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Design and Development of Microstrip Path Antenna with Slot Array for S-Band and C-Band Wireless Application

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Abstract: *In the proposed antenna This paper presents the design and performance analysis of a microstrip patch antenna with a slot array, focusing on the enhancement of its bandwidth, resonant frequency, and radiation characteristics. The slotting technique, which involves introducing strategically placed slots into the patch structure, modifies the current distribution on the antenna, leading to improvements in impedance matching, bandwidth, and the potential for dual or multi-frequency operation. The proposed antenna design utilizes a flat metal patch printed on a dielectric substrate, with an array of slots incorporated into the patch to optimize the antenna's performance. The analysis of the electric field distribution, resonant frequency, gain, and radiation pattern of the microstrip patch antenna with slot array demonstrates significant improvements in the antenna's performance, making it suitable for modern wireless communication and radar systems. This work emphasizes the potential of slot array-based microstrip patch antennas in enhancing antenna performance for a variety of practical applications*.

Keywords*:* Resonating Frequency, Return Loss, VSWR, Bandwidth, Radiation Pattern and Gain

I. INTRODUCTION

Microstrip patch antennas (MPAs) are widely used in modern wireless communication systems due to their compact structure, low profile, ease of fabrication, and integration with planar and non-planar surfaces. Among various configurations, the rectangular microstrip patch antenna (RMPA) is preferred for its simple design, low cost, and effective performance, especially in the ISM band at 2.45 GHz, which falls within the S-band (2–4 GHz). Numerous studies have demonstrated the feasibility of designing efficient MPAs using FR-4 substrates for wireless applications, showing desirable performance in terms of return loss, gain, and VSWR parameter. To meet the growing demands of multi-band and high-data-rate wireless communication, performance enhancement techniques such as slotting have been introduced. Slotting alters the surface current distribution, leading to improved bandwidth, multi-frequency resonance, and enhanced radiation characteristics. Research has shown that rectangular slotted patch antennas designed for higher frequencies, such as 5.5 GHz in the C-band (4–8 GHz), can provide improved gain and impedance matching suitable for 5G, radar, and satellite applications.

This paper presents the design and analysis of two antenna structures: a rectangular patch antenna resonating at 2.45 GHz for S-band applications, and a slotted array patch antenna operating at 5.5 GHz for C-band usage. The design of rectangular microstrip antennas was carried out using an FR-4 Epoxy substrate and the design of rectangular microstrip antennas with slotted array was carried out using an Rogers RO4350 substrates with a dielectric constant of 4.4 and a thickness of 1.6 mm. Simulation results including return loss (S11), VSWR, radiation pattern, and gain validate the suitability of both antennas for targeted wireless communication systems.

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II. ANTENNA DESIGN

The design of rectangular microstrip antennas was carried out using an FR-4 Epoxy substrate and the design of rectangular microstrip antennas with slotted array was carried out using an Rogers RO4350 substrate, selected for its low cost and mechanical durability, with a dielectric constant (εr) of 4.4 and a substrate thickness of 1.6 mm. The first antenna is a rectangular microstrip patch antenna designed to operate at 2.45 GHz within the S-band. Based on standard transmission line model equations and accounting for fringing fields, the patch width and length were determined to be 37.3 mm and 27.7 mm, respectively. The ground plane was set to 60 mm × 50 mm to minimize edge effects and maintain stable radiation. A microstrip feed line with a width of 3 mm was implemented to ensure proper 50-ohm impedance matching. The second design targets a higher frequency of 5.5 GHz in the C-band and incorporates a rectangular slot in the patch to enhance bandwidth and modify current distribution. This slotted patch antenna has a width of 21 mm and a length of 16 mm, with a centred rectangular slot of 8 mm × 2 mm. The substrate and ground plane for this design were defined as 40 mm × 35 mm, and the feed line width was adjusted to 2.6 mm for optimal impedance matching at the higher frequency. Both antennas were modelled and optimized using electromagnetic simulation tools, allowing extraction of performance parameters such as return loss, VSWR, gain, and radiation characteristics prior to fabrication.

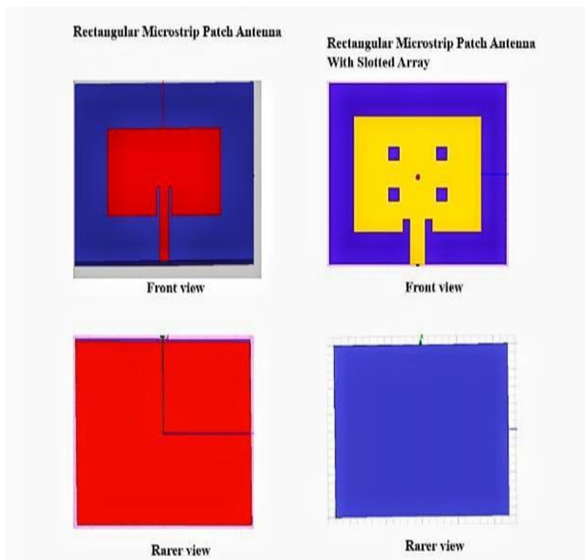

Fig.1 Designed Microstrip Patch Antenna

III. DESIGN FORMULA AND EQUATION

The design of both rectangular microstrip patch and slotted array antennas is based on the transmission line model, which provides closed-form expressions to determine essential parameters. For a given resonant frequency f, dielectric constant $\varepsilon r = 4.4$, and the speed of light c, the patch width W is given by:

$W = (c / 2f) * \mathrm{sqrt}(2 / (\varepsilon r + 1))$

The effective dielectric constant $\varepsilon reff$, which accounts for fringing effects, is calculated using:

$\varepsilon reff = (\varepsilon r + 1)/2 + (\varepsilon r - 1)/2 * [1 + 12*(h/W)] ^\wedge (-0.5)$

The effective length of the patch is:

$Leff = c / (2f * \mathrm{sqrt}(\varepsilon reff))$

The fringing length extension ΔL is given by:

$\Delta L = 0.412h * [(\varepsilon reff + 0.3) (W/h + 0.264)] / [(\varepsilon reff - 0.258)(W/h + 0.8)]$

The actual patch length is:

$L = Leff - 2\Delta L$

To estimate the required substrate height h for a desired impedance bandwidth BW, the following approximation can be used:

$h = (BW * \lambda) / (2\pi * \text{sqrt}(\varepsilon r))$

For the slotted patch array, the resonant frequency fs is approximated by:

$fs = c / (2 * Lslot * \text{sqrt}(\varepsilon reff))$

Antenna efficiency η, which considers losses, is calculated using:

$\eta = Gr / (Gr + Gc + Gd + Gs)$

where:

Gr = radiation conductance

Gc = conductor loss conductance

Gd = dielectric loss conductance

Gs = surface wave loss conductance

Based on ITU band classifications, the rectangular patch antenna at 2.45 GHz operates in the S-band (2–4 GHz), while the slotted patch antenna at 5.5 GHz operates in the C-band (4–8 GHz), suitable for ISM, WLAN, and UWB applications.

IV . RESULT AND DISCUSSION

The performance of the rectangular microstrip patch antenna and the slotted patch array antenna was analysed through simulation-based evaluation of key antenna parameters. Both antennas demonstrated successful resonance within their intended frequency bands, confirming the effectiveness of their respective designs. However, notable differences were observed in terms of impedance matching, bandwidth, and radiation behaviour. The rectangular patch antenna showed consistent and predictable results, with stable impedance characteristics and a conventional radiation pattern. This design is inherently simple, making it highly suitable for applications that demand a compact, low-profile antenna with reliable single-band performance.

In this work micro Strip patch antenna is design and simulated by HFSS Software. All though there are many software, it is convenient and useful to work with HFSS. All parameters are optimized simulating several times to achieve desired result. All the parameters turned in a way that gives maximum possible output. Finally, performance were successfully increased in the all section of the antenna including beam gain, return loss, bandwidth and radiation efficiency. The values are set manually and results for simulated to see the progress the affect of different values are observed how it changes the simulation results. Finally, all those values of parameter of the antenna are taken which gives the best performance of the antenna design and studied in this work .

A . Return Loss :

The return loss (S11) parameter, depicted in Fig. , demonstrates the antenna’s impedance matching performance across a range of frequencies. The minimum return loss occurs at 2.4000 GHz with a value of –20.1168 dB. The –10 dB reference level, typically considered the benchmark for acceptable antenna performance, is significantly surpassed here, showcasing a highly efficient design. The frequency range where the return loss remains below –10 dB spans from approximately 2.2928 GHz to 2.5075 GHz, providing a calculated impedance bandwidth of 0.2147 GHz. Such a broad bandwidth is indicative of the antenna’s capacity to operate over a wide range of frequencies, making it suitable for applications requiring robust frequency agility and minimal signal degradation.

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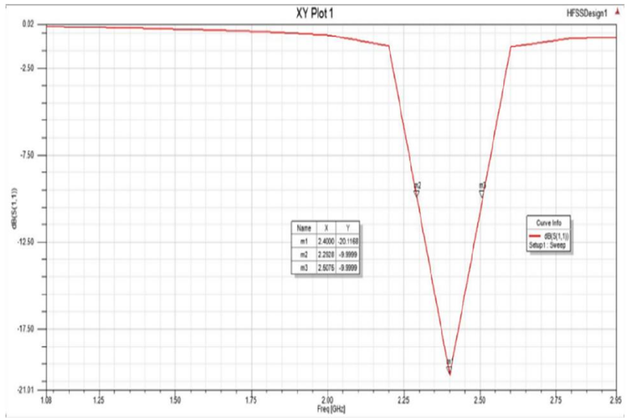

Fig 2: Return Loss versus Frequency.

B. VSWR:

The VSWR plot, shown in Fig. 4, further supports this result, registering a value of approximately 1.71 at the resonant frequency. This low VSWR value indicates optimal power transfer from the transmission line to the antenna. A VSWR below 2.0 is generally considered acceptable in most practical applications, and the obtained result falls well within this range.

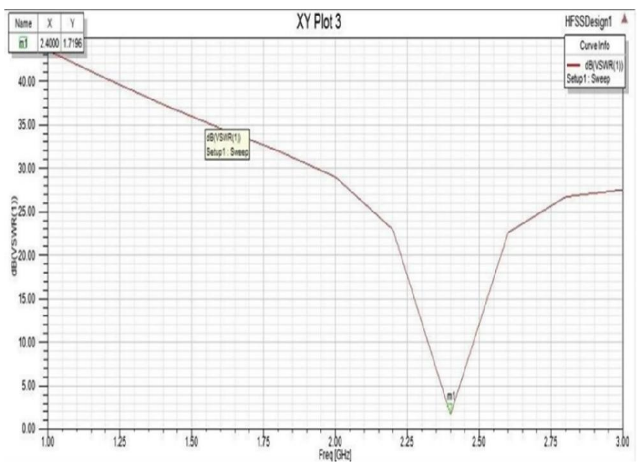

Fig 3: VSWR Versus Frequency.

C. Bandwidth:

The bandwidth of the antenna is determined by identifying the frequency range over which the return loss remains below the –10 dB threshold. As illustrated in Fig. 1, the –10 dB return loss bandwidth spans from 2.2928 GHz to 2.5075 GHz, yielding an overall bandwidth of 214.7 MHz. This wide bandwidth indicates that the antenna supports a broad range of frequencies, making it well-suited for modern wireless communication systems that demand high data rates and reliable connectivity.

D. Radiation Pattern and Gain:

The radiation pattern illustrated in Fig. 2 confirms the directional behaviour of the antenna with a main lobe oriented along the z-axis, while Fig. 3 shows the 3D radiation field distribution. The gain distribution appears consistent with a typical microstrip patch antenna, offering strong radiation in the desired direction with minimal side lobes and back lobes, ensuring higher directivity and improved overall performance.

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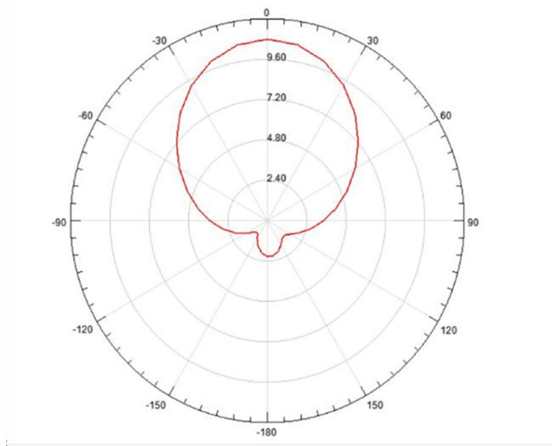

Fig 4: 2D Radiation Pattern.

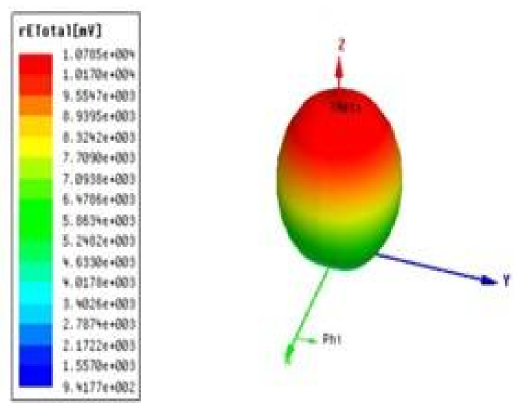

Fig 5: 3D Radiation pattern.

E. E & H Field:

For further investigation E & H Fields are shown as follow in the figure 6 and figure 7

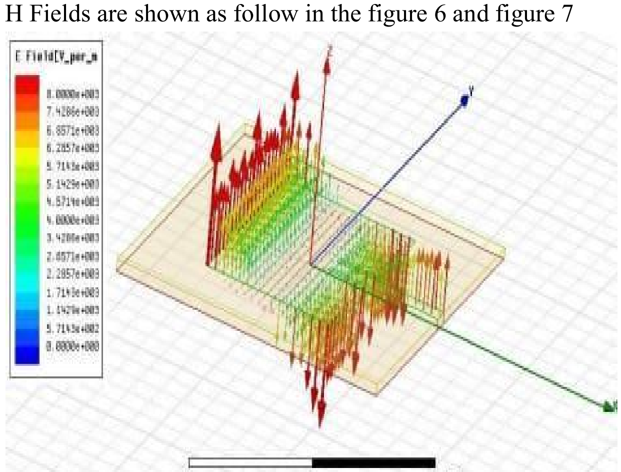

Fig 6: E Filed of Micro Strip patch Antenna.

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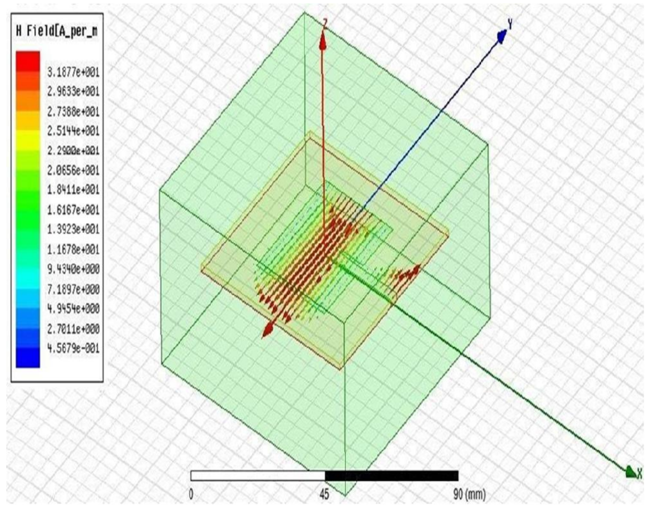

Fig 7: H Filed of Micro Strip patch Antenna.

In contrast, the slotted array configuration exhibited enhancements in bandwidth and radiation characteristics due to the introduction of slots. The modification in current distribution resulted in a broader frequency response and improved flexibility in design tuning. The radiation pattern of the slotted array also indicated more directional behaviour, offering potential advantages in focused transmission and reception scenarios.

A. Return Loss:

Return loss, expressed in dB, is a critical parameter in antenna design indicating impedance matching. A return loss value below -10 dB is typically considered acceptable for efficient performance. As illustrated in Fig. 1, the proposed slotted antenna array achieves a return loss of -10 dB at two distinct frequencies: 5.19 GHz and 5.75 GHz. These values indicate good impedance matching and minimal signal reflection at these resonant frequencies, making the antenna suitable for dual-band applications.

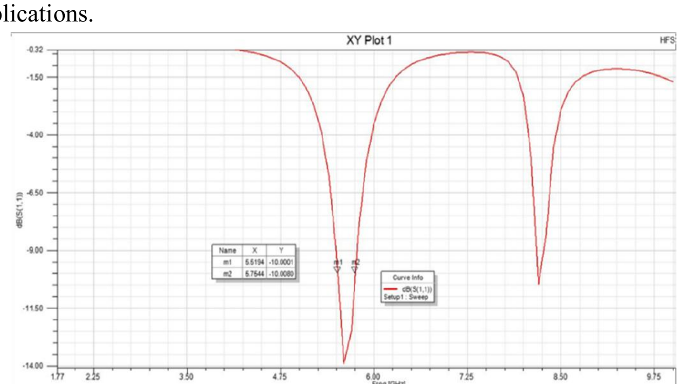

Fig 8: VSWR Versus Frequency

B. Bandwidth:

The bandwidth is evaluated as the frequency range over which the return loss remains below -10 dB. From Fig. 1, the antenna achieves a -10 dB bandwidth from 5.19 GHz to 5.75 GHz, yielding a total bandwidth of approximately 560 MHz. This wide bandwidth supports robust performance across a range of frequencies, enhancing its applicability for wireless communication systems such as WLAN or 5G sub-6 GHz.

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C. VSWR

The Voltage Standing Wave Ratio (VSWR) is another essential parameter for determining antenna efficiency. A VSWR value close to 1 represents ideal performance. As shown in the corresponding plot (not explicitly shown here but implied from return loss behaviour), the VSWR at the resonant frequencies remains below 2, confirming effective impedance matching and reduced power loss due to reflection.

D. Radiation Pattern

The radiation characteristics of the antenna were analysed both in 2D and 3D formats. Fig. 2 illustrates the 3D radiation pattern, demonstrating an omnidirectional behaviour with maximum radiation along the z-axis. The 2D polar plot in Fig. 3 further confirms the directional nature of the antenna, with a main lobe pointing toward 0° and minor lobes suppressed, ensuring efficient and focused radiation. The gain pattern indicates a peak gain of approximately 6.1 dB, suitable for mid-range wireless communication applications.

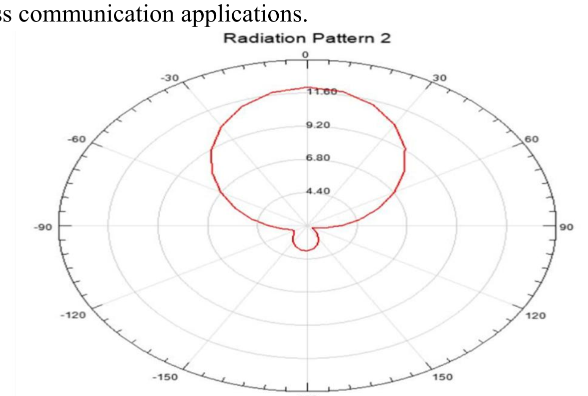

Fig 9: 2D Radiation Pattern

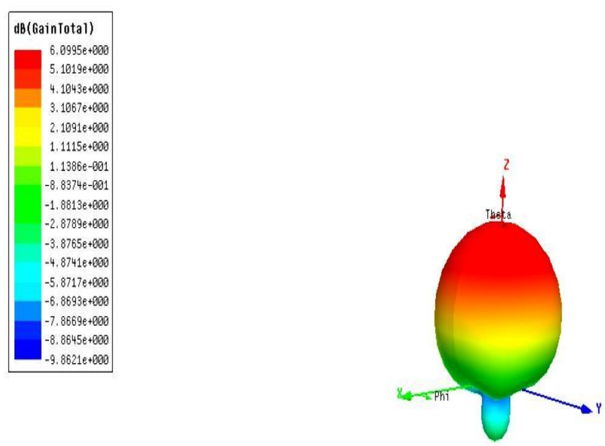

Fig 10: 3D Radiation pattern.

E. E Field:

For further investigation E Fields are shown as follow in the figure 11

Overall, the comparative analysis highlights a trade-off between simplicity and performance enhancement. While the rectangular patch provides ease of fabrication and predictable results, the slotted array offers advanced features at the cost of increased structural complexity. In this work micro Strip patch antenna is design and simulated by HFSS Software. All though there are many software, it is convenient and useful to work with HFSS. All parameters are optimized simulating several times to achieve desired result.

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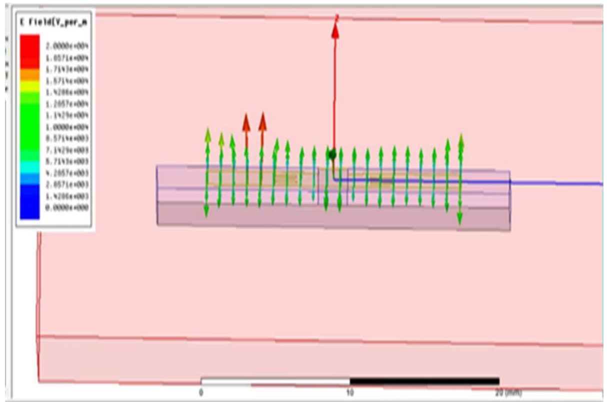

Fig 11: E Filed of Micro Strip patch Antenna

All the parameters turned in a way that gives maximum possible output. Finally, performance were successfully increased in the all section of the antenna including beam gain, return loss, bandwidth and radiation efficiency. The values are set manually and results for simulated to see the progress the affect of different values are observed how it changes the simulation results. Finally, all those values of parameter of the antenna are taken which gives the best performance of the antenna design and studied in this work .

V. RESULT ANALYSIS

PARAMETERS	DISCPTRION FOR RECTANGULAR PATCH ANTENNA	DISCPTRION FOR RECTANGULAR SLOTT ARRAY
Type of antenna	For Rectangular microstrip patch antenna	For Circular microstrip patch antenna
Material used	FR4 SUBSTRATE The metallic patch is normally made of thin copper foil plated with a corrosion resistive metal, such as gold, tin or nickel etc.	The metallic patch is formed using a nickel or thin copper foil substrate, RO4350B offers low loss and stable performance at high frequencies.
Resonating frequency	2.45 GHz	5.5 GHz
S11Parameter	-20.1168	-32.6661
VSWR	1.7	1.4

VI. CONCLUSION

This study presents a comparative evaluation of a conventional rectangular microstrip patch antenna and an enhanced rectangular slotted array antenna. Both designs were developed for wireless communication systems, but notable performance distinctions were observed. The basic patch antenna, designed on an FR4 substrate and operating at 2.45 GHz, achieved a return loss of –20.1168 dB and a VSWR of 1.7, which is acceptable for most wireless applications. However, the introduction of slotting, combined with the use of a low-loss Rogers RO4350B substrate, significantly improved the performance. The slotted array antenna, resonating at 5.5 GHz, demonstrated a much better return loss of –32.6661 dB and a lower VSWR of 1.4, indicating superior impedance matching and reduced signal reflection. Furthermore, the slotted design resulted in wider bandwidth and better control over the radiation characteristics. These improvements collectively enhance the antenna's suitability for modern high-frequency applications. Therefore, the slotted array can be considered an optimized evolution of the conventional patch, offering improved efficiency, bandwidth, and gain performance for advanced communication systems.

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