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Design and Analysis of a Circular Shaped Microstrip Patch Antenna for 5G Wireless Communication Systems

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Abstract— *This work designs a circular radiating patch antenna for the 3GHz–4GHz lower microwave frequency range. Using a microstrip feeder line and a 1.6mm thick FR-4 substrate, the antenna has an 11mm patch radius and four circular slots on the ground plane using computer simulation Technology software (CST). The design aims to improve performance metrics for 5G applications, with a bandwidth of 150MHz and a return loss of −16.84dB.*

Keywords – *Circular-radiating patch antenna, 5G applications, bandwidth, performance metrics, CST.*

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I. INTRODUCTION

Wireless networking is the area of technology that is causing the most conversation about social life in the twenty-first century. Many homes, businesses, and academic institutions now have access to new wireless local-area networks (Suriyan and Ramaingam, 2023). In the communications sector, antennas play a crucial role. It is a transducer that converts electrical energy into radio signals and radio signals into electrical energy, to put it another way.

By adjusting the design of the microstrip patch antenna for a variety of various parameters, the performance of the antenna can be increased. At many different operating frequencies, a printed antenna can be used for wireless communication. Today's world of wireless communication is one that is quickly changing and always evolving (Rana et al., 2023). An author conducted a study: a 28 GHz microstrip patch antenna is being developed for 5G communication technologies using Rogers RT/Duroid5880 substrate. Modeled using CST software, the antenna has a side lobe level of 38.348 dB, high radiation efficiency of 8.198 dB, reasonable return loss of 77 percent, and acceptable gain (Rana and Smieee, 2022; Rashmitha et al., 2020). This writer's work improves the impedance bandwidth of a slotted dual-band rectangular microstrip patch antenna by enhancing geometrical characteristics, achieving radiation efficiency of 75.457 percent at 28 GHz and 88.6237 percent at 38 GHz (Ayalew and Asmare, 2022).

This study aimed to enhance microstrip patch antenna gain using L and I shape slots in 5G antennas. The CST Studio Suite simulator was used for optimization and simulation. Results showed significant increase in gain with symmetric LI slots and rectangular slots (Nahas, 2022).

Another study simulated a hexagonal microstrip patch antenna for wireless 3.5 GHz backhaul, constructing up to 18 array elements using CST's software. This antenna offers focused radiation and high-capacity network connectivity, primarily used for point-to-point communications, with a good return loss and high gain at 3.5 GHz (Al-gburi and Ibrahim, 2022).

There are many algorithms that can be used in the design and optimization of microstrip antennas for 5G wireless communication. Some of the commonly used algorithms are:

a). Genetic Algorithm (GA): GA is a well-liked optimization technique applied to antenna design. It is based on the ideas of genetic recombination and natural selection (Dellaoui et al., 2018; Comisso et al., 2019).

b). Particle Swarm Optimization (PSO): A swarm of particles is used by the population-based stochastic optimization (PSO) technique to find the best solution. Each particle is a possible solution, and its motions are determined by its location at both the individual and global levels (Fu et al., 2022).

c). Ant Colony Optimization (ACO): ACO is a metaheuristic optimization method that draws inspiration from how ants forage. It functions by mimicking how ants leave pheromone trails to indicate the quickest route to food sources. ACO may be used in antenna design to find the ideal microstrip antenna shape (Jiang et al., 2020).

d). Differential Evolution (DE): Another well-liked optimization technique, DE, is based on the ideas of mutation and natural selection. It functions by integrating the disparities between randomly chosen solutions from the existing population to produce new potential solutions (Mahouti, 2019).
e). Simulated Annealing (SA): SA is a probabilistic optimization approach that gradually shrinks the search field through the use of a cooling schedule. It is based on the annealing procedure used in metallurgy to create materials with desired qualities. The best microstrip antenna parameters may be found in antenna design using SA (He et al., 2022).
The low profile, light weight, simplicity of production, and low cost of microstrip patch antennas make them a common component of wireless communication systems. Microstrip patch antennas for 5G communication systems can be difficult to design and optimize, though. The difficulties are as follows:
a). Bandwidth: High data rates need a broad bandwidth for 5G communication systems to handle. Depending on its size, shape, and substrate material, a microstrip patch antenna's bandwidth might vary. To get the desired bandwidth, designers must carefully pick these characteristics (Karami et al., 2021).
b). Frequency: Due to air attenuation, rain attenuation, and other variables, 5G communication employs higher frequencies than earlier wireless communication systems. As a result, signal loss may be enhanced. By optimizing the antenna's size and form, microstrip patch antenna design must account for these losses and try to reduce them (Hum and Xiong, 2010).
c). Polarization: Signals are sent and received by 5G communication systems using both linear and circular polarization. In order to obtain the correct polarization, the geometry and feeding mechanism of microstrip patch antennas must be optimized (Saeidi-Manesh and Zhang, 2019).
d). Antenna Efficiency: A microstrip patch antenna's efficiency is a measurement of the proportion of input power that is emitted as electromagnetic waves. A microstrip patch antenna's efficiency is influenced by a variety of elements, including the substrate material, the antenna's size and form, and the feeding method. To increase the antenna's effectiveness, antenna designers must carefully choose these factors (Karami et al., 2021).
e). Radiated Power: High radiated power is necessary for 5G communication systems to cover a vast region. In order to attain the necessary radiated power, the size and form of microstrip patch antennas must be optimized in relation to the communication system's power needs (Tarade and Khot, 2023).
In general, constructing and refining microstrip patch antennas for 5G communication systems necessitates a thorough comprehension of the underlying physics and a careful choice of the antenna's characteristics.
5G wireless communication necessitates microstrip patch antennas with higher frequencies, greater gain, and better impedance matching. Advanced techniques for designing and refining these antennas are essential:
a). Metamaterials: Metamaterials, artificial substances with unique properties, can enhance microstrip patch antenna performance by altering their electromagnetic properties, such as negative refractive index antennas, thereby boosting gain and reducing cross-polarization (Sumathi et al., 2021).
b). Millimeter-wave antennas: Millimeter-wave frequencies (30–300 GHz) enable 5G wireless communication due to high bandwidth availability and the use of high conductivity and low loss materials like graphene for microstrip patch antennas (Belabbas et al., 2021).
c). Reconfigurable antennas: Microstrip patch antennas with adjustable capacitors or varactors enable real-time reconfigurability of radiation pattern, polarization, or resonant frequency to meet evolving communication needs (Lavadiya et al., 2022).
d). Artificial intelligence (AI) optimization: AI methods like genetic algorithms, particle swarm optimization, and neural networks can optimize the design of microstrip patch antennas for 5G wireless communication, identifying ideal solutions (Aaref, 2021).
In general, these state-of-the-art technologies provide exciting design and upgrade opportunities for microstrip patch antennas for 5G wireless communication, enabling higher performance, more flexibility, and higher efficiency.

II. PROPOSED ANTENNA DESIGN

In this article a circular microstrip patch antenna is proposed with one circle placed over a substrate and ground plane. The ground plane is made of 0.035-thick copper electrical material and has the same substrate dimensions as the antenna. The antenna is built on a 1.6 mm thick FR-4 substrate with a 4.3 permittivity, 0.025 loss tangent, and five 3 mm circular defects directed in opposition to one another in the ground construction.
Moreover, the resonance frequency of this proposed model is suitable for 5G applications, such as smartphones, etc.
The cavity model equations are used in calculating the resonant frequency and radius of a circular patch:

2.1 Resonant Frequency Fr

Fr = (Summation of operating frequency bands)/2 …… Eqn 1

2.2 Radius of the Circular Patch

$F = (8.791 \times 10^9) / (fr \sqrt{\varepsilon r})$ …… Eqn 2

$r = F / (1 + 2h / (\pi \varepsilon r F [\ln(F\pi/2h) + 1.7726]^{0w5}))$ …… Eqn 3

where r = the radius of the patch; h = the height of the substrate; f = the resonance frequency in hertz; ε = the effective dielectric constant of substrate; Fr = the resonant frequency; F = the resonant factor.

Length and width of the substrate can be calculated by:

Substrate-length, Lsub = 6h + r = 6 × (Er) + r ………. Eqn 4

Substrate-width, Wsub = 6h + r = 6 × (Er) + r ………… Eqn 5

Where; h = height of substrate thickness. Also, same values for the ground length and width.

The antenna-wavelength:

λ = c/Fr ………. Eqn 6

Where, λ = Wavelength, c = Speed of light (3×10^8 m/s), Fr = Resonant frequency (Mukta et al., 2021). Below is the Antenna design layout:

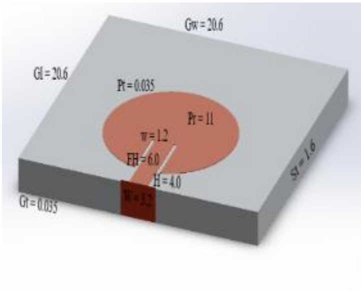

Fig. 1a – Front view

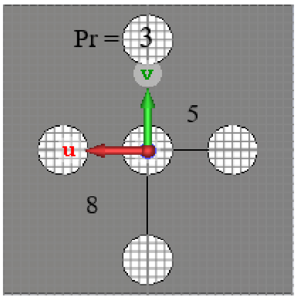

Fig. 1b – Back view

III. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

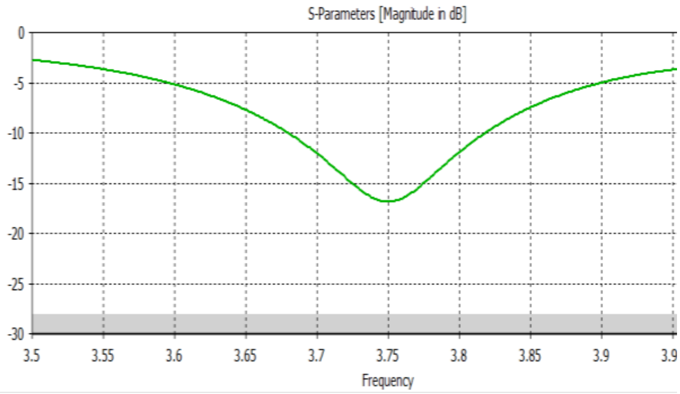

Fig. 2: Simulated reflection coefficient of the proposed antenna

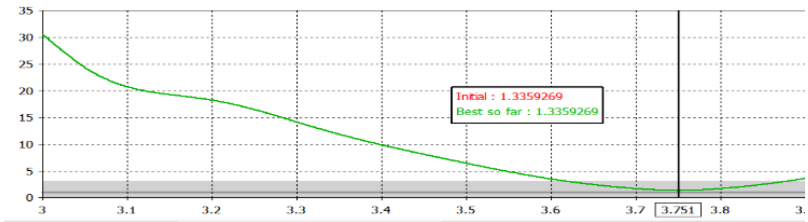

Fig. 3: Simulated voltage standing wave ratio for the proposed antenna (VSWR)

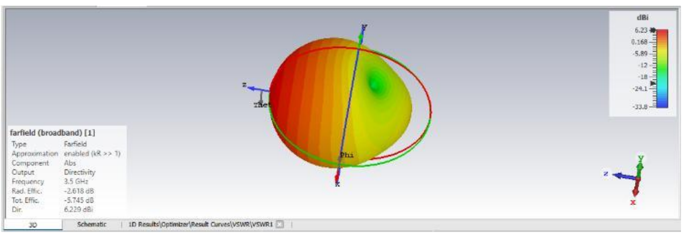

Fig. 4: Simulated directivity for the proposed antenna

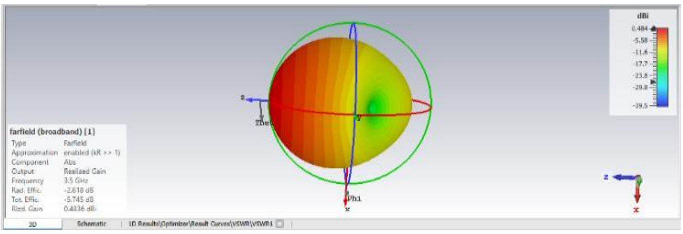

Fig. 5: Simulated 3D far-field realized gain for the proposed antenna

Table 1: Initial parameters of the proposed antenna

No	PARAMETER	L (mm)	W (mm)	H (mm)
1	Patch radius	–	–	R=11, H=0.035
2	Substrate	20.6	20.6	1.6
3	Microstrip feed line	6.0	3.2	0.035
4	Ground	20.6	20.6	0.035
5	Patch to feeder gap	4.0	1.2	–
6	Defected ground configuration	8.0	3.0	5.0

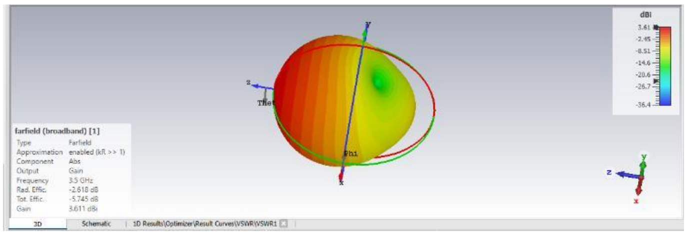

Fig. 6: Simulated 3D far-field gain for the proposed antenna

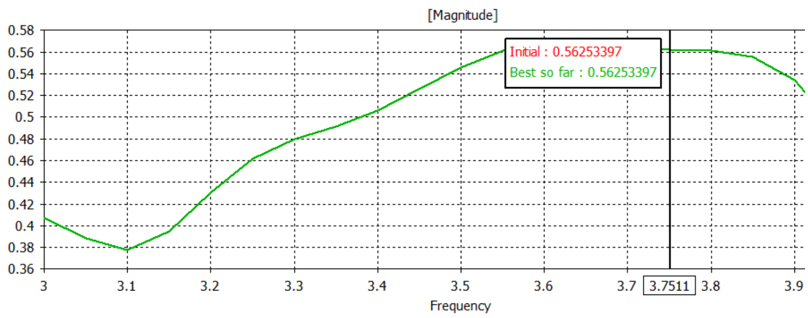

Fig. 7: Simulated antenna radiation efficiency for the proposed antenna

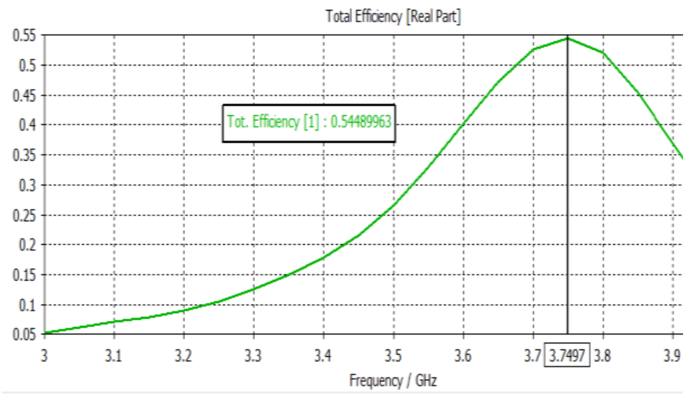

Fig. 8: Simulated antenna total efficiency for the proposed antenna

Table 2: Optimized parameter values

S/N	Proposed antenna result summary	Value
1	Circular patch radius @ 3.7GHz	11.03
2	S-parameter (S1,1)	-16.84
3	Bandwidth (MHz)	150
4	VSWR	1.33
5	Gain (dBi)	3.61
6	Realized gain (dBi)	0.483
7	Directivity (dBi)	6.229
8	Radiation Efficiency (%)	56
9	Total Efficiency (%)	54

Table 3: Proposed antenna result summary

S/N	PARAMETER	OPTIMIZED VALUE (mm)
1	Circular patch	11.03
2	Patch thickness	0.035
3	Ground length	20.63
4	Ground width	20.66
5	Ground height or thickness	0.034
6	Substrate length	20.63
7	Substrate width	20.66
8	Substrate height or thickness	1.5

IV. CONCLUSION

This work presented the design and simulation of a circular microstrip patch antenna operating within the 3GHz–4GHz lower microwave frequency band, targeting 5G wireless communication applications. The antenna was constructed on a 1.6mm thick FR-4 substrate with a dielectric permittivity of 4.3 and a loss tangent of 0.025, employing a microstrip feed line and a defected ground structure comprising five circular slots to enhance radiation characteristics.

The optimized circular patch radius of 11.03mm achieved resonance at 3.7GHz, with a return loss (S1,1) of −16.84dB, confirming strong impedance matching at the target frequency. The antenna exhibited a bandwidth of 150MHz and a VSWR of 1.33, which is well within the acceptable threshold of 2.0, indicating efficient power transfer with minimal reflection. The simulated gain of 3.61dBi and directivity of 6.229dBi demonstrate adequate far-field radiation performance suitable for 5G base-level applications. Radiation efficiency and total efficiency were recorded at 56% and 54% respectively, reflecting the inherent trade-off associated with the FR-4 substrate's moderate loss characteristics.

A key finding of this work is that the narrow bandwidth property is a direct consequence of the inverse relationship between the substrate's relative permittivity constant and the achievable bandwidth. Since commercially available substrates commonly exhibit permittivity values greater than 3.4, this imposes an inherent constraint on bandwidth expansion. The defected ground structure was found to partially mitigate this limitation by improving the impedance bandwidth without significantly altering the antenna's compact footprint. Overall, the proposed antenna satisfies the fundamental performance requirements for 5G lower-band applications and offers a low-cost, lightweight, and easily fabricable solution.

V. FUTURE WORK

Several promising directions emerge from the findings of this study for further investigation.

First, the introduction of a dual-band configuration on the circular microstrip patch antenna operating within the same 3GHz–4GHz lower microwave frequency band is recommended. This would increase spectral utilisation, accommodate more simultaneous users, and improve overall system capacity — directly addressing the bandwidth limitation identified in this work.

Second, alternative low-loss substrate materials such as Rogers RT/Duroid 5880 ($\varepsilon r = 2.2$) or Rogers RO4003C ($\varepsilon r = 3.55$) should be explored as replacements for FR-4. Given that the current design's 56% radiation efficiency

is constrained by FR-4's relatively high loss tangent, migration to a lower-loss substrate is expected to yield significant efficiency improvements, potentially exceeding 80%.
Third, the integration of a defected ground structure (DGS) with a more complex slot geometry — such as H-shaped or cross-shaped slots — could be investigated to further broaden the impedance bandwidth beyond the current 150MHz, without increasing the antenna's physical footprint.
Fourth, array configurations of the proposed antenna (2×1, 2×2) could be designed and simulated to evaluate gain enhancement for 5G beamforming and MIMO applications, where gain values of 8–12dBi are typically targeted.
Finally, physical fabrication and measurement of the proposed antenna using a vector network analyser (VNA) is essential to validate the CST simulation results and assess the impact of manufacturing tolerances on the antenna's resonant frequency and impedance characteristics.

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