) are width and length of a ground, (Wf, Lf) represents the feed width and length and (Wt, Lt) represents the transmission line width and length and Rp represents the radius of the patch.

A. Proposed Antenna I (Before CSRR)

In the proposed Antenna-I a patch is designed as per the design specifications tabulated in Table 1 and further the multiple doughnut slots is inserted as per the dimensions mentioned in Table 2 and Fig. 2 displays the overview of proposed antenna design with the detailed dimensions and Fig. 5 shows the design of the proposed Antenna I.

Dimensions	Values(mm)
Width of the Ground Plane (Wg)	7
Length of the Ground Plane (Lg)	7
Height of the substrate	0.8
Dielectric constant (RT3003)	3
Ground Thickness	0.035
Radius of the patch (R_P)	1.72
Width of the feed line (Wf)	1.6
Length of the feed line (Lf)	1.35
Width of the transmission line (Wt)	0.5
Length of the transmission line (Lt)	3.2
Major axis of the inner doughnut slot	0.65
Minor axis of the inner doughnut slot	0.5
Major axis of the outer doughnut slot	0.95
Minor axis of the outer doughnut slot	0.8

Table 1 Dimensions of the Circular Microstrip Patch Antenna with inserted doughnut slot

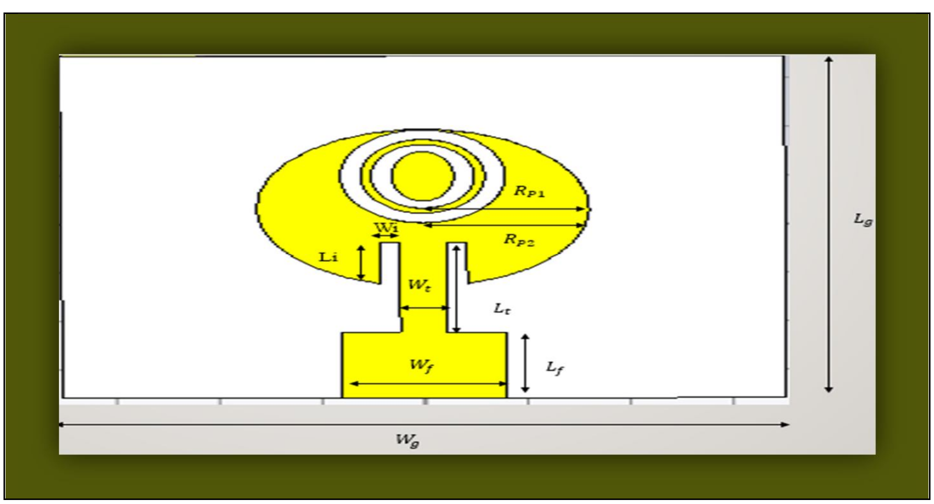

Fig. 2 Overview of the proposed Antenna I

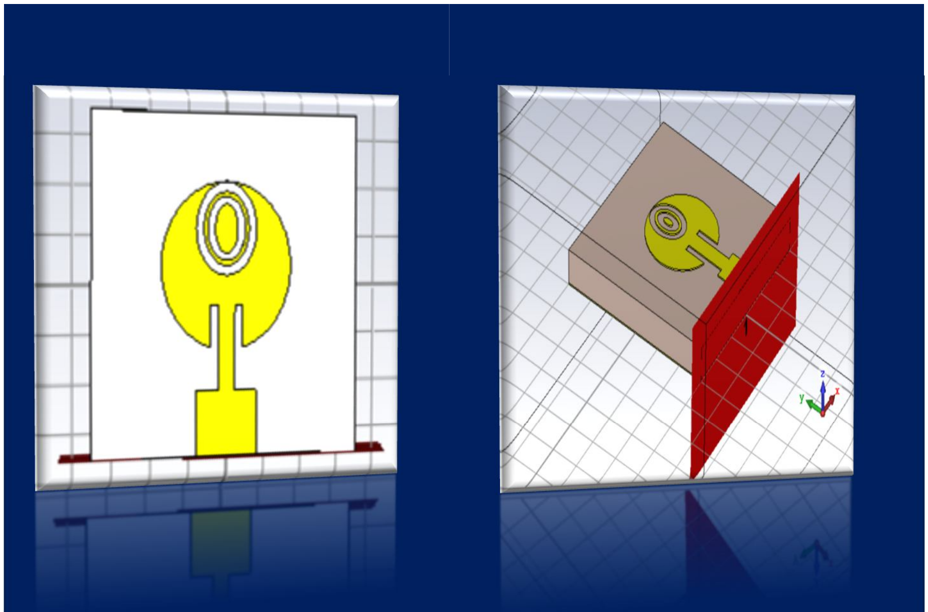
Fig. 3 Front View
Fig. 4 Side View

Fig. 5 Proposed Antenna I

The Fig. 3 and the Fig. 4 display the front and the back view of the proposed antenna I without CSRR loaded structure.

The Simulation results given for the circular patch antenna with a multiple doughnut slot before CSRR etched ground structure, is given in the Fig.6, Fig.7 and in Fig.8.

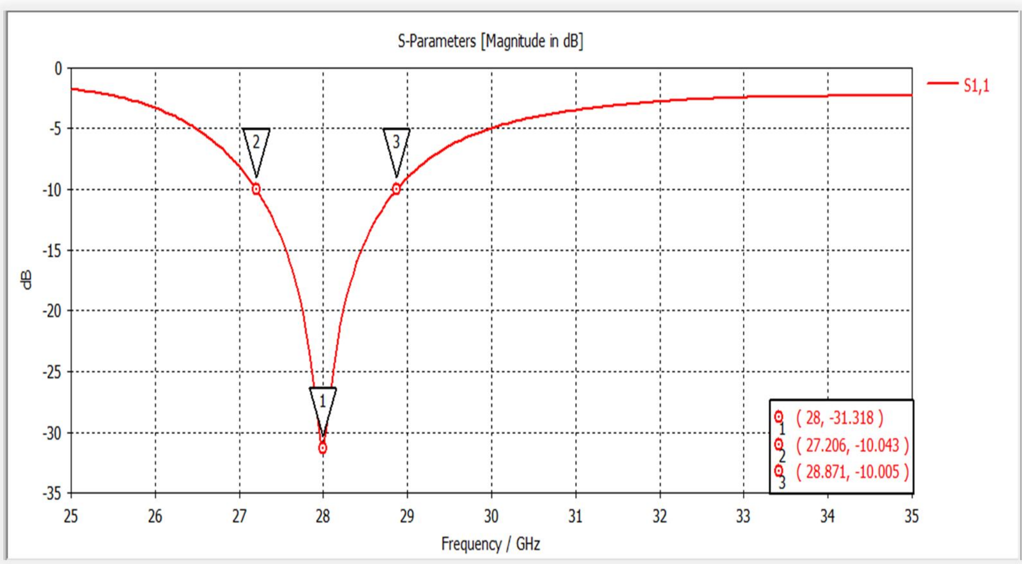

Fig. 6 Return Loss(S11) Plot of the Proposed Antenna I

From the return loss plot, we can observe that the value of the optimal geometry dimensions obtained. The reflection coefficient S11 of the proposed model I with doughnut slot before CSRR added ground plane is shown in Fig. 6. The value of S11 is found about -31.318 dB at the resonant frequency of 28GHz shown in Fig. 6. The antenna bandwidth (BW) is said to be that range of frequencies where the return loss (S11) is greater than – 30 dB. In our case, we can observe from the S11 curve that the bandwidth is equal to 1.665 GHz.

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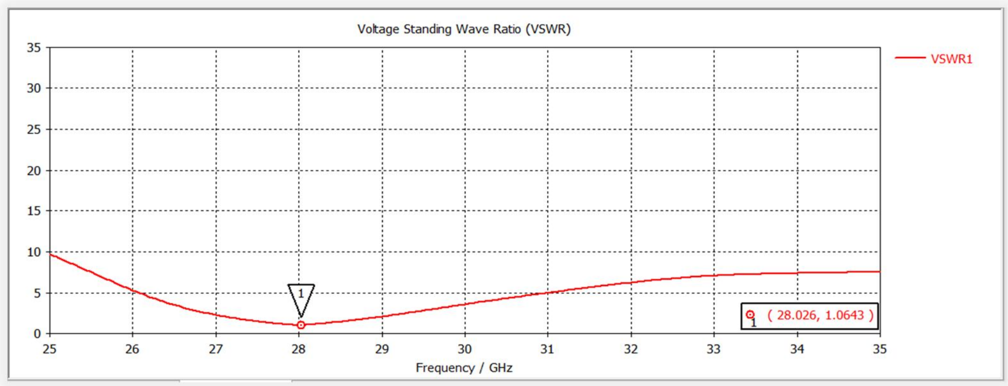

Fig. 7 VSWR Plot of the Proposed Antenna I

The voltage standing wave ratio (VSWR) of the proposed antenna-I is found to be 1.0643.

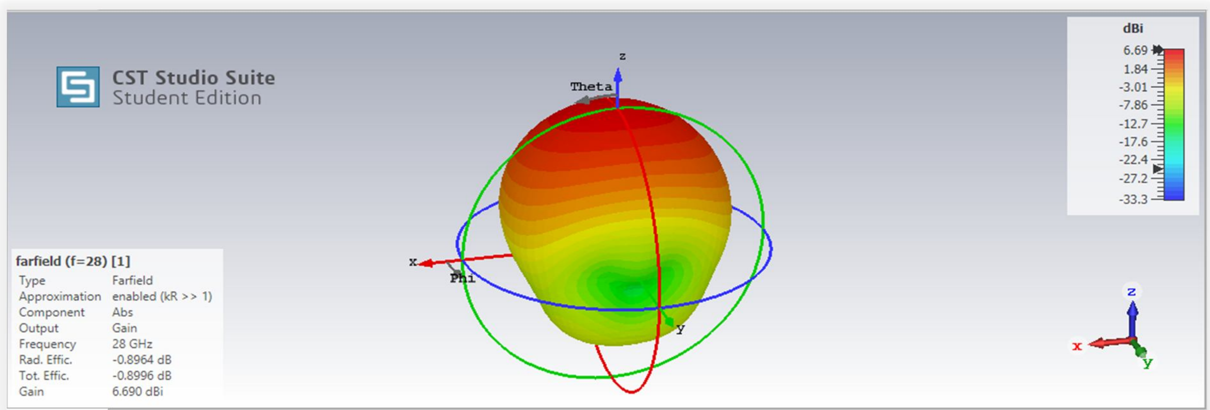

Fig. 8 3D Radiation Pattern displays gain of the proposed Antenna I

The 3D radiation pattern for the gain, provided by the proposed Antenna I, is shown in the Fig. 8 which is equal to 6.690 dB.

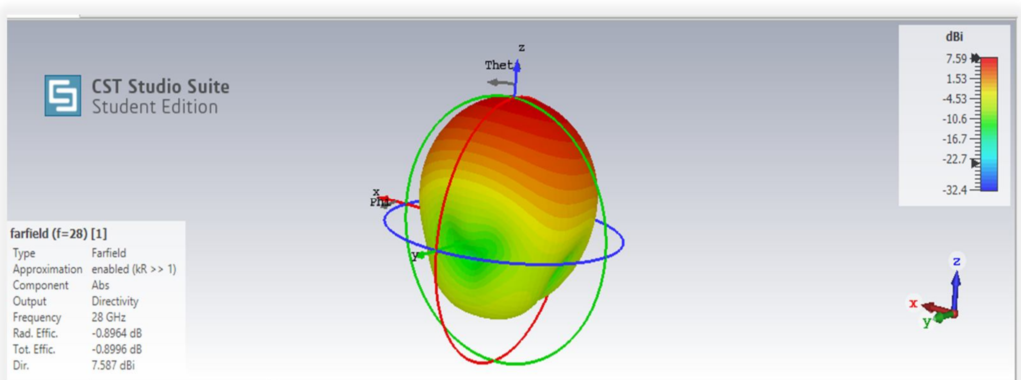

Fig. 9 3D Radiation Pattern displays directivity of the proposed Antenna I

The Fig. 9 shows the 3D radiation pattern of the directivity, provided by the proposed Antenna I, it is shown that the total directivity at 28GHz equals to 7.587 dB and the incident power is 1 W. The radiated power is found to be 26.085 dBm with radiation efficiency 81.35%.

The Table 2 summarizes the obtained simulations for the Antenna I, before CSRR for the optimum notch geometries.

Parameter	Proposed Antenna I
Return Loss	-31.318 dB
VSWR	1.0643
Gain	6.690 dBi
Directivity	7.587 dB
Bandwidth	1.665 GHZ
Radiated Power	26.085 dBm
Efficiency	81.35 %

Table 2 Simulation Results Obtained for Proposed Antenna I

B. Proposed Antenna II (After CSRR etched ground structure)

The Novel technique introduced on the ground plane for reducing the dimensions of patch antenna. The procedure is a complementary split ring resonators (CSRRs) for increasing the slow-wave effect on the radiator, and therefore augmenting its electrical length, which implicates the modified designed antenna gets a lower physical dimension than a conventional one for given frequency looking for preserving the electric characteristics of the antenna, such as a gain, the radiation pattern, the bandwidth, among others[2].Thus, the following Fig.12 the overview Proposed Antenna II C with CSRR etched ground plane detailed dimensions have tabulated in the table 3 and the fig. 15 show the design of Proposed Antenna II.

Dimension	Values
Outer radius (r1)	1.1025
Inner radius (r2)	0.9525
Width of the ring (w)	0.1
Thickness of the Ring (t)	0.1
Gap between the Ring (g)	0.1

Table 3 Design Specifications of CSRR Ring for Proposed Antenna II

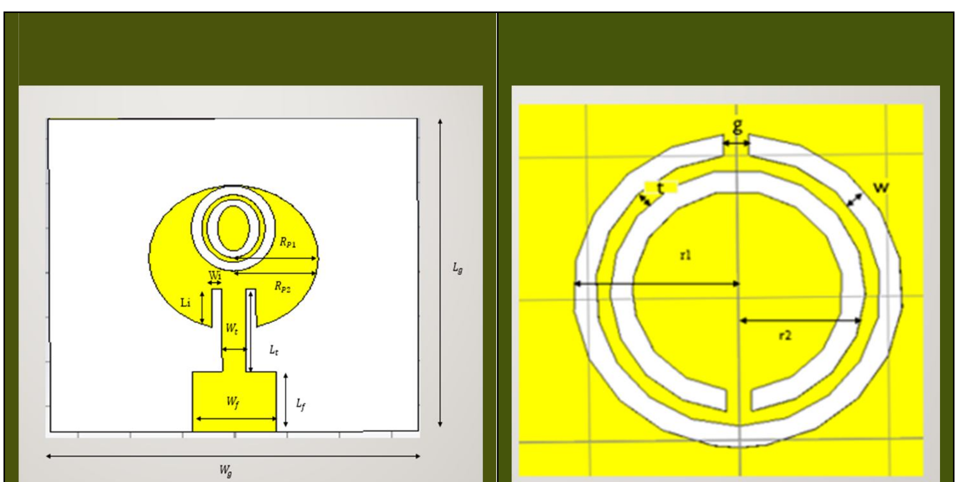

Fig. 10 Front View Fig. 11 Back View

Fig. 12 Overview of the proposed Antenna II

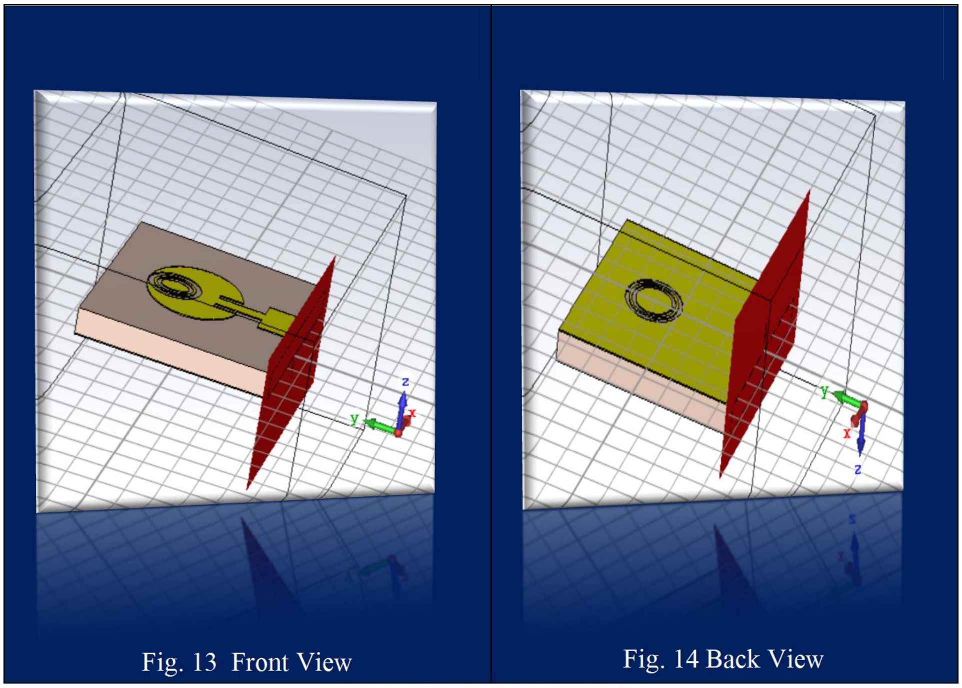

Fig. 13 Front View

Fig. 14 Back View

Fig. 15 Proposed Antenna II

The Fig.13 and the Fig.14 shows the front and the back view of the proposed Antenna I

The Fig.16 presents the return loss plot, after introducing the CSRR.

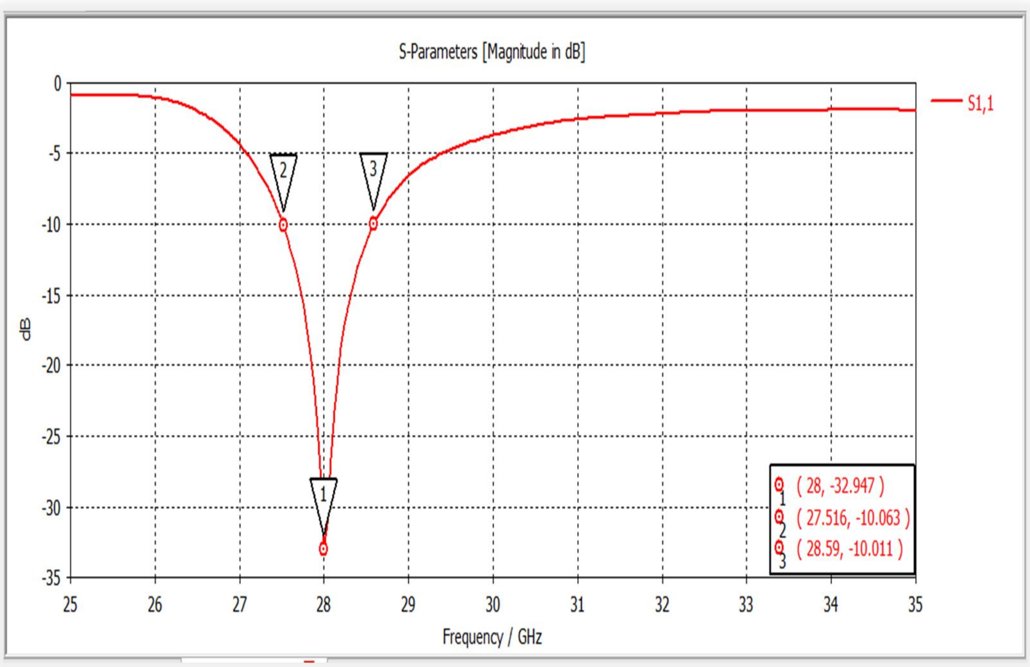

Fig. 16 Return Loss(S11) Plot of the Proposed Antenna II

From the plot, we can observe that after introducing the CSRR on the ground plane, the return loss has improved slightly from -31.318 dB to -32.947 resonating at 28 GHz. But the Bandwidth is slightly reduced from 1.6GHz to 1.07GHz

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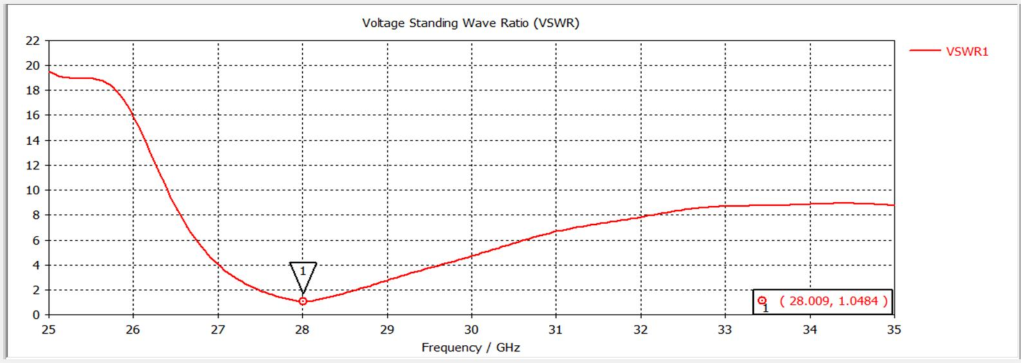

Fig. 17 VSWR Plot of the Proposed Antenna II

The VSWR plot shows that there is a improvement in the result after introducing CSRR in the structure from 1.0643 to 1.0484 which indicates that there is a good matching property. The Fig.18 shows the Radiation Pattern for the gain after the introduction of CSRR in the ground plane.

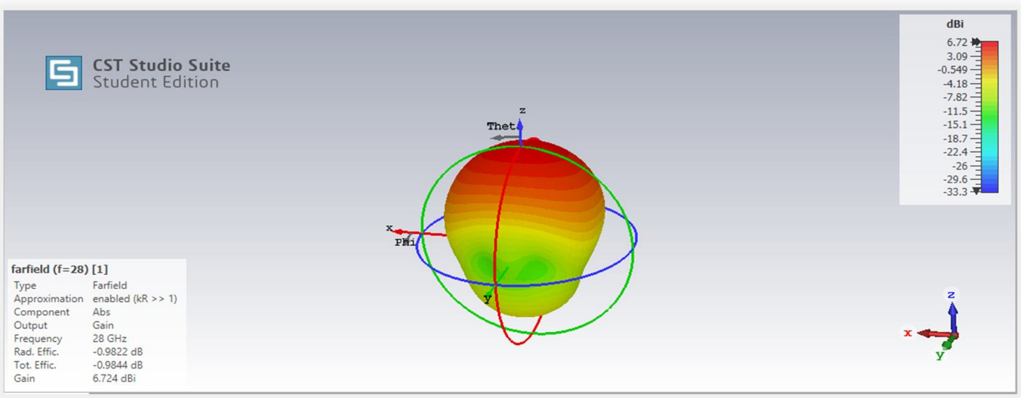

Fig. 18 Radiation Pattern displays the gain of the Proposed Antenna II

It is proved that from the radiation pattern obtained, that the gain of the antenna has improved significantly from 6.690 dBi to 6.724 dBi, which is a very important optimization of the proposed antenna.

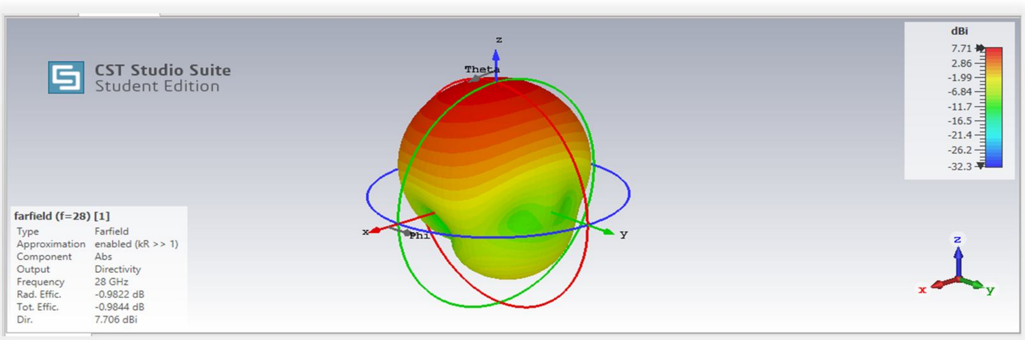

Fig. 19 Radiation Pattern displays the directivity of the Proposed Antenna II

It is proved that from the radiation pattern obtained, that the gain of the antenna has improved significantly from Same evident can be noticed in the case of the total directivity shown in the fig.19, which has raised from 7.587dB to 7.706 dB after an introduction of the CSRR and the incident power is 1 W. The radiated power is found to be 26.085 dBm with radiation efficiency 98% which is greater than the proposed Antenna I result.

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The Table 4 displays the comparison between the Proposed Antenna I and II and the Fig.20 shows the comparison graph. The return loss plays a major role in determining the antenna performance. The fig. 20 shows the comparison of return losses obtained by the proposed models. 6.690 dBi to 6.724 dBi, which is a very important optimization of the proposed antenna.

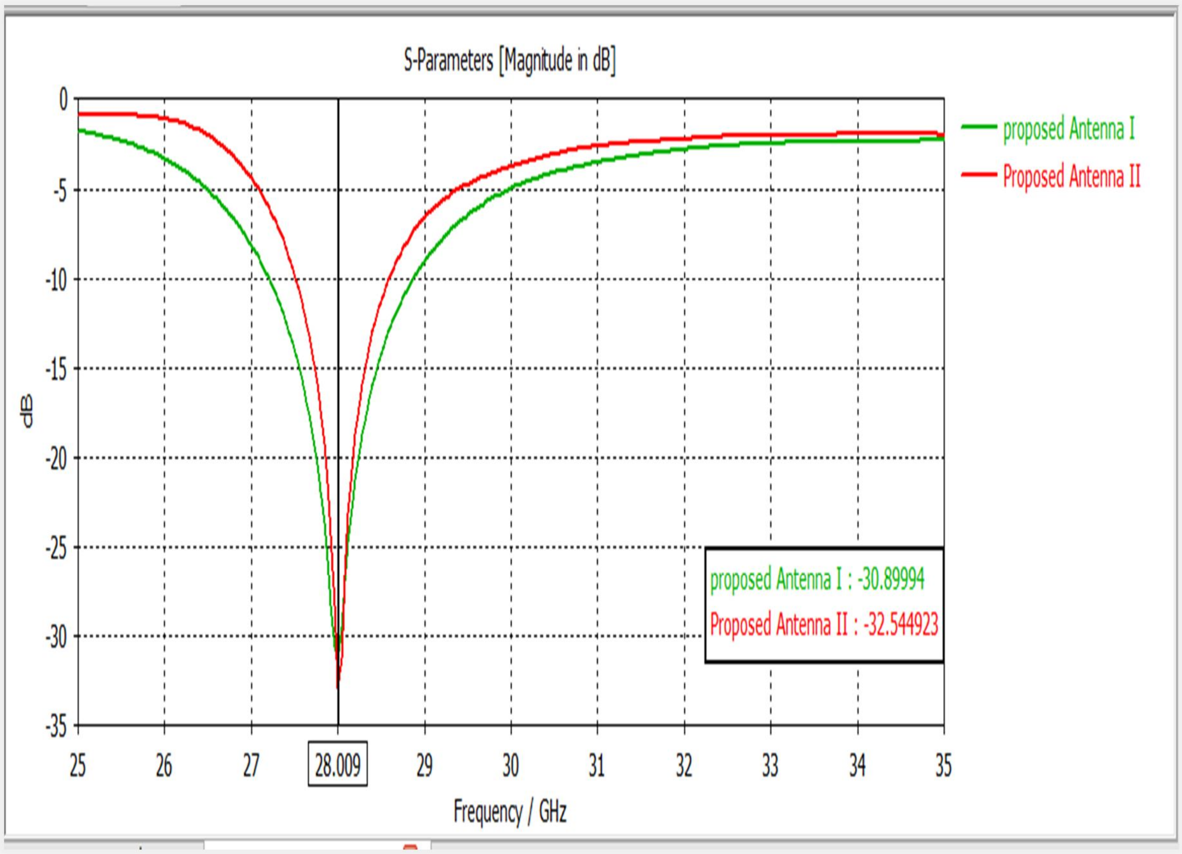

Fig. 20 Comparison graph of the Proposed models

Parameter	Proposed Antenna I	Proposed Antenna II
Return Loss	-31.318 dB	-33 dB
VSWR	1.0643	1.04
Gain	6.690 dBi	6.72 dBi
Directivity	7.587 dB	7.7 dB
Bandwidth	1.665 GHZ	1 GHZ
Radiated Power	26.085 dBm	26 dBm
Efficiency	81.35 %	98 %

Table 4 Comparison between the Proposed Antenna I and II

C. Comparison With the Related Works

In this section, a comparison is made between our proposed a prototype and previously published work [1] of a microstrip patch antenna with different slots or without slots and with and without novel technique which is solely applicable for 5G applications. The following table summarize the simulated results of the past and proposed work. By calculating the improvement rate of the previous work [1], we can notice there is an improvement of return loss, gain, directivity, efficiency, and VSWR operating at 28GHz in the proposed work which is considered to be suitable for 5G applications.

Published Antenna	Size (mm)	Slot & Technique	Return loss (dB)	VSWR	Bandwidth (GHz)	Gain (dBi)	Directivity (dB)	Efficiency (%)
[11]	20*25*1.575	Triangular slot	-40.64	-	4	5.75	-	-
[6]	10*10*0.787	-	-19.5	1.24	1.3	6.48	-	-
[10]	12*12.5*0.8	T slot & DGS technique	-38	-	2.62	6.5	7.45	90
[5]	8*8*0.8	H & E slot	-40.9	1.018	-	5.48	-	70
[7]	5*5*0.787	H slot	-16.9	1.335	2.8	-	-	82
[9]	7*7*0.8	Rectangular slot	-27.79	1.08	2.62	6.59	7.45	82
Proposed Antenna	7*7*0.8	Doughnut slot & CSRR technique	-33	1.04	1.04	6.72	7.7	98

Table 5 Comparison of proposed Antenna with the Existing designs

From the comparison Table 5 it is evident that the proposed antenna-II provides excellent performance over the existing antennas with better characteristics in terms of the size, the return loss, the bandwidth, the gain. Directivity, and efficiency.

IV. ANALYSIS OF RESULTS

The simulated results of proposed model I and II are pictured in above sections. So from the analyses it is cleared and evident that the proposed antenna II possess good characteristics than proposed Antenna I in terms of return loss it is found that is -31dB to -33dB which results that there is more amount of power is delivered to the antenna and less amount is reflected back to the source. The VSWR plot shows good matching property obtained from Antenna II compared to antenna I and the 3D radiation pattern shows that the ration of maximum radiation intensity to the average radiation intensity and the ratio of maximum radiation intensity of a subject antenna to the isotropic antenna also enhanced in terms of directivity and gain in propose antenna II. The bandwidth denotes the user occupancy it also good from the obtained result and the ratio of power radiated in all directions to the total input power supplied to the terminals in terms of efficiency also improved. Table 5 shows the comparison of the existing works with the proposed results. The gain, directivity, efficiency, VSWR, return loss and compactness are improved than the other antenna designs. Compared to the existing works, the proposed antenna shows compactness with miniaturized size of $7 \times 7 \times 0.8$ mm. The proposed compact antenna also provides the better gain of 6.7 dB and improvement in the bandwidth of 1 GHz which is good and the efficiency is much greater than the existing works.

V. CONCLUSION

The present work displays improved performance with variations in doughnut slots. By adding more number of slots the effective area gets decreased and the bandwidth enhanced which increases the user occupancy which is necessary for 5G mobile communication. And by adding CSRR etched ground plane the patch size reduced compared to the conventional one without affecting the electrical characteristics and notably there is an enhancement in performance characteristics. The overall dimension of the proposed antenna is 7 mm × 7 mm × 0.8 mm. The return loss is −33 dB with VSWR 1.04 which is less than 2 with the gain of 6.7 dBi and the directivity of 7.7 with the efficiency of 98%. As the analysis it is concluded that the gain, directivity, efficiency, return loss, VSWR bandwidth and compactness are improved. The proposed antenna-II provides excellent performance over the existing antennas with better characteristics. The size is compact and can be operated with good performance for 5G mobile communication system. Due to its compactness highly sensitive setup is required for fabrication as well as testing. In future scope, the designed antenna applicable solely for 5G antenna can be fabricated and tested.

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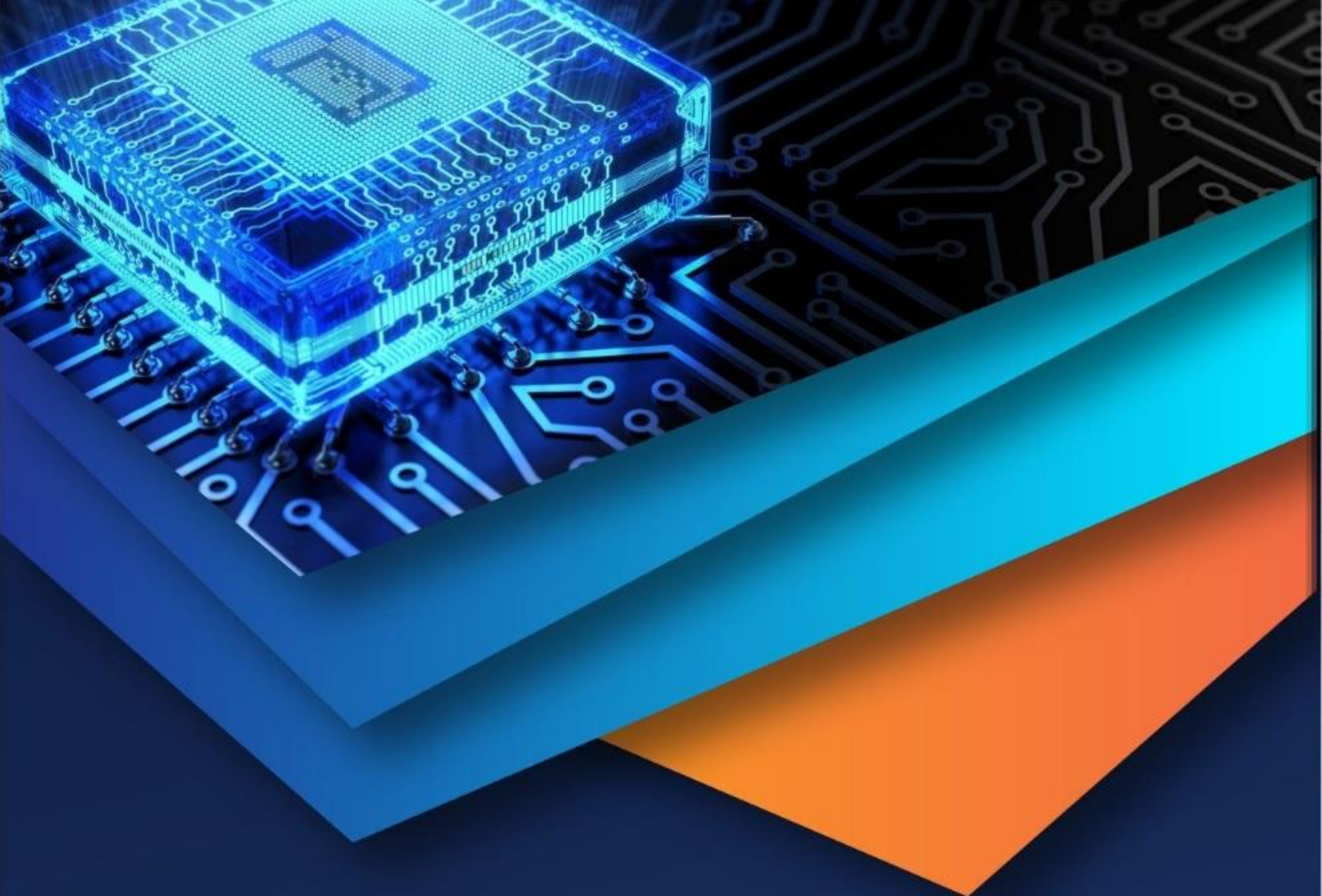

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