Amplifying Antenna Performance: Techniques for Gain Enhancement in Microstrip Patch Array Antennas

Md. Motahar Hossain
Department of Electrical Electronic and Communication Engineering
Military Institute of Science and Technology
Dhaka, Bangladesh
navy1732@gmail.com

Dr. Hossain K A
Former Head of NAME, MIST
Professor /Researcher /Examiner of *Bangladesh University of Engineering and Technology (BUET)*
Dhaka, Bangladesh.
hossaindrakhter@gmail.com

Abstract— **In the contemporary landscape of communication systems, Microstrip Patch Antennas (MPAs) have gained immense popularity owing to their low profile, light weight, compactness, cost-effectiveness, and fabrication simplicity. In high-performance aircraft, spacecraft, satellite, and missile applications, where size, weight, cost, performance, ease of installation, and aerodynamic profile are constraints and low-profile microstrip antennas may be potent candidate. Despite their widespread use, MPAs exhibit a notable drawback in the form of low gain response. Researchers are actively engaged in overcoming this limitation, exploring diverse techniques to enhance MPA performance for specific applications. High gain antennas are particularly desirable in practical scenarios, providing extended coverage compared to their low gain counterparts. Microstrip array antennas emerge as promising candidates for achieving high gain, leveraging multiple radiating elements on a single substrate for versatile wireless applications. This paper delves into the background and current state of the problem surrounding MPA gain limitations. Various strategies reported in the literature to address these limitations include the use of parasitic patches, thick substrates, multi-resonator techniques, conventional array techniques, large ground planes, and stacked patches. However, each technique presents its own set of drawbacks, such as increased antenna size, complexity in multilayer fabrication, and additional impedance matching circuit requirements. Notably, conventional array antennas necessitate impedance matching circuits and transmission lines for connecting array elements, leading to bulkiness and increased internal losses, thereby compromising efficiency. The results of this study should greatly advance the field of micro strip antenna technology, creating new opportunities for useful and effective wireless communication systems. The 4x2 and 2x2 microstrip patch antennas developed in this study are intended to lower return loss while increasing gain and efficiency. Also compared with the other designs of earlier studies, it is observed that the 4x2 microstrip patch antenna achieves 97% efficiency with gain of 32 dB which indicates the superiority over others.**

Keywords—Antenna Array, Gain improvement, Double-sided MIC technology, Microstrip antenna, Radar band applications

I. INTRODUCTION

The rapid evolution of communication technology in the modern era has propelled Microstrip Patch Antennas (MPAs) to the forefront of wireless communication systems. Renowned for their low profile, lightweight construction, cost-effectiveness, and case of fabrication, MPAs have become integral components in various communication applications. However, a persistent challenge has impeded their widespread adoption namely, the limitation in gain response, which hinders their effectiveness in certain scenarios. Antenna gain, which measures an antenna's ability to focus transmitted or received signals in a certain direction, has a direct impact on the efficiency and performance of communication networks. In numerous instances, the need for extended communication ranges, enhanced signal clarity and swifter data transmission rates necessitates antennas with more substantial gains. Gain enhancement is particularly pertinent in applications comprising long-distance communications, satellite links, and wireless networks, where the stable and efficient exchange of information is paramount. Furthermore, as communication systems continue to push past the edges of what is feasible, the quest for novel methods to enhance antenna gain becomes a driving force in broadening the capabilities of wireless technologies.

In the context of enhanced antenna gain, Microstrip Patch Antennas (MPAs) have emerged as pivotal components in contemporary wireless communication systems, including wireless local area networks (WLAN) [1], military and defence systems specially in UAV and missile technology [2], satellite communication [3], radio frequency identification (RFID) [4], and fifth-generation (5G) cellular networks [5]. This widespread adoption can be attributed to their compelling advantages, such as ease of design and fabrication, low profile and planar structure, and ease of integration with consumer products & [6-8]. These attributes, along with their compatibility with integrated circuit technology, make MPAs highly suitable for seamless integration into a diverse range of devices.

However, the inherent limitation of MPAs lies in their typically low gain, which can hinder their performance in applications requiring long-distance coverage, enhanced signal strength, or demanding transmission requirements [9]. To overcome this constraint, antenna arrays have emerged as a viable solution, employing multiple MPA elements strategically arranged on a shared substrate to achieve significant gain enhancement. By arranging these elements in specific geometries and feeding them with controlled phase differences, constructive interference can be achieved, resulting in a more focused and powerful beam [10-13]. The performance of these MPA arrays is intricately linked to the design and implementation of efficient feeding networks, which ensure proper impedance matching, minimise signal reflections, and distribute power evenly among the radiating elements [14].

This paper gives an analysis on [1], [7], [8], [10], [15] which discuss a range of techniques for enhancing MPA gain, many of which present limitations such as increased size and complexity, particularly for array antennas. Among these techniques, this article further focuses on Microwave Integrated

http://dx.doi.org/10.31364/SCIRJ/v13.i08.2025.P0825XX

Circuit (MIC) technology, a promising approach for enhancing MPA gain. There are several advantages of MIC technology,

particularly the both-sided MIC technique, which utilizes both sides of the substrate for transmission lines.

By utilizing both sides of the substrate, both-sided MIC

technology allows for a more compact design compared to traditional feeding methods. This compactness is particularly beneficial for array antennas, where multiple elements and their feeding networks can be efficiently integrated onto a single substrate. [16]

Both-sided MIC simplifies the design process by allowing for easier integration of various transmission lines, such as microstrip lines, slot lines, and coplanar waveguides. This simplified design also translates to easier fabrication, making it a more practical approach for realizing high-gain MPA [17].

MIC technology allows for precise impedance matching, ensuring efficient power transfer from the feed line to the radiating elements [18]. This improved matching minimizes signal reflections and contributes to higher gain and overall antenna efficiency.

By minimizing the use of conductive material in feed lines, both-sided MIC reduces conduction losses, leading to increased radiation efficiency [7-8]. [7-8] provide examples of both 2x2 and 4x2 microstrip patch arrays using both-sided MIC achieving significantly higher gain and efficiency compared to conventional array designs.

This research seeks to optimize MPAs using both-sided MIC approaches, offering a practical and efficient solution for applications necessitating greater coverage and improved signal strength with a straightforward feeding network [19-20]. The impetus for this research is to enhance antenna technology to address the pressing requirements of modern communication, providing an innovative and efficient solution to the ongoing issue of low gain in microstrip patch antennas. The expected results seek to provide significant insights and breakthroughs to the wider domain of communication technology, promoting advancements that enhance various applications in our interconnected world.

II. DESIGN PROCEDURE

This section outlines the design of the antenna, using optimal parameters. The Advanced Design System (ADS 2021) was employed for simulation purpose.

A. *Mathematical Analysis*

In this section, the structural configuration and geometry of the patch antenna is described. The length L and the width W of the patch were obtained using equations (1-4) for a design resonance frequency f_r, dielectric permittivity ε_r, and substrate thickness h in accordance with James & Hall, (1989). Also ϵ_0, is the permittivity of the free space, is the permeability of the free space while v_0 is the speed of light.

$$\frac{\Delta L}{h} = 0.412 \frac{(\varepsilon_{reff} + 0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W}{h}+0.8)} \quad (1)$$

$$L = \frac{1}{2f_r \sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L \quad (3)$$

$$W = \frac{1}{2f_r \sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \quad (4)$$

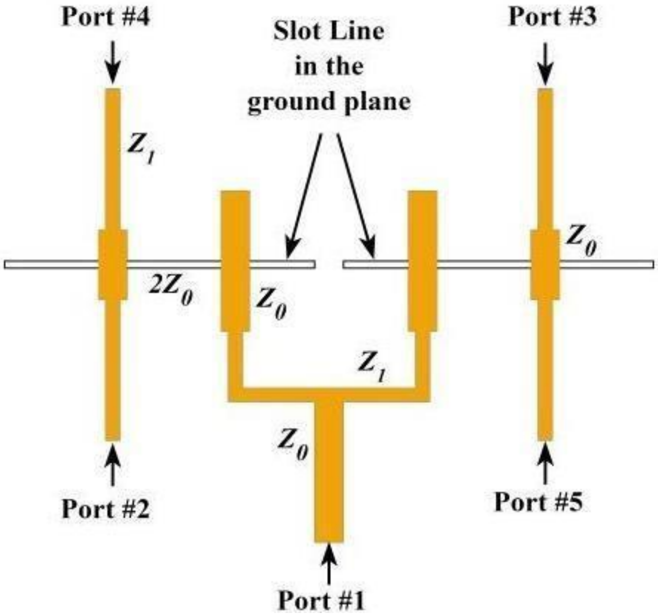
B. *Feeding Structure Design of A 2 X 2 Microstrip array Using Both-Sided MIC*

A feeding structure has been designed for 2x2 arrays using both-sided MIC technique. Both sides of the substrate are employed by transmission line. On the top of the substrate microstrip lines and another sides slot lines are employed. There not electrically connected but electromagnetically coupled. The slot lines are cut in to the ground plane in such way so that the impedance of the slot line is twice than that of microstrip line. In this case impedance of microstrip line is 50Ω and slot line is 100Ω. The required impedance in all sections is maintained by designing the appropriate width of all sections.

Feed network for the proposed microstrip array antenna is depicted in Figure 1. The signal is routed into input port #1 before being separated into two microstrip lines, which are then coupled with the slot lines to produce the microstrip-slot branch. The network is completed by two more microstrip lines formed by slot-to-microstrip line branches and makes room for four patches. The feed network is developed and simulated numerous times for optimal results after inserting four pins in place of four patches. Since ports #2, #4, and port #3, #5 is symmetrical, only ports #2 and #3 with respect to port #1 are being evaluated here. The isolation between ports has been inspected, and it is obvious from Figure 1 that the feed structure has excellent isolation between ports.

C. *A 4 X 2 Microstrip Array Design for Gain Enhancement*

Figure 2 illustrates the proposed microstrip patch array antenna structure, supported by a Teflon substrate with a dielectric constant of 2.15. A 0.2 mm slot line is etched into the ground plane for implementing double-sided MIC technology. The array consists of eight patches arranged in a 4x2 configuration. Figures 2 and 3 show the top and cross-sectional views.



http://dx.doi.org/10.31364/SCIRJ/v13.i08.2025.P0825XX

ISSN 2201-2796

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2} \quad \left(\frac{W}{h}\right) > 1 \qquad (2)$$

Figure 1: Feed network for the proposed 2x2 array using both-sided MIC

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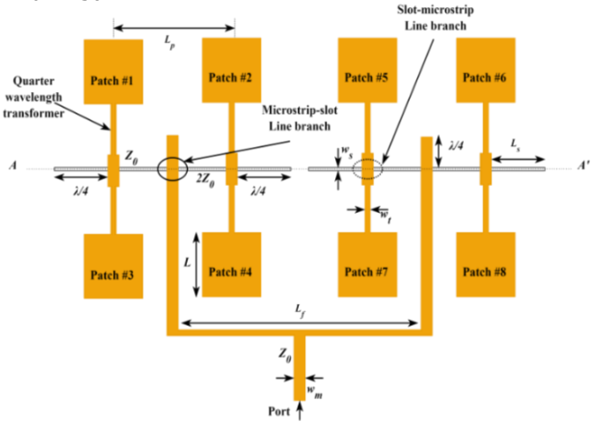

Figure 2: Top view of 4x2 Array

D. *Current Distributions in the Array Elements:*

Because of the use of both sided MIC in the feeding structure, each patch of the array experienced identical electric field as fed. Figure 3 depicts the proposed array antenna's current distribution. Because the antenna's two row elements, each of which contains four element, receive the split signal from slot micro strip junctions, the elements' electric fields should be in the same direction, as shown in the figure.

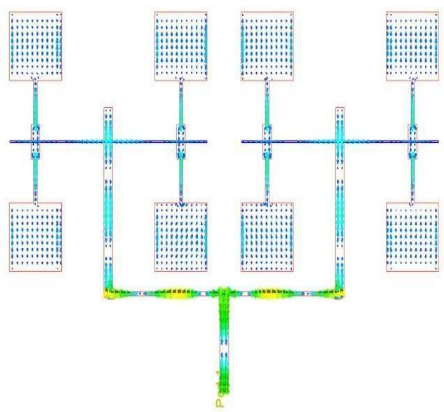

Fig-3 Simulated current distribution of the proposed array antenna.

E. *Design Parameters:* The simulated optimized design parameters of the proposed antenna is displayed in the table-1.

TABLE-I DESIGN PARAMETERS OF PROPOSED MICROSTRIP PATCH ARRAY ANTENNA

Substrate	Teflon Glass Fiber
Relative dielectric constant, εr	2.15
Height of substrate, hs	0.8 mm
Patch dimension, L x W x t	9.7 mm x 9.7 mm x 0.018 mm
Micro strip line impedance, Z0	50 Ω
Qtr wavelength transformer impedance, Z1	104.88 Ω
Qtr wavelength transformer width, wt	0.8 mm
Micro strip line width, wm	2.2 mm
Slot line width, ws	0.2 mm
Patch to patch length, Lp	27 mm
Feed to feed length, Lf	47 mm
Overall size of antenna	40 mm x 40 mm (For 2 x 2) 80 mm x 60 mm (For 4 x 2)

40 RESULT ANALYSIS

A. *Broadside Gain*

Figure 4 presents the simulated broadside gain of the proposed array antenna, showing a peak gain of approximately 25.02 dB in the broadside direction. The side lobe gain is around 5 dB, demonstrating the antenna's high gain and strong directivity towards the main lobe.

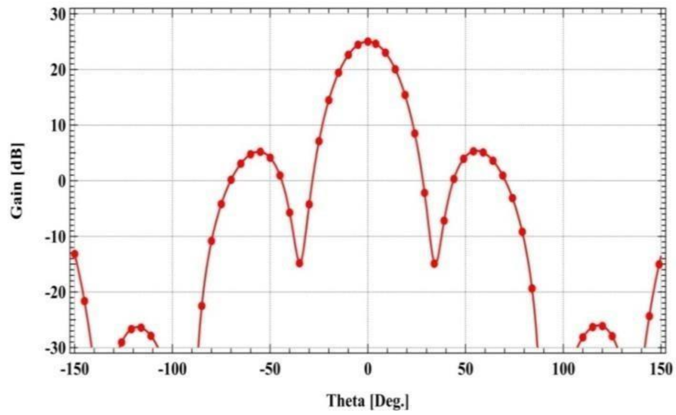

Figure 4: Simulated broadside gain of the proposed 2x2 array antenna

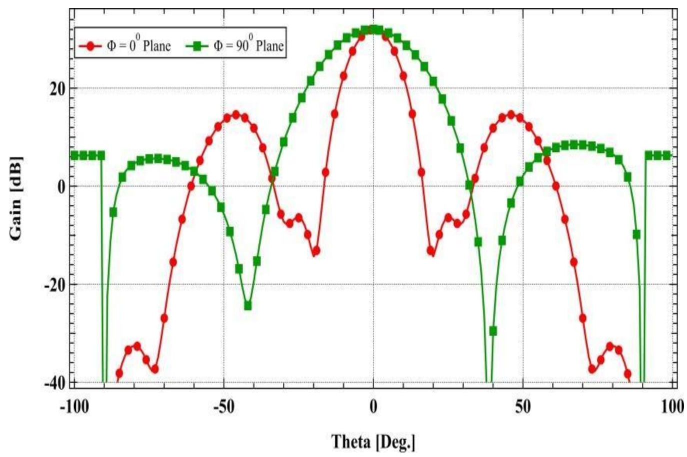

Figure 5: Simulated 2D radiation pattern of the proposed 4x2 array antenna versus theta

Figure 5 illustrates the simulated broadside gain in dB for both plane cuts. The diagram presents the antenna's 3 dB half-power beam width (HPBW) of 90° in the φ = 90° plane and 30° in the φ = 0° plane. The array configuration, consisting of four horizontally aligned elements and two vertically stacked elements, results in differing beam widths across the two planes. The antenna achieves a broadside gain of 32 dB, highlighting its effective directivity.

A. *Return Loss*

a) 2x2 Array Antenna: Figure 6 displays the return loss for both the single patch and array antennas. The graph clearly shows that the single patch and suggested array are properly matched in resonance frequency of 10 GHz. Both antennas have a return loss of less than -20 dB at the resonant frequency. The designed array perfectly matched at its resonant frequency as it exhibit the return loss of -45dB.

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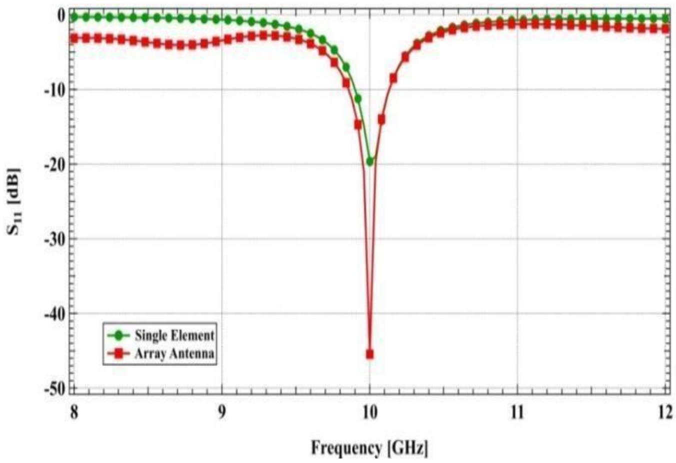

Figure 6: Simulated return loss of the proposed antenna

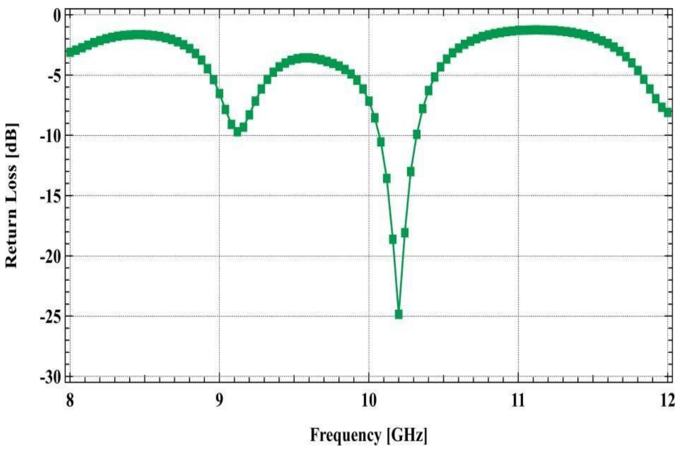

Figure 7: Return loss of the proposed 4x2 micro strip patch array antenna

b) *4x2* Array Antenna: Through the parametric analysis i.e. by the variation of patch to patch distance and feed to feed distance optimized value of return loss and isotopic gain isobtained at L_p = 27mm, L_f = 47mm and L_S = 5.0 mm . Figure 7 displays the return loss.

B. *Antenna Efficiency:*

a) *2x2* Array Antenna: Antenna radiation efficiency is a key performance indicator that measures how effectively an antenna converts input power into radiated electromagnetic energy. Microstrip patch antennas experience ohmic losses due to the resistance in feed lines, which reduces efficiency. By utilizing Both-Sided MIC technology, the conductive material in the feed line is minimized, significantly enhancing overall radiation efficiency. Figure 8 illustrates that the designed antenna achieves an impressive 86% radiation efficiency at its resonant frequency, ensuring efficient signal radiation.

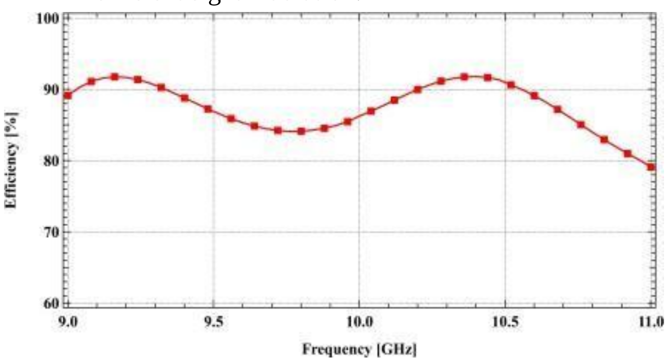

Figure 8: Antenna Efficiency with respect to frequency of the proposed 2X2 array antenna

b) *4x2* Array Antenna: The radiation efficiency of a microstrip array antenna indicates the fraction of input power effectively radiated as electromagnetic waves, reflecting the antenna's ability to convert electrical power into radiated power. Expressed as a percentage, radiation efficiency (η) ideally reaches 100%, signifying that all input power is radiated. However, practical antennas experience losses in various components, including the feed network, dielectric substrate, and radiation resistance, which reduce overall efficiency. Figure 9 shows the efficiency at different frequency.

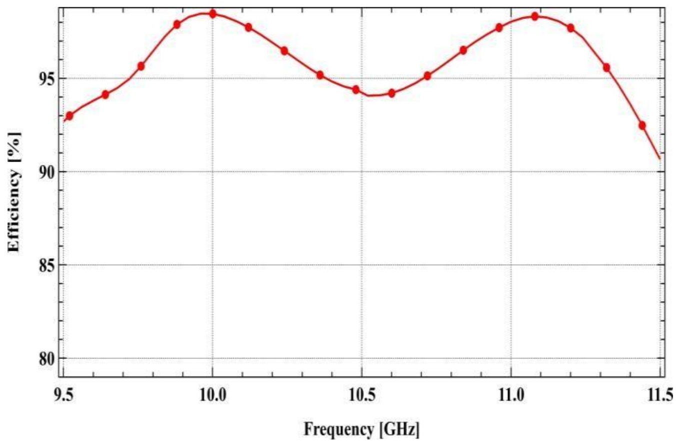

Figure 9: Efficiency of the proposed array antenna

C. *Radiation Pattern:* The 3D radiation pattern of the proposed antenna are shown in figure 10 and fig-11.


Figure 10: Simulated 3D radiation pattern of the proposed 2X2 microstrip array antenna


Figure 11: Simulated 3D radiation pattern of the proposed 2X2 microstrip array antenna

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The antenna exhibits a very well shaped beam in the broad side direction, as indicating in the pictures. In case of increased number of elements as indicating in fig-11 the beam has become narrower and more directed. It is also evident that the side lobes and back lobes are almost negligible with respect to the main lobe.

IV. COMPARISON WITH RELEVANT WORKS

A Comparison with some previous work has been given in Table 3. The proposed 2x2 and 4x2 array exhibit maximum broadside gain of 25.02dB and 32dB respectively where as other arrays of same number of elements have very lesser gain. Furthermore, the proposed arrays exhibit notably lower return loss, indicating enhanced impedance matching compared to their counterparts. This improved matching is a significant advantage. Additionally, the radiation efficiency of the proposed arrays is remarkable, reaching 86% for the 2x2 array and 97% for the 4x2 array. These efficiencies surpass those of the compared designs by a significant margin. It's worth noting that none of the referenced papers utilize the both-sided MIC technique in their antenna designs. This underscores the innovative approach taken in the proposed designs. The integration of the both-sided MIC technique not only simplifies the design process but also contributes to the observed improvements in gain and efficiency. Overall, these findings highlight the efficacy of incorporating both-sided MIC in antenna design, resulting in superior performance metrics compared to conventional approaches.

TABLE-II COMPARISOON WITH RELEVANT WORKS

Ref	Array Element	Return Loss	Broadside Gain	Efficiency	Remarks
[10]	2 x 2	-16dB	7.713dB	-	Intl Conference, India, 26-28 May 2023
[15]	2 x 2	-30dB	12.5dB	-	GS journal, Apr 2022
[1]	2 x 2 4 x 2	-14.5dB -13dB	7.2dB 10.1dB	49% 45%	BJET, AUG 2017
[7]	2 x 2	-45dB	25.02dB	86%	ICICT4SD, 2023
[8]	4 x 2	-25dB	32dB	97%	ICCIT, 2023

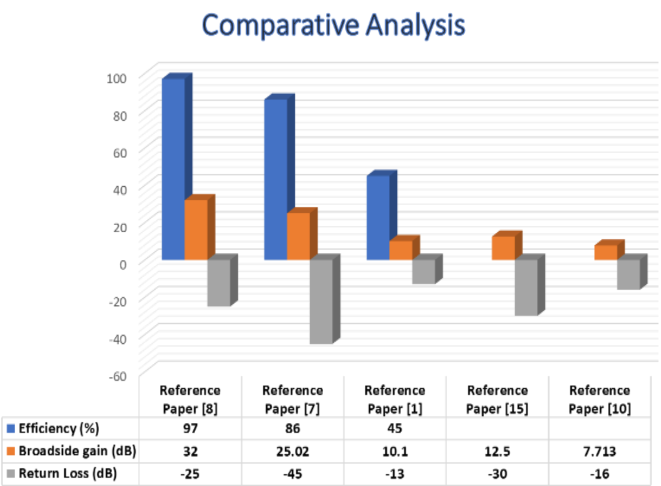

Figure 12: Comparison of the 5 reference papers with respect to their efficiency, broadside gain and return loss

V. ADVANTAGES AND APPLICATION

A. Advantages:

In comparison to single-element antennas, microstrip array antennas with both-sided MICs have many practical advantages due to the effects of combining several kinds of transmission lines and the effective use of both sides of the substrate. The following are some salient points.

1) Design Flexibility: By printing the antenna parts on both sides of the substrate, the entire surface area is used more effectively
2) Gain Enhancement: More radiating elements can be added by utilizing both sides, which raises directivity and gain.
3) Feed Network: By distributing the feed network between the two sides, losses may be minimized and total efficiency can be raised.
4) Size Reduction: More compact systems are possible with both-sided designs since they can perform comparably to bigger single-sided arrays.
5) Transmission Line Impedance: A very wide range of transmission line impedance is available.
6) Simple Coupling Efficiency: The orthogonal transmission lines are easily constructed using the "even/odd transition modes". In addition, a very tight line coupling is also achieved without any difficulty.
7) Maximized Substrate Integration: Higher integration can be achieved by using both sides of the substrate effectively.
8) Versatile Device Integration: Active or passive devices can be effortlessly connected in series or parallel with transmission lines, as Both-Sided MICs utilize coplanar lines like slot lines or coplanar waveguides.

B. Application:

Microstrip patch array antennas with both-sided MICs are essential for practical applications because of their multiple advantages in improving gain. Some potential applications are as follows.

1) Satellite Communication: Microstrip patch array antennas with enhanced gain are critical in satellite communication systems. The improved gain contributes to better link budgets, enabling for more dependable and efficient communication between ground stations and satellites.
2) Military and Defense Systems: Military applications frequently demand antennas with superior performance. Microstrip patch arrays with enhanced gain are employed in defense systems for communication, surveillance, and reconnaissance, providing a tactical advantage in the field.
3) Radar Systems: High-gain microstrip patch arrays are vital in radar systems for long-range detection and precise target tracking. Enhanced gain elevates the radar's sensitivity and detection range, making it appropriate for both military and civilian scenarios.
4) Aerospace and Aviation: Microstrip patch array antennas play a crucial role in aerospace applications, including aircraft and Unmanned Aerial Vehicles (UAVs). Enhanced gain enables these antennas to maintain stable communication links over longer distances, contributing to reliable navigation and data transmission.

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5) Remote Sensing: Remote sensing applications, such as Earth observation satellites, benefit from microstrip patch array antennas with enhanced gain. These antennas facilitate the collection of high-resolution data over large areas, supporting environmental monitoring, disaster management, and agricultural applications.
6) 5G Communication Systems: With the ongoing implementation of 5G networks, antennas with improved gain are crucial for achieving the high data rates and low latency that 5G technology promises. MPA antennas play a role in both base station and user equipment antennas in 5G networks [21].
7) Wireless Networks: Wi-Fi access points are perfect potential applications of MPAs with both-sided MICs for heavily crowded regions or huge buildings since their higher gain antennas help extend coverage and capacity.
8) IoT Devices: Improved gain can facilitate better communication between sensors and data aggregation sites in smart city and industrial applications.
9) Automotive Applications: In Advanced Driver-Assistance Systems (ADAS) high-gain antennas are essential for radar-based systems that improve vehicle safety features such as collision avoidance and adaptive cruise control.
10) Radio Astronomy: In radio astronomy, where sensitivity and precision are paramount, microstrip patch arrays with enhanced gain can be employed for radio telescopes. These antennas facilitate tbe reception of faint signals from celestial bodies, enhancing progress in astronomy.
11) Medical Imaging: In MRI and ultrasound some imaging systems use microstrip antennas to enhance signal quality and depth resolution, thereby improving diagnostic capabilities.

VI. FUTURE RESEARCH SCOPE

While this research has reached important milestones, there are several potential avenues for future work to explore.

1) Real-World Testing: Fabrication based on simulated results can be pursued to conduct real-world testing, allowing for a thorough analysis of the proposed microstrip array antenna's performance.
2) Integration of Active Components: Investigating the incorporation of active components could enhance the functionality of the microstrip array, particularly for specific applications such as phased array systems.
3) Advancements in MIC Technologies: Exploring new advancements in MIC technologies and materials may further improve compactness, integration, and overall performance in microstrip array designs.

VII. CONCLUSION

In conclusion, the research presented in this thesis focused on the design and optimization of a microstrip array antenna for gain enhancement using both-sided MIC technique for simplifying the feeding structure. The initial design of a single microstrip patch antenna demonstrated proper resonance at 10 GHz, establishing the foundation for subsequent array configurations. The designed 2x2 array antenna is properly matched at 10 GHz with an impressive return loss of -45 dB and has a maximum isotropic gain of 13.42 dBi in the specified X-band frequency range. By increasing the number of patches to a 4x2 array, the maximum isotropic gain of 16.12 dBi is observed at its resonance frequency. The implementation of both-sided MIC technique proved effective in achieving equitable signal distribution, reduction of conduction loss (i'r loss), leading to high gain and directed beam patterns with a simplified feeding network. By using quarter wavelength impedance transformer for matching, the all elements are fed at their edge and hence unnecessary alteration of patches' geometry has been avoided in the design. The 2x2 microstrip patch array demonstrated impressive results, including a well-shaped 3D radiation pattern, minimized side lobes and back lobes, and the antenna exhibit the maximum broad side gain of 25.02 dB with an efficiency of 86%. Again by increasing the number of elements the designed 4x2 array has the radiation pattern with more focused and narrower beam. In this case the maximum broad side gain is 32dB and antenna efficiency attains 97% at the resonance frequency. The proposed array outperformed larger array configurations in terms of gain, highlighting the advantages of both-sided MIC technology in achieving significant gains while simplifying the design. A Comparison with some previous work has been given in Table 5.2. In conventional array cases it was observed that the antenna efficiency reduced with the increase of array elements because of losses in transmission line [11]. It is to be mentioned that none of the compared papers uses the both-sided MIC.

In essence, the utilization of the both-sided MIC technique in antenna design not only streamlined feeding structures but also propelled gains and efficiencies to unprecedented levels, solidifying its position as a transformative innovation in the field.

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