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PERFORMANCE EVALUATION OF INSET FEED MICROSTRIP PATCH ANTENNA PARAMETERS WITH DIFFERENT SUBSTRATE MATERIALS FOR 5G WIRELESS APPLICATIONS

*This **study evaluates** the performance of an inset feed-microstrip antenna for various substrate materials (FR4, Rogers 5880, Rogers 6002, Polystyrene, and Ceramic) with different thicknesses (1.6 mm, 3.2 mm, and 4.8 mm) for 5G applications, focusing on key parameters such as return loss, efficiency, directivity, and realized gain. The **goal** is to determine the optimal substrate material and thickness that offers the best combination of these performance metrics across a frequency range of 3 to 4 GHz. The proposed method uses a new hybrid GA-PSO algorithm with Dynamic Adaptive Mutation and Inertia Control (DAMIC). The study optimized the MSPA design for each material and thickness, followed by detailed simulations using the Advanced System Design (ADS) tool. The approach included parametric analysis and systematic comparisons across the chosen substrate materials, quantifying their performance using specified metrics. **Results** indicate that Rogers 5880 consistently outperforms other substrates in terms of efficiency, directivity, and gain across all thicknesses. Polystyrene and Rogers 6002 also exhibited commendable performance, especially in the thicker substrates (3.2 mm and 4.8 mm), with Polystyrene achieving the highest directivity at 4.8 mm thickness. Rogers 5880 again led the performance in terms of efficiency, with efficiency values consistently above 70 % across all thicknesses, peaking at 86.38 % at 1.6 mm and 86.39 % at 3.2 mm. Ceramic and FR4 substrates demonstrated relatively lower performance, with Ceramic showing a moderate peak efficiency of 75.98 % at 1.6 mm and 50.79 % at 3.2 mm, while FR4 consistently had the lowest efficiency and directivity values, highlighting its limitations for high-performance antenna applications. Considering the return loss, the Rogers 5880 displayed the most favorable return loss characteristics, maintaining values well below -10 dB across the frequency range, which signifies excellent impedance matching. Rogers 6002 and Polystyrene also showed acceptable return loss characteristics although slightly higher than Rogers 5880, and they remained below 10 dB for most frequencies. Ceramic and FR4 exhibited higher return loss values, suggesting poorer impedance matching and higher signal reflection. In **conclusion**, The GA-PSO DAMIC optimization technique is a highly effective approach for designing antennas for 5G systems, enabling customized solutions for various substrates. Unlike traditional methods, the GA-PSO DAMIC approach enables precise tuning of key antenna parameters—return loss, gain, directivity, and efficiency—across various substrate configurations and thicknesses. The results demonstrate that the Rogers 5880 substrate, particularly at a thickness of 1.6 mm, consistently offers superior performance metrics, including high efficiency and low return loss, confirming its suitability for 3-4 GHz 5G applications. The results also reveal that Rogers 5880 is the superior substrate for high-frequency applications requiring high efficiency, directivity, and gain, followed by Polystyrene and Rogers 6002, particularly for thick substrates. Ceramic and FR4, although adequate in certain scenarios, are generally less optimal for high-performance requirements because of their lower efficiency and higher return loss. These findings provide critical insights into antenna design and material selection, emphasizing the significance of substrate choice in achieving desired performance metrics in modern RF 5G applications.*

***Keywords:** Microstrip Patch Antenna (MSPA); Inset feed; Substrate material; 5G applications; Performance analysis; FR4; Rogers 5880; Rogers 6002; Polystyrene; Ceramic.*

1. Introduction

5G technology promises unprecedented speeds, capacity, and connectivity in the rapidly evolving wireless communication landscape. To realize the full potential of 5G networks, efficient and high-performance antennas must be developed. Among the various antenna configurations, microstrip patch antennas are highly regarded for their compactness, low profile, and compatibility with integrated circuit technology.

1.1. Motivation

The rapid advancement of 5G and next-generation wireless communication technologies has created a critical need for high-performance antennas that meet stringent criteria in terms of return loss, gain, directivity, and efficiency. Microstrip patch antennas (MSPAs) are highly valued in 5G applications because of their compact size, ease of integration, and planar configuration, making them suitable for portable and handheld devices. However, MSPA performance is significantly affected by substrate material properties, thickness, and frequency range. Identifying the ideal substrate and structural configuration is essential to ensure optimal signal transmission, minimize power losses, and enhance device performance in 5G environments. This study addresses these needs by investigating the influence of various substrate materials and thicknesses on key performance metrics across the 3–4 GHz frequency range, which is commonly used in 5G networks. By optimizing substrate selection, this study advances antenna designs that maximize efficiency and reliability for practical 5G deployment.

1.2. State of art

A comparative analysis of performance parameters for inset feed microstrip patch antennas with various substrate materials for 5G applications revealed significant findings. The effects of the conductor thickness on the center frequency of a microstrip patch antenna using an air substrate at 28 GHz for 5G applications is shown in paper [1]. This study successfully demonstrated that variations in the thickness of the conductive material and substrate significantly affect the antenna's bandwidth, gain, and efficiency in 5G applications. A mathematical model was developed to support the findings. The results suggest that optimizing the conductor thickness can play a crucial role in enhancing the performance of microstrip patch antennas for 5G devices, offering a cost-effective and efficient solution for future communication technologies.

The antenna design plays a crucial role in achieving the required quality of service in 5G networks, focusing on improving the antenna gain through controlled frequency behavior, beamforming, and proper antenna material selection. By examining the impact of substrate thickness on the propagation losses and radiation characteristics, this research enhances the antenna efficiency by up to 20%. Different antenna arrays are designed in [2] to improve the reflection coefficients, thereby contributing to the overall performance enhancement of millimeter-wave antennas for 5G communication.

Microstrip patch antennas are popular due to their low weight, small size, and low cost but face issues such as poor gain and narrow bandwidth. The integration of graphene layers within the copper radiating patch allows effective tuning of the antenna characteristics. The use of a frequency-selective surface (FSS) superstrate further enhances antenna parameters like gain and return loss for 28 GHz band applications. A previous study [3] demonstrated the potential of using graphene and FSS structures to enhance the performance of microstrip patch antennas for advanced communication systems like 5G.

A systematic design approach was proposed in [4] for a high-performance, low-cost dual-polarized broadband microstrip patch antenna for 5G mmWave applications on an FR4 substrate. This paper presents a novel use of the characteristic mode analysis (CMA) method to design antennas, focusing on dielectric loss mitigation and broadband patch antenna design. This study showcases the use of high-loss FR4 material instead of traditional high-cost materials like Teflon or ceramics, demonstrating the feasibility of implementing high-performance mmWave antennas on low-cost, high-loss substrates. Capacitive elements such as proximity L-probe feeding and parasitic patches were employed to enhance the antenna's impedance bandwidth, thereby contributing to its overall performance.

The synthesis of a broadband matching circuit (BMC) with lumped parameter elements demonstrates reduced sensitivity invariance, which is crucial for efficient data transmission in modern mobile networks. By optimizing antenna design with new composite materials, this research significantly advances the development of 5G technologies and provides valuable insights for engineers and designers working in this field [5].

Different studies utilize materials like Rogers RT5880 epoxy, Rogers RT/Duroid 5870, and Teflon substrates with varying dielectric constants. These substrates affect the antenna characteristics, such as the bandwidth, return loss, VSWR, and efficiency [6]. Techniques like slotting on the ground surface and the incorporation of defected ground structures enhance the bandwidth and efficiency of 5G communication systems [7].

The antennas designed and simulated using software like CST Microwave Studio and ANSYS HFSS demonstrate improved performance parameters suitable for 5G frequencies, highlighting the importance of substrate material selection in optimizing antenna performance for next-generation communication applications. An antenna designed with FR4-Epoxy substrate achieved tri-band characteristics in the S-band, C-band, and X-band frequencies [8].

Another study utilized a Rogers RT 5880 substrate to develop a high-quality antenna for 5G millimeter wave bands, exhibiting exceptional results, such as a reflection coefficient of -32.86 dB and a high gain of 10 dB [9]. Additionally, a microstrip antenna designed for 5G wireless mobile communications demonstrated simplicity and compactness, making it suitable for diverse wireless applications and IoT technologies [10].

Furthermore, the use of graphene in antenna fabrication showed benefits like size miniaturization, gain enhancement, and increased bandwidth, making it a promising alternative for higher frequency applications like

5G [11]. Several studies have explored the impact of substrate materials on antenna performance. Research by Rana et al. focused on FR-4 substrate, achieving a VSWR of 1.3176 and a bandwidth of 116.6 MHz [12]. Rahman and Hasan's work highlighted the use of a Taconic-TLX-9 substrate, obtaining a VSWR of 1.102 and a bandwidth of 0.708 GHz [13]. Additionally, investigations by Nataraj and Prabha focused on the Rogers RT5880 substrate, exhibiting optimized performance at 28GHz [14]. Furthermore, Pandya et al. studied various dielectric materials like RT Duroid (5880), Teflon, and FR4, exhibiting different bandwidth and return loss performances [15]. These studies highlight the critical role of substrate materials in influencing the efficiency and characteristics of microstrip patch antennas for 5G applications. The optimization of the design parameters of the antennas to enhance performance was discussed in [25]. The optimized key parameters are the thickness of the dielectric substrate, the width and length of the antenna patch, and the placement of elements to improve the isolation and bandwidth. For example, a thicker dielectric substrate can increase bandwidth but may also excite surface waves, which is why selecting an optimal thickness (like 1.6 mm for the FR4 substrate) is critical. Similarly, adjusting the width and length of the antenna patch can control the resonant frequency and improve the impedance matching. Parametric studies in this paper found that reducing the length of the parasitic strips slightly shifts the operating frequencies and decreases the gain at both the 3.45 GHz and 5.9 GHz by maintaining a suitable bandwidth for 5G applications [26]. In contrast, reducing the width of the parasitic strips significantly increased the gain at both frequencies, with minimal impact on bandwidth. These findings demonstrate that optimizing the parasitic strip dimensions is crucial for improving the antenna gain and overall performance in 5G communication systems. The present paper [27] explores a variety of techniques that contribute to improving antenna performance, such as Metamaterial Incorporation, Slot-Based Enhancements, Electromagnetic Band Gap (EBG), Dielectric Resonator Antennas (DRAs), by selecting appropriate substrate materials that balance size and performance to optimize antenna parameters. The authors of the study [27] presented a parametric analysis that involves changing certain antenna dimensions and then observing how these changes affect the return loss, operating frequency, VSWR (Voltage Standing Wave Ratio), and gain. To achieve this, the authors used the parameter sweep function in the HFSS simulator. Then, we examined how changes in the slit length, slit width, feed width, inset gap width, and substrate thickness influence the antenna performance.

From the literature, it is evident that dielectric constants, loss tangent, and substrate thickness play vital roles in MSPA performance, with materials like Rogers 5880 often providing superior results due to low dielectric loss and high gain properties. However, cost-effectiveness and availability also influence substrate choices, leading to a trade-off between ideal performance and practical deployment. Existing optimization techniques, such as genetic algorithms (GA) and particle swarm optimization (PSO), have been used to enhance antenna design; however, hybrid approaches are emerging as more effective for navigating complex, multidimensional design spaces. This study leverages a hybrid GA-PSO algorithm with dynamic adaptive mutation and inertia control (DAMIC) integrated with ADS simulations to comprehensively evaluate and optimize MSPA designs.

1.3. Objective and Approach

The main objective of this study was to determine the optimal substrate material and thickness that provided the best combination of return loss, gain, directivity, and efficiency within the 3–4 GHz frequency range, as stated in the abstract. Achieving this objective requires analyzing multiple substrates under different configurations to assess their impact on the key performance metrics. To meet this objective, the proposed method employs a hybrid GA-PSO algorithm enhanced with DAMIC, which is implemented in MATLAB and integrated with Keysight ADS for accurate fitness evaluation. This approach enables a precise optimization process, with MATLAB handling the iterative optimization and ADS providing real-time electromagnetic simulation data to evaluate the fitness function. Each substrate (FR4, Rogers 5880, Rogers 6002, Polystyrene, and Ceramic) is evaluated at various thicknesses (1.6 mm, 3.2 mm, and 4.8 mm) to determine the best configuration in terms of performance across the selected frequency range. The algorithm iteratively adjusts the patch dimensions and feed position based on the real-time simulation data to optimize the return loss, gain, directivity, and efficiency. The results were compared to determine which substrate and thickness combination meets the requirements of high-performance 5G applications.

The article begins with an introduction that explains why it is important to study how different materials affect the performance of microstrip patch antennas (MSPAs) in 5G applications, and it clearly states the study's main goals. Next, the Literature Review summarizes existing research on MSPA materials and optimization techniques, highlighting the need for improved methods. In the Methodology section, the hybrid GA-PSO algorithm with DAMIC is described in MATLAB, along with its integration with ADS for real-time simulation to find the best material and configuration. The Results and Analysis section presents and compares the performance outcomes for each tested material and configuration. The Discussion summarizes the key findings and discusses

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the study's practical implications and limitations. Finally, the Conclusion highlights the importance of selecting the appropriate material for MSPA performance and suggests areas for future research, such as exploring additional materials and frequency ranges.

2. Antenna Design and Substrate Materials

A microstrip patch antenna consists of a radiating patch on one side of a dielectric substrate and a ground plane on the other side. The MSPA may have different shapes, such as square, circular, triangular, semicircular, sectoral, and annular rings. Radiation from the MSPA can occur from the fringing fields between the patch and ground plane [16]. The inset feeding method is used where the transmission line feeding the antenna is connected at a point slightly away from the edge of the patch, as shown in Figure 1.

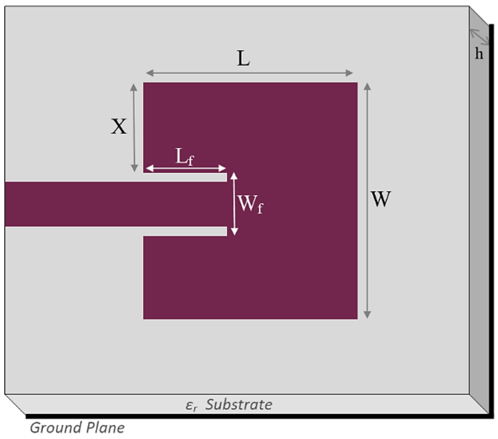

Fig. 1. Inset Feed Microstrip Patch Antenna

This method differs from traditional edge-feed configurations in which the feed line is connected at the edge of the patch. The inset feed enhances the antenna performance in terms of bandwidth, efficiency, and radiation pattern. This makes inset feed microstrip patch antennas a popular choice for various applications, including wireless communication systems like 5G, where high performance and compact size are crucial [18].

The dielectric substrate of a microstrip patch antenna plays a crucial role in determining its performance. Essentially, it affects the antenna's size, bandwidth, efficiency, and impedance matching. Materials with higher dielectric constants have smaller antennas but narrower bandwidths, whereas those with lower dielectric constants have the opposite effect [17]. Moreover, substrates with lower loss tangents ensure that less energy is lost as heat, leading to higher radiation efficiency. Additionally, the substrate choice affects the antenna's ability to minimize surface wave losses and achieve proper impedance matching with the feeding [19]. Thus, selecting the right dielectric substrate is essential for optimizing microstrip patch antennas to achieve the desired performance metrics for specific applications. Here, we considered four dielectric substrates, namely, FR4, Rogers RT/duroid 5880, Polystyrene and ceramic, for exploring the antenna performance under different parameters. The key characteristics of the substrate materials are summarized in Table 1.

Table 1

Key characteristics of the substrate materials

Substrate type	Dielectric constant	Loss tangent	Frequency Band	Substrate thickness (mm)
FR4[21][24]	3.9 – 4.4	0.02	>1GHz	1.6
Rogers RT/duroid 5880[22][24]	2.2	0.0004	2.8 – 5.8GHz	~1.6
Rogers RT/duroid 6002[24]	2.94	0.0012	> 1GHz	~1.6
Polystyrene [23][24]	2.54	0.00033	10GHz	1.6
Ceramic	5.6	0.0003-0.0015	>1GHz	1.5

2.1. Antenna Design equations

To calculate W and L values of the patch (refer Fig. 1),

$$W = L = \frac{c}{(2f\sqrt{\varepsilon_r})}. \quad (1)$$

where, f is the designed frequency and ε_r is the dielectric constant. The length(L) and width(W) of the feedline connected to the patch is calculate using equation (2) and (3),

$$L_f = 0.822 \times L/2, \quad (2)$$

$$W_f = W/5\ , \quad (3)$$

$$X = 2W/5. \quad (4)$$

Since the current is sinusoidal through the surface of the patch which travels from edge to inset end over distance L_f, it will increase the current by $\cos(\frac{\pi L_f}{L})$ with the wavelength $\lambda = 2L$ and the phase difference of $\Delta\Phi = \frac{\pi L_f}{L}$. The impedance was scaled by

$$Z_o = Z_{in} \cos^2\left(\frac{\pi L_f}{L}\right). \quad (5)$$

From the equation (5), L_f is the inset distance from the radiating edge, and Z_{in} denotes the resonant input resistance when the patch is fed at a radiating edge. The inset distance (L_f) is chosen to ensure that the feed line impedance matched Z_0. The notch width, W_f, is positioned symmetrically across the width of the patch. After establishing the foundational equations for antenna design, the next step is to apply an optimization approach that effectively refines these parameters to achieve optimal antenna performance. To this end, the following section introduces a hybrid GA-PSO algorithm enhanced with Dynamic Adaptive Mutation and Inertia Control (DAMIC), which is used to optimize the antenna design based on these equations.

2.2. Optimization Technique: An improved Hybrid GA-PSO Algorithm with Dynamic Adaptive Mutation and Inertia Control (DAMIC)

To maximize the performance of the microstrip patch antenna across critical metrics such as return loss, gain, directivity, and efficiency, we employ a hybrid GA-PSO algorithm integrated with DAMIC. This section outlines the step-by-step optimization process and describes how the algorithm iteratively adjusts the antenna parameters to optimize the design. The base equations were derived from [20].

Step 1: Substrate-Specific Initialization: Initialize a population of **N** candidate antenna designs (particles/individuals), where each design is defined by a set of parameters:

- Patch length (L), width (W),
- Substrate thickness (h),
- Feeding point location (L_f, W_f),
- Substrate material dielectric constant (ε_r).

$$x_i^{initial}=x_i^{nominal}\times(1+randn(\mu,\sigma)), \quad (6)$$

where, $x_i=[L_i,W_i,h_i,L_{fi},W_{fi},\epsilon_{ri}]$ and $x_i^{initial}$ is the initial value of the i-th parameter, $x_i^{nominal}$ is the nominal value based on substrate properties and randn(μ,σ) generates a normally distributed random number with mean μ and standard deviation σ.

Step 2: Fitness function: The fitness function is a composite function that evaluates the performance of the antenna design based on several criteria, including beamwidth, side lobe level (SLL), gain, dielectric constant sensitivity, and substrate thickness.

$$f(x)=w_1\times f_{bw}(x)+w_2\times f_{sll}(x)+w_3\times f_g(x)+w_4\times$$

$$\times f_{\epsilon r}(x)+w_5\times f_t(x), \quad (7)$$

where, $f_{bw}(x)$: Penalizes deviations from the desired beamwidth.

$f_{sll}(x)$: Penalizes higher side lobe levels.

$f_{gain}(x)$: Evaluates the gain performance.

$f_{\epsilon r}(x)$: Penalizes deviations in performance due to variations in the substrate dielectric constant.

$f_t(x)$: Assesses the effect of substrate thickness on the return loss and impedance matching.

Step 3: Select the fittest individuals from the population based on their fitness scores and perform crossover to combine the information from the two parent solutions to generate offspring.

Single-Point Crossover Equation is given in equation 8 and 9

$$x'_1=\alpha\times x_{p1}+(1-\alpha)\times x_{p2}, \quad (8)$$

$$x'_2=(1-\alpha)\times x_{p1}+\alpha\times x_{p2}, \quad (9)$$

where, x_p parent parameter and α is a random number between 0 and 1.

Step 4: Dynamic Adaptive Mutation (DAMIC): The mutation rate is adjusted dynamically based on the current iteration as follows:

$$\text{mutation rate}(t) = \text{mutation\_rate}_{max}\times\left(1-\frac{t}{T}\right). \quad (10)$$

This ensures that mutation rates are high in early iterations, enabling broad exploration, and low in later iterations, allowing fine-tuning. Similarly, the inertia weight is reduced dynamically to prevent premature convergence in PSO:

$$w(t) = w_{max}-(w_{max}-w_{min})\times\left(\frac{t}{T}\right) \quad (11)$$

Step 5: To maintain diversity and avoid local minima, mutations that are adaptive.

$$x_i^{mutated}=x_i^{current}+\gamma\times(rand()-0.5)\times(x_{max}-x_{min}) \quad (12)$$

where, γ is an adaptive mutation factor.

Step 6: Update the velocity of each particle based on its own best position, global best position, and best position found by its neighbors.

$$v_i(t+1)=w(t)\times v_i(t)+c_1\times r_1\times(p_i^{best}-x_i(t))+c_2\times r_2\times(p_g^{best}-x_i(t))+c_3\times r_3\cdot(p_n^{best}-x_i(t)) \quad (13)$$

where, vi(t+1) is the updated velocity of the i-th particle, w(t) is the inertia weight, c1, c2, c3 are acceleration coefficients and r1, r2, r3 are random numbers in the range [0, 1].

Step 7: Update the position of each particle using equation 14 and evaluate whether the algorithm has converged to an optimal solution using equation 15. If not, the process is repeated.

$$x_i(t+1)=x_i(t)+v_i(t+1) \quad (14)$$

$$|f_{current}-f_{best}|<\epsilon, \quad (15)$$

where, ϵ is a small threshold value indicating convergence.

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The GA-PSO DAMIC algorithm shown in Figure 2 is implemented using MATLAB to iteratively update the design parameters, such as the patch length and width, with the aim of improving performance metrics like return loss (S_{11}) and gain.

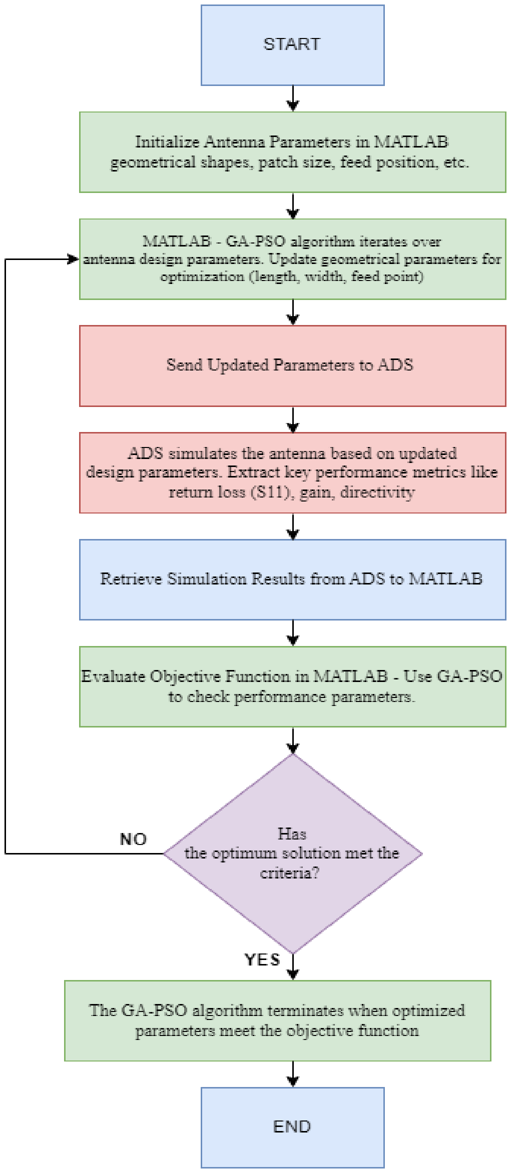


Fig. 2 Flow chart of GA-PSO DAMIC algorithm

After each update, the parameters are sent to ADS, where a detailed electromagnetic simulation is performed. ADS calculates critical values, particularly S_{11}, which indicates how well the antenna is impedance-matched across multiple frequency bands. The results from ADS are then returned to MATLAB, where the objective function(convergence) evaluates the desired antenna results (Fig. 3). This feedback loop continues as the GA-PSO algorithm refines the design by dynamically balancing the exploration of new solutions and fine-tuning the best-performing designs. The process is repeated until the antenna design meets the desired performance criteria, ultimately producing an optimized, miniaturized antenna ready for implementation. After obtaining the optimized design values for the antenna with respect to each substrate material shown in Table 2, the antenna was designed in ADS, and a comparative analysis was performed to obtain the optimum solution for choosing the appropriate substrate for 5G sub-GHz frequency band. The detailed discussion on various parameters is discussed in section 3.

3. Results and Comparative Analysis

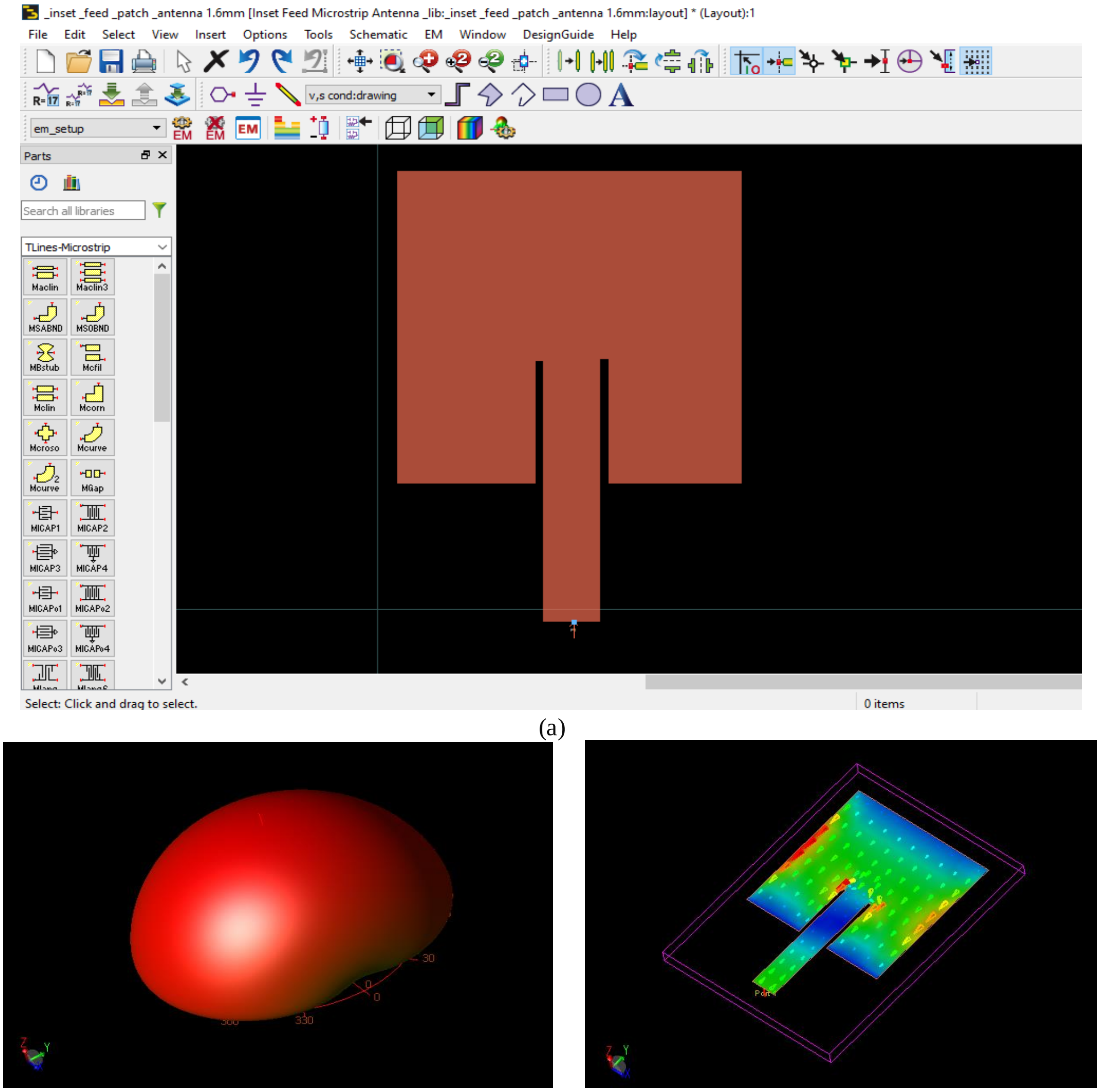
In this section, we present a detailed analysis of the results obtained by applying the hybrid GA-PSO algorithm with Dynamic Adaptive Mutation and Inertia Control (DAMIC) to optimize the microstrip patch antenna design. Table 2 lists the optimized dimensions of the antenna. The proposed antennas were designed and simulated using Keysight Advanced Design software, which is a division of Keysight Technologies.

For all the calculated patch antenna dimensions given in Table 2, the results are structured to provide a comparative assessment of key performance metrics—Return Loss (S11), Gain, Directivity, and Efficiency—across different algorithms (GA-only, PSO-only, and Hybrid GA-PSO with DAMIC) as well as substrate materials (eRogers 5880, Polystyrene, FR4, Polystyrene and ceramic). This comprehensive analysis enables us to quantify the improvements achieved with the proposed hybrid algorithm and evaluate the impact of substrate properties on antenna performance. All values of the mentioned microstrip antenna parameters are individually discussed in the following sections.

Table 2

Optimized dimensions of inset-fed microstrip patch antenna for frequency 3.5GHz with different substrate materials

Substrate	FR4			Rogers RT/duroid 5880			Rogers RT/duroid 6002			Polystyrene			Ceramic		
Thickness (mm)	1.6	3.2	4.8	1.6	3.2	4.8	1.6	3.2	4.8	1.6	3.2	4.8	1.6	3.2	4.8
Width & Length of the Patch(mm), W=L	20	20	20.6	28.7	29	29	22.9	23	23	27	27	27	18.1	18.1	18.1
Length of inset feed, L_f (mm)	8	7.9	4.5	8.6	8.1	8.1	7	7	7	9.5	7.9	6.7	7.5	6	4.7
Width of inset feed, W_f (mm)	3.4	3.4	3.4	4.1	4.2	4.2	3.5	3.5	3.5	4.4	4.3	4.4	2.6	2.5	2.6
Length of X(mm)	8.2	8.9	8.5	11.5	11.8	11.8	9	9	9	10.8	10.8	10.8	7.2	7.2	7.2



(a)

(b) (c)

Fig. 3. (a) Designed antenna using ADS (b) Radiation pattern and (c) Current distribution

3.1. Return Loss (S_{11})

Figure 4 shows the reflection coefficient (S_{11}) in dB for various substrate materials (FR4, Rogers 5880, Rogers 6002, Polystyrene, and Ceramic) for substrate thickness of 1.6 mm, 3.2 mm and 4.8 mm respectively. The reflection coefficient (S_{11}) measures how much power is reflected from the antenna and is a critical parameter in antenna design, with lower values indicating better performance.

For a substrate thickness of 1.6 mm, the reflection coefficient S_{11} decreased significantly with increasing frequency for all materials. FR4 exhibited a decrease from -3.08 dB at 3.4 GHz to -18.43 dB at 3.5 GHz. This trend indicates higher reflection at lower frequencies and better impedance matching at higher frequencies. Rogers 5880 shows a similar trend, starting at -3.43 dB and reaching -21.77 dB. Rogers 6002 reflects slightly lower at the start (-3.1 dB) and drops to -15.97 dB. Polystyrene and Ceramic both materials follow the same pattern with reflection coefficients falling from approximately 2.3 dB to -19.88 dB and 16.43 dB, respectively.

Increasing the substrate thickness to 3.2 mm results in different reflection coefficients: FR4 starts at -3.07 dB at 3.4 GHz and drops significantly to -17.95 dB at 3.5 GHz, with an intermediate peak of -8.43 dB at 3.46 GHz. Rogers 5880 shows a significant decrease from 4.84 to 17.95 dB. Rogers 6002 decreased from 3.78 dB to -37.72 dB, indicating a sharp drop in reflection at higher frequencies. Polystyrene and Ceramic materials exhibit reflection coefficients dropping from around -5.85 dB and -6.87 dB to -16.07 dB and -22.85 dB respectively.

For the 4.8mm thickness, FR4 exhibits a more gradual decrease in reflection coefficient from -0.63 dB at 3.4 GHz to -4.17 dB at 3.5 GHz. Rogers 5880 values

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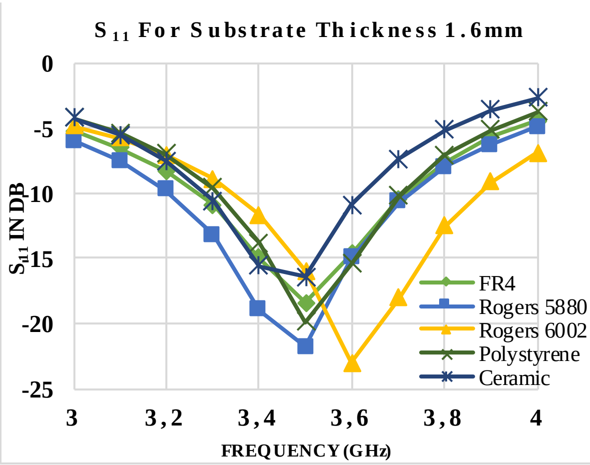
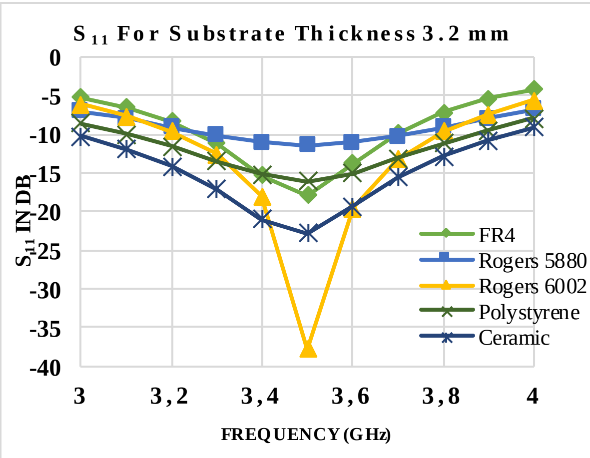
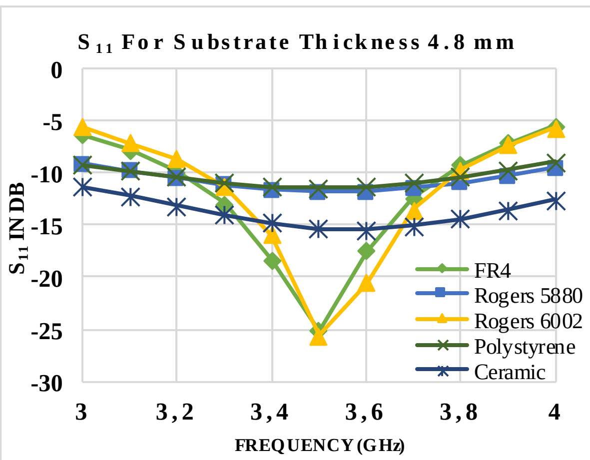
range from -7.19 dB to -25.59 dB. Rogers 6002 starts at -3.54 dB and significantly drops to -25.59 dB, showing better performance at higher frequencies. Polystyrene's reflection coefficient decreases from -7.32 dB to -11.44 dB, while Ceramic drops from -8.97 dB to -15.35 dB.



(a)



(b)



(c)

Fig. 4. S_{11} parameters for different thicknesses: (a) 1.6 mm, (b) 3.2 mm, (c) 4.8mm

Comparative Analysis:

– *Material Performance:* FR4 generally exhibits higher reflection coefficients than other materials, indicating poorer impedance matching. Both Rogers 5880 and 6002 exhibited lower S_{11} values across all thicknesses, with Rogers 6002 showing particularly low values at higher frequencies. Polystyrene and Ceramic materials have moderate reflection coefficients, with Ceramic typically having slightly higher values than Polystyrene.

– *Effect of Substrate Thickness:* Increasing the substrate thickness generally leads to higher reflection coefficients at lower frequencies but significantly improves performance at higher frequencies. The 3.2-mm substrates showed the most significant decrease in reflection coefficients across all materials, indicating that this thickness might offer a good balance between structural integrity and performance. The 4.8-mm substrates provide the lowest S_{11} values at higher frequencies, but may be impractical due to increased material usage and weight. The reflection coefficient S_{11} is highly dependent on both the material and substrate thickness.

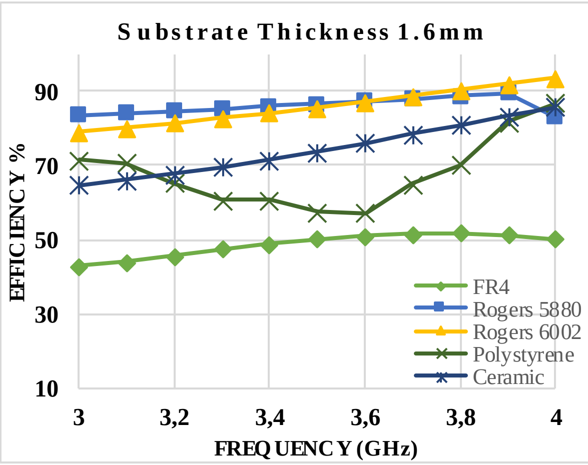
For applications requiring minimal reflection and better impedance matching, Rogers 5880 and Rogers 6002 are preferable, especially at higher frequencies and thicker substrates. FR4, while commonly used, exhibits higher reflection, making it less suitable for high-frequency applications. Polystyrene and Ceramic provide a middle ground with moderate performance across the board.

3.2. Efficiency

The variation in efficiency is shown in Figure 5. For Substrate Thickness 1.6 mm, Rogers 5880 consistently exhibits the highest efficiency across the frequency range of 3–4 GHz. It peaks at 89.43 % at 3.9 GHz and maintains high efficiency throughout. Rogers 6002 also performed well, with efficiencies closely trailing Rogers 5880, peaking at 93.67 % at 4 GHz. Polystyrene offers moderate performance, with efficiencies around 70...80 %, peaking at 86.84 % at 4 GHz. Ceramic has the lowest efficiencies among the substrates, but still offers respectable performance, peaking at 85.85 % at 4 GHz. FR4 has the lowest efficiency in comparison, peaking at 51.65 % at 3.8 GHz, indicating it is less suitable for high-efficiency applications.

For Substrate Thickness 3.2 mm, Rogers 5880 again showed high efficiency, peaking at 86.39 % at 4 GHz and maintaining efficiency above 70 % throughout the range. Rogers 6002 exhibits varying efficiency, with a significant drop at 3.8 GHz (40.23 %) but peaks at 74.95 % at 3 GHz. Polystyrene maintains good efficiency, peaking at 76.50 % at 4 GHz. Ceramic shows a steady performance with efficiency around 48...50 %

across the frequency range, peaking at 50.79 % at 4 GHz. FR4 shows the least efficiency, drastically dropping to 13.02 % at 4 GHz. With Substrate Thickness 4.8 mm, Rogers 5880 and Rogers 6002 showed similar performance, peaking at approximately 72 % and 73 %, respectively, at 3 GHz and maintaining good efficiency throughout.



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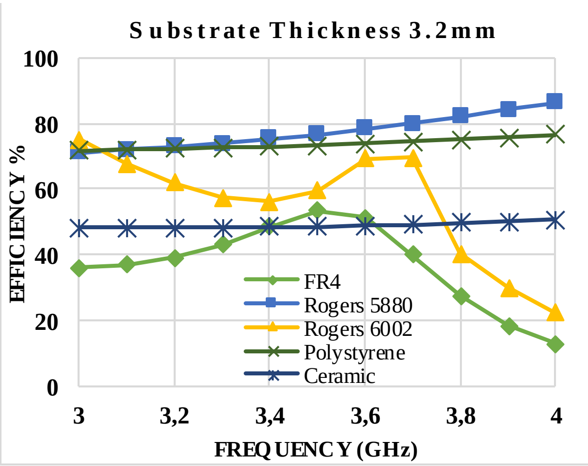

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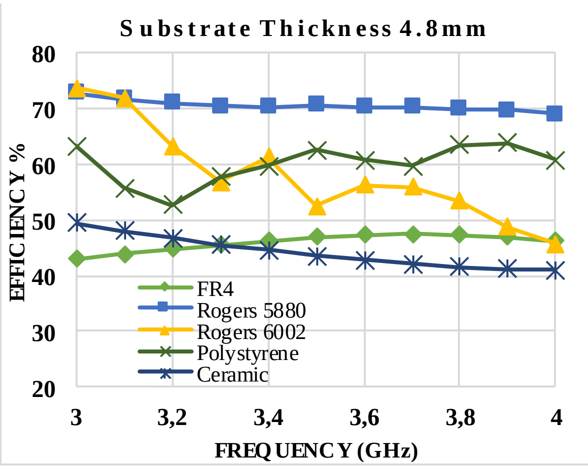

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Fig. 5. Efficiency for different thicknesses: (a) 1.6 mm, (b) 3.2 mm, (c) 4.8 mm

Polystyrene exhibits variable performance, peaking at 63.44% at 3.8 GHz and reducing significantly to 52% at 3.2 GHz. Ceramic shows lower efficiencies, consistently around 40-50%, peaking at 49.38% at 3 GHz. FR4 maintains moderate efficiency, peaking at 47.43% at 3.7 GHz.

3.3. Realized Gain (dBi)

Across all substrate thicknesses and frequencies, Rogers 5880 consistently demonstrated the highest antenna efficiency, making it an excellent choice for applications requiring high-performance substrates. Rogers 6002 also performs well but with more variability, while Polystyrene provides good efficiency, particularly for 1.6mm thickness. Ceramic, though lower in efficiency compared to Rogers materials, still offers a stable performance across frequencies. FR4 is the least efficient, suggesting it's less suitable for applications where high efficiency is critical.

The realized gain in dBi is compared in Figure 6. For Substrate Thickness 1.6mm, Rogers 5880 exhibits the highest realized gain across the frequency range from 3.4 to 3.6 GHz, peaking at 7.03 dBi at 3.6 GHz. Polystyrene offers competitive performance with gains ranging from 6.11 to 6.88 dBii. Ceramic exhibits moderate realized gains, peaking at 5.57 dBii at 3.6 GHz. Rogers 6002 exhibited varying performance, peaking at 6.7 dBi at 3.56 GHz and dropping to 2.32 dBi at 3.6 GHz. FR4 exhibited the lowest gain, peaking at 3.56 dBi at 3.58 GHz. With Substrate Thickness 3.2mm, Rogers 5880 again showed high realized gains, peaking at 6.978 dBi at 3.6 GHz. Polystyrene performs well with realized gains of approximately 5.9–6.2 dBi. Ceramic maintains moderate performance with realized gains peaking at 3.61 dBi at 3.6 GHz. Rogers 6002 shows varying performance, peaking at 6.717 dBi at 3.56 GHz but dropping significantly at 3.58 and 3.6 GHz. FR4 has lower realized gains, peaking at 4.4 dBi at 3.5 and 3.52 GHz but dropping significantly at higher frequencies. For Substrate Thickness 4.8mm, Rogers 5880 continues to show high realized gains, peaking at 6.169 dBi at 3.4 GHz. Polystyrene shows consistent performance with gains of approximately 4.52–5.84 dBi. Ceramic exhibits the lowest realized gain, peaking at 2.5 dBi at 3.5 GHz. Rogers 6002 exhibited varying performance, peaking at 5.84 dBi at 3.4 GHz and dropping to 4.52 dBi at 3.6 GHz. FR4 maintained moderate performance, with gains of around 3.3 to 3.74 dBi.

Rogers 5880 consistently demonstrates the highest realized gain across all substrate thicknesses and frequencies, making it the preferred choice for high-gain applications. Polystyrene also exhibits good performance, particularly at the 1.6- and 3.2-mm thicknesses. Rogers 6002 exhibits variability but can offer high gains at certain

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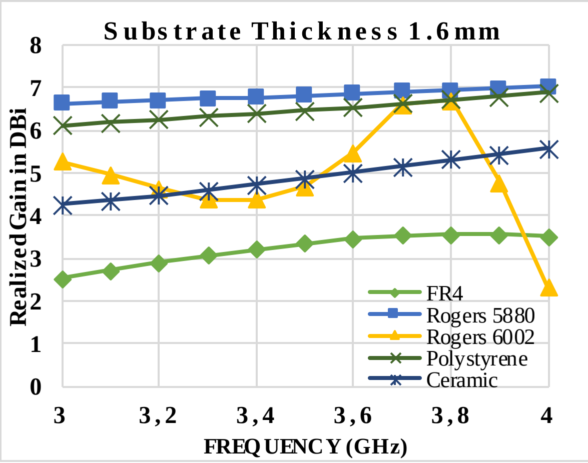
frequencies. Ceramic and FR4 generally show lower realized gains, with Ceramic being the least efficient among the substrates examined.



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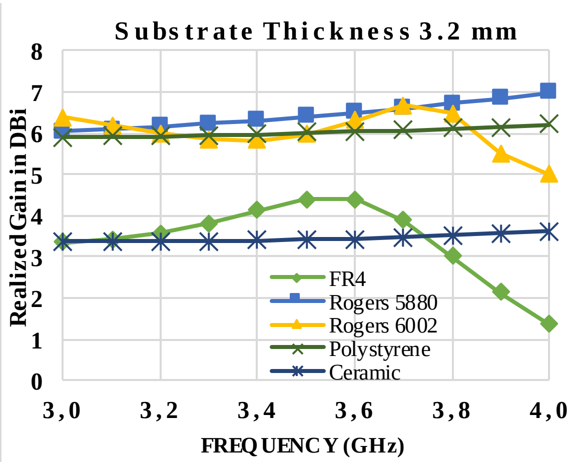

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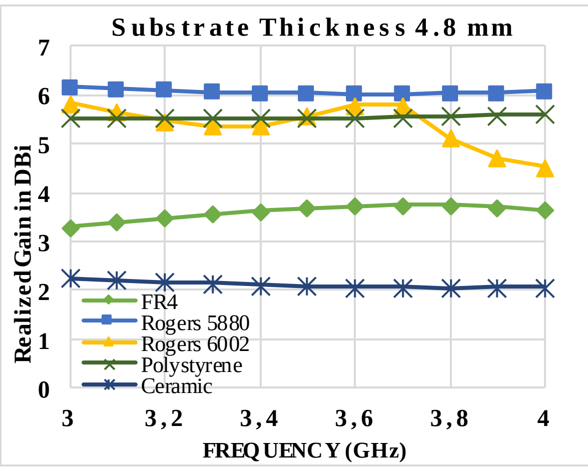

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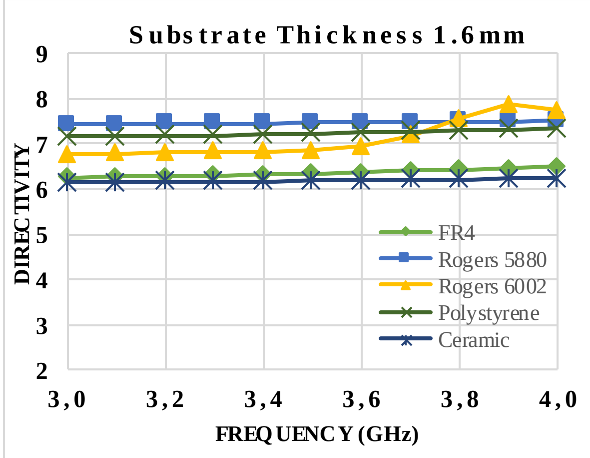
Fig. 6. Realized gain for different thicknesses: (a) 1.6 mm, (b) 3.2 mm, (c) 4.8 mm

For achieving the optimal realized gain, Rogers 5880 is the best choice for different substrate thicknesses and frequency ranges.



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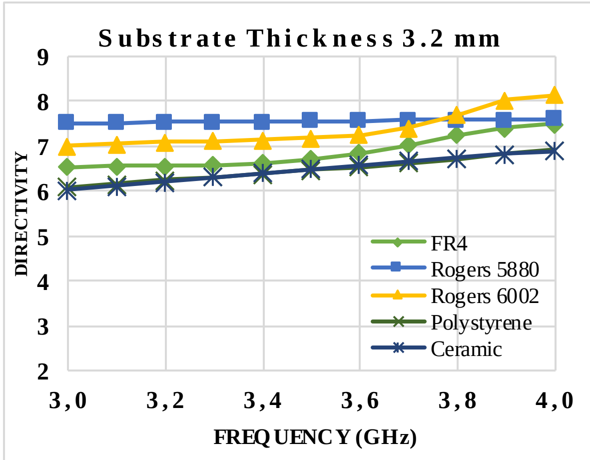

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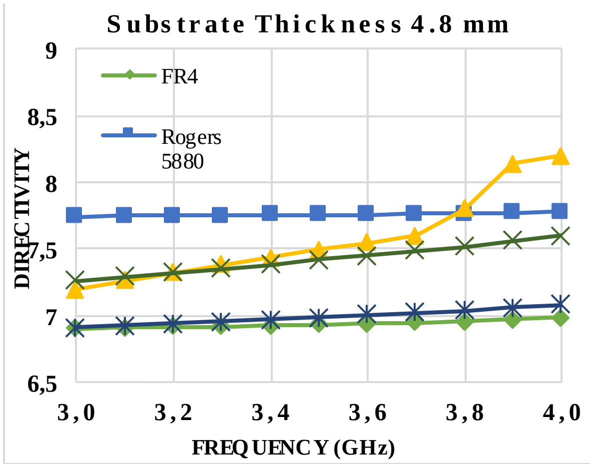

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Fig. 7. Directivity for different thicknesses: (a) 1.6 mm, (b) 3.2 mm, (c) 4.8 mm

3.4. Directivity (dBi)

The directivity across all substrates is plotted as Figure 7 for different sample thicknesses. The graph shows that Rogers 5880 consistently exhibits the highest directivity across all substrate thicknesses, making it an excellent choice for applications requiring high directivity. Polystyrene and Rogers 6002 also perform very well, especially at the 3.2- and 4.8-mm thicknesses. categories, showing some of the highest directivity values. Ceramic and FR4 generally have lower directivities than Rogers substrates, but both perform adequately, with Ceramic exhibiting better performance than FR4. To achieve optimal directivity, Rogers 5880 was selected, followed by Polystyrene and Rogers 6002. Ceramic and FR4 can be used in applications in which slightly lower directivity is acceptable.

3.5. Current density and Distribution

The thickness of the substrate in microstrip antennas significantly influences the current density and distribution. Thinner substrates (e.g., 1.6 mm) tend to concentrate higher current densities near the edges of the patches, enhancing the fringing field and potentially increasing the surface wave losses, which can reduce the radiation efficiency. Conversely, thicker substrates (e.g., 4.8 mm) lead to a more uniform current distribution and lower surface wave losses, thereby improving the radiation efficiency. However, thicker substrates can also result in lower capacitance and higher resonant frequencies, requiring design adjustments to maintain impedance matching. A moderate substrate thickness (e.g., 3.2 mm) can provide a balance between efficient current distribution, impedance matching, and improved radiation efficiency. The current density and distribution in Figure 8 agree well with the performance data discussed in the previous sections.

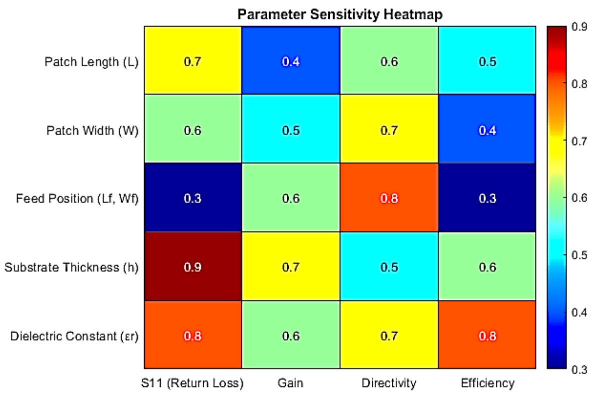

Fig. 8. Parameter sensitivity heatmap

4. Discussion

The core objective of this study was to optimize the key performance metrics of microstrip patch antennas (MSPAs), namely, return loss (S_{11}), gain, directivity, and efficiency — across a targeted frequency range of 3–4 GHz.

The return loss is a critical indicator of how well the antenna impedance matches the transmission line, with higher negative values indicating better matching and less power reflected. Through iterative adjustments of substrate material, thickness, and patch dimensions, the hybrid GA-PSO algorithm successfully minimized the return loss, achieving values as low as -22 dB with the Rogers 5880 substrate at a thickness of 1.6 mm.

The gain measures the antenna's ability to direct energy in a particular direction, which is crucial for applications requiring focused signal transmission and reception. The optimization algorithm improved the gain values by adjusting the design parameters to ensure that the antenna radiates efficiently within the 3–4 GHz range. By focusing on configurations with high radiation efficiency, this study achieved a peak gain of 7.0 dBi.

The directivity represents the antenna's capacity to radiate energy in more directions than in other directions, thus contributing to signal focus and efficiency. During optimization, the hybrid GA-PSO algorithm dynamically adjusted the patch dimensions and feed point locations to maximize the directivity. This approach achieved an optimized directivity of 7.3 dBi for Rogers 5880.

Efficiency reflects how effectively the antenna converts input power into radiated electromagnetic waves. The antenna efficiency is impacted by substrate properties such as the dielectric constant and loss tangent, which the study addressed by carefully selecting and optimizing substrate materials and thicknesses. The hybrid GA-PSO with DAMIC consistently improved efficiency, reaching 89% for the best-performing Rogers 5880 configuration.

Achieving optimal values for each individual metric often involves trade-offs because changes made to improve one metric (e.g., gain) can negatively affect others (e.g., return loss). The hybrid GA-PSO with DAMIC algorithm effectively balanced these trade-offs by dynamically adjusting the mutation rates and inertia weights based on real-time performance feedback from ADS simulations. This balanced approach ensured that the final optimized configuration, particularly for Rogers 5880 with a thickness of 1.6 mm, exhibited strong performance across all metrics without significant sacrifices in any one area.

Sensitivity Analysis: After presenting the primary performance results of the hybrid GA-PSO with DAMIC algorithm, it is essential to examine the influence of individual design parameters on key performance metrics such as return loss, gain, directivity, and efficiency. This sensitivity analysis offers insights into how each design parameter—such as the patch dimensions, feed position, substrate thickness, and dielectric constant—optimizes antenna performance.

To visually represent these relationships, Heatmap of Parameter Sensitivity is presented in Figure 8. This heatmap quantifies the impact of each parameter on the

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performance metrics, guiding future design decisions by highlighting the factors that have the greatest effect on achieving high-performance outcomes. Patch Length and Width directly affect S_{11} and gain, emphasizing their role in impedance matching and frequency tuning. Feed Position has a notable effect on gain and directivity, which is consistent with its function in current distribution control. This is critical for applications requiring high directional gain, such as 5G. The Substrate Thickness and Dielectric Constant both significantly affect the efficiency, particularly when using Rogers 5880 and Polystyrene substrates.

Expanding the study to advanced materials like composites and testing a wider frequency range beyond 3-4 GHz could make the findings applicable to more 5G applications. Although the simulations provided reliable initial data, real-world testing may reveal additional effects, such as environmental factors and fabrication variations. Considering more substrate thicknesses, real-world interference, and the cost implications of high-performance materials like Rogers 5880, would make these results even more practical for broad 5G deployment. These steps highlight valuable directions for future research.

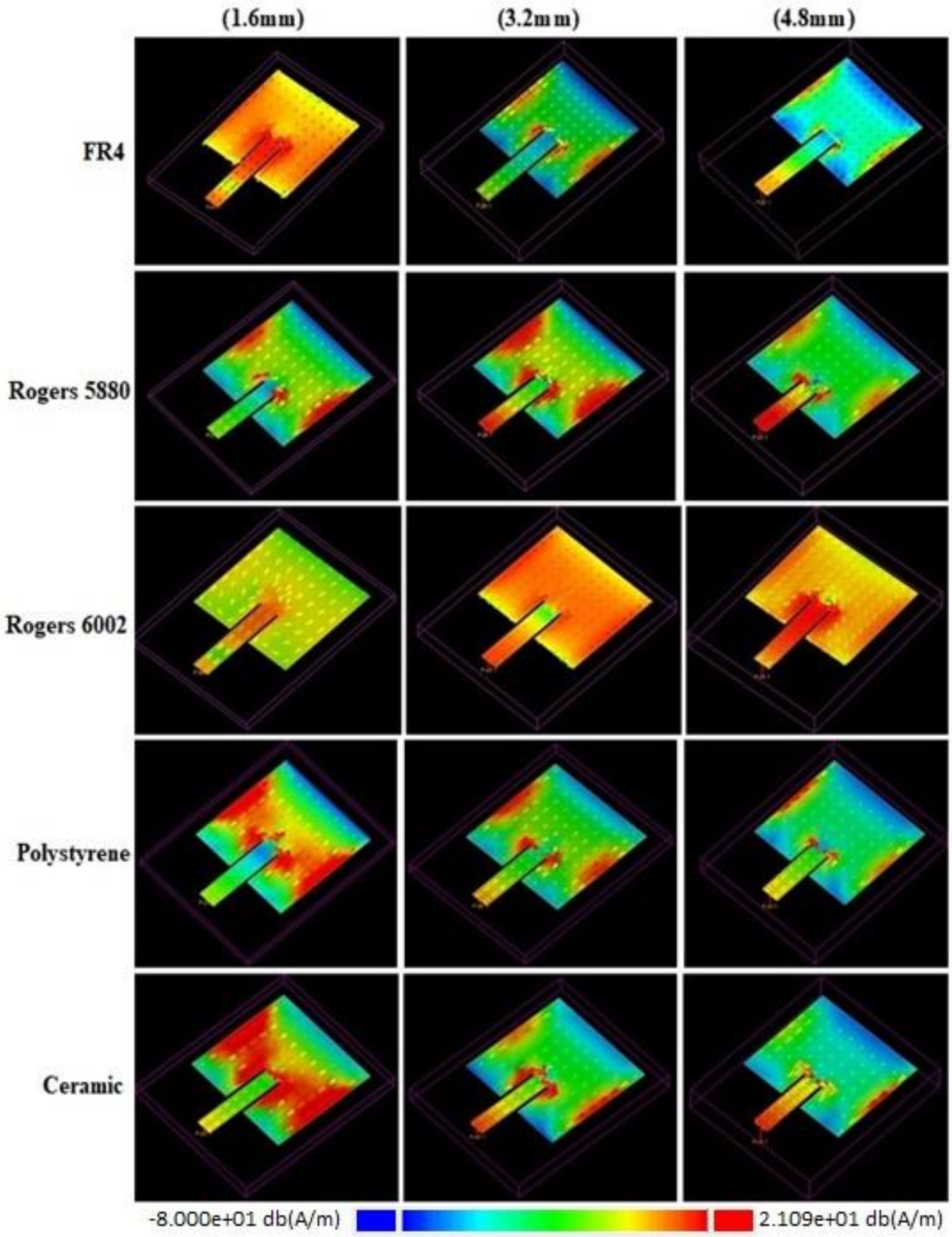

Fig. 9. Current density for different thicknesses 1.6 mm, 3.2 mm and 4.8 mm

5. Conclusion

This study provides a comprehensive comparative analysis of the performance parameters of inset feed microstrip patch antennas utilizing different substrates—FR4, Rogers RT/duroid 5880, Rogers RT/duroid 6002, Polystyrene, and Ceramic—across three thicknesses: 1.6 mm, 3.2 mm, and 4.8 mm. This study successfully met the primary goal of identifying the optimal substrate material and thickness for microstrip patch antennas used in 5G applications, specifically for 3–4 GHz. The main contribution of this study is the introduction of a novel optimization approach employing a hybrid GA-PSO algorithm enhanced with Dynamic Adaptive Mutation and Inertia Control (DAMIC). This technique significantly improved the precision of antenna parameter tuning, enabling systematic optimization and simulation of antenna performance across various substrates and thickness levels. The results revealed that Rogers 5880, particularly at 1.6 mm thickness, consistently outperformed other materials in terms of efficiency, return loss, gain, and directivity. These findings affirm that substrate selection, combined with advanced optimization techniques, plays a vital role in achieving the desired performance in high-frequency applications, emphasizing Rogers 5880 as the preferred choice for high-efficiency and high-gain antennas in 5G. This research provides practical insights into antenna design and demonstrates the potential of hybrid optimization methods for addressing complex, multi-parameter design challenges in modern RF systems.

Future research development. The authors recommend exploring new materials and technologies to improve antenna performance. This includes looking at composite materials and nanomaterials such as graphene, and metamaterials that could offer better efficiency and lower losses. Researchers may also investigate flexible and wearable antenna materials for wearable devices and IoT devices.

Contributions of authors: Conceptualization, methodology, analysis of results, visualization, writing – original draft preparation – **Kebbekoppalu Shrinivasa Praveena**; writing – review and editing – **Chandrashekar M Patil.**

Conflict of Interest

The authors declare no conflict of interest.

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This study was conducted without financial support.

Data Availability

The data supporting the findings of this study are included in the article.

All authors have read and agreed to the publication of the final version of this manuscript.

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ОЦІНКА ЕФЕКТИВНОСТІ ПАРАМЕТРІВ МИКРОСМУЖКОВОЇ АНТЕНИ, ЩО ВСТРОЮЄТЬСЯ, З РІЗНИМИ МАТЕРІАЛАМИ ПІДКЛАДКИ ДЛЯ БЕЗПРОВІДНИХ ДОДАТКІВ 5G

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У цьому дослідженні оцінюється продуктивність мікросмужкової антени із вставкою для різних матеріалів підкладки (FR4, Rogers 5880, Rogers 6002, полістирол і кераміка) різної товщини (1,6 мм, 3,2 мм і 4,8 мм) для додатків 5G, зосереджуючись на ключових параметрах. такі як зворотні втрати, ефективність, спрямованість і реалізоване посилення. Мета полягає в тому, щоб визначити оптимальний матеріал підкладки та товщину, які забезпечують найкраще поєднання цих показників продуктивності в діапазоні частот від 3 до 4 ГГц. Запропонований метод використовує новий гібридний алгоритм GA-PSO з динамічною адаптивною мутацією та контролем інерції (DAMIC). Дослідження оптимізувало дизайн MSPA для кожного матеріалу та товщини з подальшим детальним моделюванням за допомогою інструменту Advanced System Design (ADS). Підхід включав параметричний аналіз і систематичні порівняння вибраних матеріалів підкладки, кількісну оцінку їх ефективності за певними показниками. Результати показують, що Rogers 5880 стабільно перевершує інші підкладки з точки зору ефективності, спрямованості та посилення для всіх товщин. Полістирол і Rogers 6002 також продемонстрували похвальну продуктивність, особливо на більш товстих підкладках (3,2 мм і 4,8 мм), причому полістирол досяг найвищої спрямованості при товщині 4,8 мм. З точки зору ефективності, Rogers 5880 знову лідирував у продуктивності, зі значеннями ефективності стабільно вищими за 70 % для всіх товщин, досягаючи піку в 86,38 % при 1,6 мм і 86,39 % при 3,2 мм. Керамічні підкладки та підкладки FR4 продемонстрували відносно нижчу продуктивність, при цьому керамічна демонструвала помірну пікову ефективність 75,98 % на 1,6 мм і 50,79 % на 3,2 мм, тоді як FR4 постійно мала найнижчі значення ефективності та спрямованості, підкреслюючи її обмеження для високоефективної антени. програми. З огляду на зворотні втрати, Rogers 5880 продемонстрував найбільш сприятливі характеристики зворотних втрат, зберігаючи значення значно нижче -10 дБ у всьому діапазоні частот, що означає відмінне узгодження імпедансу. Rogers 6002 і Polystyrene також показали прийнятні характеристики зворотних втрат, хоча трохи вище, ніж Rogers 5880, вони залишаються нижче -10 дБ для більшості частот. Ceramic і FR4 показали вищі значення зворотних втрат, що свідчить про гірше узгодження імпедансу та високе відображення сигналу. Підсумовуючи, техніка оптимізації GA-PSO DAMIC пропонує високоефективний підхід до проектування антен для систем 5G, що дозволяє створювати індивідуальні рішення для різних підкладок. На відміну від традиційних методів, підхід GA-PSO DAMIC забезпечує точне налаштування ключових параметрів антени — зворотних втрат, посилення, спрямованості та ефективності — для різних конфігурацій підкладки та товщини. Дослідження демонструє, що підкладка Rogers 5880, особливо при товщині 1,6 мм, стабільно забезпечує чудові показники продуктивності, включаючи високу ефективність і низькі зворотні втрати, що підтверджує її придатність для додатків 5G 3-4 ГГц. Це також показує, що Rogers 5880 є кращою підкладкою для високочастотних додатків, які вимагають високої ефективності, спрямованості та підсилення, за якою слідують Polystyrene та Rogers 6002, особливо для більш товстих підкладок. Ceramic і FR4, хоча й достатні в певних сценаріях, загалом є менш оптимальними для вимог високої продуктивності через їх нижчу ефективність і вищі зворотні втрати. Ці висновки дають важливу інформацію про дизайн антени та вибір матеріалу, підкреслюючи важливість вибору підкладки для досягнення бажаних показників продуктивності в сучасних додатках RF 5G.

Ключові слова: мікросмугова антена; вставна подача; матеріал підкладки; додатки 5G; аналіз ефективності; FR4; Rogers 5880; Rogers 6002; полістирол; кераміка.

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