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Design and Simulation of a 3 GHz Rectangular Microstrip Patch Antenna Using ADS

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Rectangular Microstrip Patch Antenna.
Bandwidth.
Inset Feed.
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ABSTRACT

This study presents the design, simulation, and performance analysis of a rectangular microstrip patch antenna (RMPA) intended for wireless communication systems operating at 3 GHz. The antenna is modelled using Advanced Design System (ADS) software and fabricated on a RO4360 substrate with a dielectric constant of 6.15 and a thickness of 1.524 mm. The RO4360 material is selected due to its low loss, high-frequency stability, and compactness at microwave frequencies. To ensure proper impedance matching, an inset-fed microstrip line technique is employed. Simulation results demonstrate a return loss of -24.735 dB at 3.019 GHz and a fractional bandwidth of 1.2%, satisfying the bandwidth target for narrowband applications. Due to the single patch configuration, the radiation pattern is nearly omnidirectional with modest gain. The paper also reviews various enhancement techniques—such as feeding optimization, substrate modification, use of parasitic elements, and defected ground structures—to overcome limitations in bandwidth and gain. The proposed antenna design is suitable for compact and cost-effective wireless devices.

تصميم ومحاكاة هوائي رقعة ميكروستريب مستطيل بتردد 3 جيجاهرتز باستخدام ADS

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الكلمات المفتاحية:
هوائي رقعة ذو الشرائح الرقيقة (ميكروستريب) على شكل مستطيل.
عرض النطاق.
التغذية المدخلة.
الأداء.

الملخص

تعرض هذه الدراسة تصميم ومحاكاة وتحليل أداء لهوائي رقعة مستطيلة يعمل بتردد 3 جيجاهرتز لأنظمة الاتصالات اللاسلكية. تم تصميم الهوائي باستخدام برنامج Advanced Design System (ADS) وتنفيذه على ركيزة من نوع RO4360 ذات ثابت عزل قدره 6.15 وسماكة 1.524 مم. تم اختيار مادة RO4360 نظرًا لانخفاض الفقد فيها واستقرارها العالي في الترددات العالية، بالإضافة إلى قدرتها على تحقيق تصميم مدمج عند ترددات الميكروويف. تم استخدام تقنية التغذية المدخلة لتحقيق مطابقة مقاومة 50 أوم. أظهرت نتائج المحاكاة أن فقدان الإرجاع بلغ -24.735 ديسيبل عند التردد 3.019 جيجاهرتز، وبلغ عرض النطاق النسبي 1.2%، مما يفي بمتطلبات التطبيقات ذات النطاق المحدود. ونظرًا لاستخدام رقعة مفردة، كان نمط الإشعاع شبه متساوي الاتجاه وبكسب منخفض نسبيًا. كما تستعرض الورقة تقنيات تحسين الأداء مثل تحسين أسلوب التغذية، تعديل خصائص الركيزة، استخدام العناصر الطفيلية، وتطبيق الهياكل الأرضية المعيبة لزيادة الكسب وعرض النطاق الترددي. يُعد هذا التصميم مناسبًا للأجهزة اللاسلكية المدمجة ومنخفضة التكلفة.

1. Introduction

Microstrip patch antennas have become fundamental components in modern wireless communication systems due to their advantages in terms of compact size, low profile, low manufacturing cost, and ease of integration with planar circuitry. Among the various geometries, the rectangular microstrip patch antenna (RMPA) is the most widely used because of its simple design, predictable behaviour, and ease of analysis. These features make RMPAs suitable for applications such as mobile communication, radar, satellite systems, and wireless local area networks (WLANs).

Despite their popularity, microstrip patch antennas suffer from certain inherent limitations most notably, narrow bandwidth, low gain, and limited radiation efficiency. Typically, the bandwidth of a conventional microstrip antenna is only about 1% to 5% of the centre frequency. These shortcomings restrict their use in broadband and high-performance systems unless specific enhancement techniques are applied [1][2].

Figure 1 illustrates the structure of a rectangular patch antenna characterised by its width (W), length (L), and substrate thickness (h). The patch behaves like a resonant cavity, radiating mainly through its edge fringing fields when its length is approximately half of the guided wavelength. These fields are influenced by the dielectric constant and thickness of the substrate. A low dielectric constant improves radiation efficiency and bandwidth, while an increased substrate height can

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enhance bandwidth albeit at the cost of increased surface wave losses. The selection of the substrate is therefore crucial in achieving the desired performance characteristics [2][3].

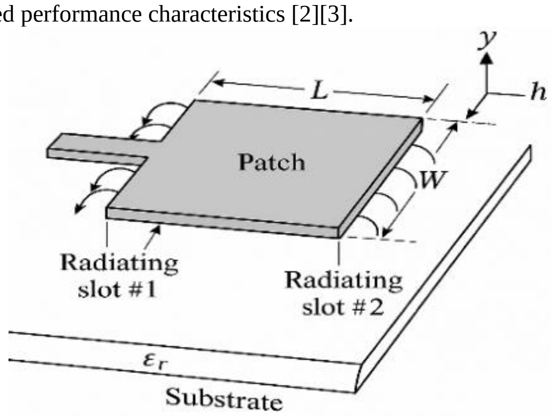

Fig 1: Rectangular microstrip patch antenna

Another major factor influencing antenna performance is the feeding technique, which determines how RF energy is delivered to the patch. The four most commonly used feeding approaches are: microstrip line feed (inset feed), coaxial probe feed, aperture coupling, and proximity coupling. In the present work, the inset-fed microstrip line method is used. This contacting technique provides a fully planar structure, as the feed line is etched directly on the same substrate as the patch. By adjusting the inset depth, impedance can be matched precisely to 50 ohms without external matching networks. This technique is preferred for its simplicity, fabrication ease, and compatibility with single-layer substrates—making it ideal for compact and low-cost wireless devices. However, it should be noted that thicker substrates may introduce increased surface wave losses and spurious radiation with this method [4].

This paper presents the simulation and performance analysis of a rectangular microstrip patch antenna designed to operate at 3 GHz, using the Advanced Design System (ADS) software. The antenna is implemented on a RO4360 (Rogers) substrate with a dielectric constant of 6.15 and a thickness of 1.524 mm. The RO4360 material was selected for its low dielectric loss, stable performance at microwave frequencies, and ability to support compact antenna designs.[5] The objective is to assess key performance metrics such as return loss, impedance matching, bandwidth, and radiation pattern, and to explore various enhancement techniques for future design optimization.

2. The Proposed Antenna Design Equations

Design formulas will be used to determine the antenna dimensions which include the patch's width and length (W, L), the feed line's length and width ($l0$, $w0$), the length of inset feed d as shown in Fig 2.

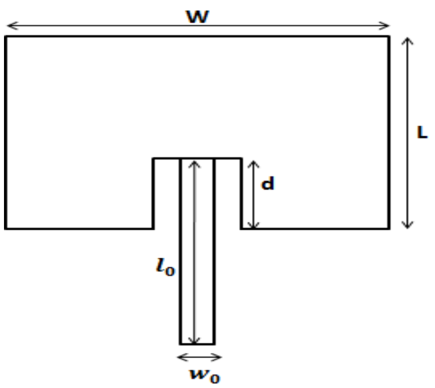

Fig 2: The dimensions of the rectangular patch antenna

2.1. The rectangular patch antenna

In designing a rectangular microstrip patch antenna, several parameters must be determined to achieve optimal performance. These include the patch width, length, feed line dimensions, and the inset distance. The design process is based on standard microstrip antenna theory and is supported by analytical equations.[6]

To create an effective radiator, the width of the RMPA should be calculated as half of a wavelength as indicated in Equation (1). The width of the antenna W controls both the input impedance and the radiation pattern; as the width increases, the impedance lowers.

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

Where,

f_r: Operating (resonant) frequency
μ_0: Permeability of the free space
W: The width of the patch
ε_0: Permittivity of the free space
ε_r: Permittivity of the dielectric
c: Speed of light

The length of the microstrip patch determines the resonant frequency, which is computed using Equation (2). This requires the effective permittivity ε_{eff} and the length's extension ΔL.

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

Where,

L: The length of the microstrip patch
ε_{eff} : Dielectric effective permittivity
ΔL: Extended incremental length

Because of the fringing field effect, the patch appears longer than its actual dimensions. An approach for determining the extension length ΔL is shown in Equation (3).

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}+0.258)(\frac{W}{h}+0.8)} \quad (3)$$

Where, h: Thickness of the dielectric

The effective dielectric constant ε_{eff} is somewhat less than the permittivity of the dielectricε_r, due to the fringing field surrounding the patch spreading in the air along with the dielectric substrate

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\,[1+12\frac{h}{W}]^{-\frac{1}{2}} \quad (4)$$

2.2. The length of the inset feed

The input impedance of the antenna varies with the length of the inset feed. As indicated in Figure 2, the distance d from the end must be determined in order to calculate the feed line. Equation (5) simplifies the computation of the antenna's inset length, as documented in [7].

$$d = \frac{L}{2} \times 10^{-4}(0.001699\varepsilon_r{}^7 + 0.13761\varepsilon_r{}^6 - 6.1783\varepsilon_r{}^5 + 93.187\varepsilon_r{}^4 - 682.69\varepsilon_r{}^3 + 2561.9\varepsilon_r{}^2 - 4043\varepsilon_r + 6697) \quad (5)$$

Where, d: The length of the inset fed

2.3. The transmission line width and length

The design formulas for determining the feed line's height and length apply to any microstrip transmission line. A one-half wavelength of the operating frequency is considered when designing the microstrip transmission line. The width of the feed line can be calculated through Equation (6). [6][8]

$$\text{For } A > 1.52,\quad \frac{w_0}{h} = \frac{2}{\pi}\left\{B - 1 - \ln(2B-1) + \frac{\varepsilon_r+1}{\varepsilon}\left[\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon}\right]\right\} \quad (6)$$

Where the values of A and B are calculated from Equations 7 and 8 respectively.

$$A = \frac{Z_0}{60}\left(\frac{\varepsilon_r+1}{2}\right)^{\frac{1}{2}} + \frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \quad (7)$$

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}} \quad (8)$$

Equation (9) determines the length of the feed line.

$$l_0 = \frac{\lambda_g}{2} \quad (9)$$

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}}$$

For $\frac{w_0}{h} = 1.468 > 1$, the ε_{eff} of the transmission line is determined by Equation 10.

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\,[1+12\frac{h}{w_0}]^{-\frac{1}{2}} \quad (10)$$

Where;

w_0: The width of the feed line
λ_g: guide wavelength
l_0: The length of the feed line

3. Methodology

The rectangular microstrip patch antenna (RMPA) was modelled and simulated using the Advanced Design System (ADS). ADS is a comprehensive RF and microwave design platform that offers electromagnetic (EM) simulation, schematic capture, layout tools, and frequency-domain analysis. It is widely used in antenna design and provides accurate modelling of planar structures including microstrip antennas.t. It is capable of computing the S-parameters and the 2- and 3-dimensional graphs of the antenna's directivity patterns as well as the far field [9]. The specifications of the proposed RMPA design are listed in Table 1.

Table 1: The specified parameters of the RMPA design

Antenna parameters	The value
Operating frequency	3 GHz
Bandwidth	10dB, %5
Gain	4 dB
Input impedance	50 Ohm
Substrate dielectric constant	6.15

The input parameters, such as patch width, length, substrate thickness, and feed line dimensions, were calculated using analytical equations discussed in the previous section. The resulting patch parameters are listed in Table 2. All calculations for patch dimensions are applied onto ADS for assessment.

Table 2: Summary of patch parameters

Antenna parameters	Dimension (mm)
Patch width W	26.44
Patch length L	19.8
The inset length d	6.82
The feed line width w0	2.24
The feed line length $l0$	23.78

4. Results and Discussions

4.1. Simulation Results and Analysis

The S-parameters, the performance, and the radiation patterns of the designed antenna are illustrated in this section. Fig 3 shows the 2-D and 3-D of the 3GHz antenna design using ADS package.

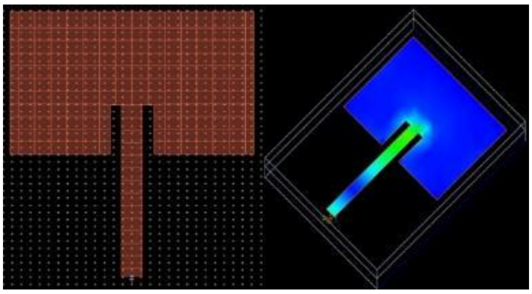

Fig 3: ADS layout of the RMPA design

The antenna simulation's findings are displayed in Fig 4. The operating frequency is selected where the insertion loss is at its minimum value. The design resonant is at 3.019 GHz which is approximately equal to the specified frequency (3GHz). The fringing field surrounding the antenna, which gives the appearance of a longer antenna, is the main reason for this shift.

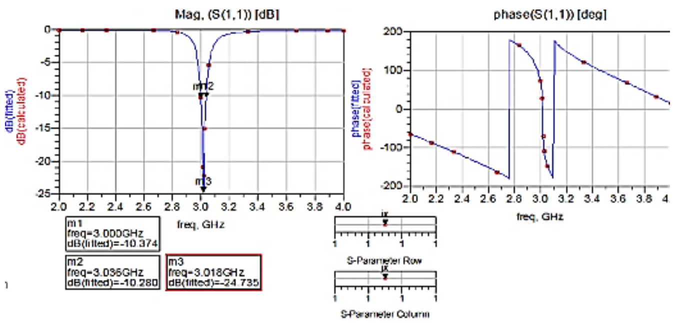

Fig 4: The frequency and phase response of the RMPA design

As illustrated in Fig 4, the return loss curve shows a strong resonance at 3.019 GHz, with a minimum return loss of −24.735 dB, indicating excellent impedance matching. The return loss remains below −10 dB between 2.982 GHz and 3.019 GHz, resulting in a fractional bandwidth of 1.2% which aligns with the design target for narrowband communication. The phase response of S11 shows a zero-phase crossing at the resonant frequency of 3.019 GHz, confirming a stable and predictable radiation behaviour at the design frequency.

The Smith chart shown in Fig 5 confirms the impedance matching of the antenna to the standard 50-ohm input. The matching point lies very close to the center of the chart, indicating minimal mismatch and efficient power transfer at the operating frequency.

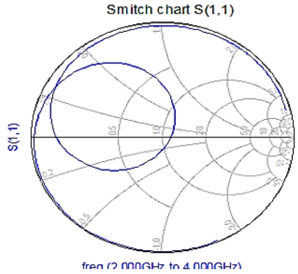

Fig 5: The antenna impedance is perfectly matched to 50 ohm

The 3D far-field radiation pattern of the antenna is shown in Fig 6. The radiation is nearly isotropic, which is typical for a single patch antenna with low directivity.

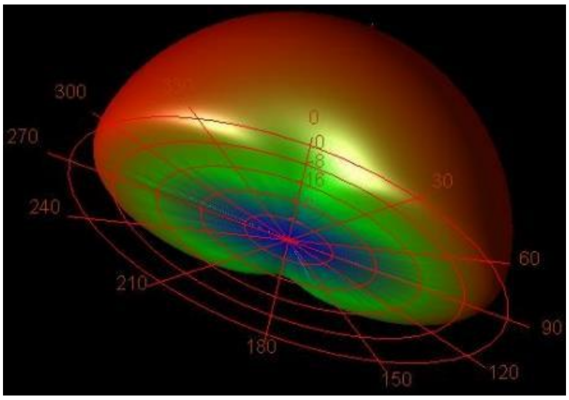

Fig 6: 3-D radiation pattern of the RMPA design

4.2. Discussions

The simulated rectangular microstrip patch antenna (RMPA) achieved a resonant frequency of 3.019 GHz with a return loss of 24.735 dB, confirming excellent impedance matching with the 50-ohm feed line. The fractional bandwidth was measured at 1.2%, which is consistent with the narrowband behaviour typical of single-layer, single-patch antennas. Additionally, the nearly isotropic far-field observed in Figure 6 aligns with expectations for low directivity, single-patch structures. While these results validate the core design parameters, they also highlight inherent limitations of the basic RMPA design. Several enhancement techniques can be employed to improve bandwidth, gain, and overall performance:

Substrate material and thickness significantly affect antenna performance. In [10], the use of a low-loss Rogers RT/Duroid 5880 substrate was shown to improve both bandwidth and gain for a 28 GHz 5G antenna, yielding a gain of 8.21 dB and efficiency above 75%. Conversely, [11] demonstrates that even with a higher-loss FR-4 substrate, efficient design and precise dimension control can still achieve satisfactory gain and bandwidth performance.

Incorporating slots into the radiating patch can create multiple resonant paths, improving impedance bandwidth and facilitating multiband operation. The work in [12] introduced a U-slot into a microstrip patch, achieving bandwidth enhancement and improved gain due to additional current paths. Similarly, [11] [13] used slot techniques to enable resonance at multiple 5G bands, ensuring compactness and enhanced radiation performance.

Parasitic patches placed near or around the driven element can increase the effective aperture and improve bandwidth. In [14], parasitic elements helped broaden the bandwidth of the main patch through capacitive and inductive coupling effects, resulting in a stable radiation pattern with enhanced gain. Similarly, [15] proposed a high-gain rectangular patch antenna with parasitic patch mushrooms for future 5G communication networks. This antenna offers significant gain and can operate across a broad frequency range, making it a strong candidate.

Defected Ground Structures (DGS) involve etching specific patterns on the ground plane to suppress surface waves and modify the antenna's current distribution. In [16], a DGS structure introduced beneath the radiating patch led to significant improvement in impedance matching and bandwidth. Similarly, [17] utilised DGS to achieve dual-band operation at 28 and 38 GHz, with improved isolation in MIMO configurations.

The feeding technique greatly influences return loss and bandwidth. The aperture coupled design proposed in [18] achieved a return loss of approximately −40 dB, compared to −19 dB using the inset-fed method. It also provided a significantly larger impedance bandwidth (over 15% higher than the inset-fed line), along with moderate gain (~5 dB) and 30% efficiency at around 1.5 GHz.

The most common method for achieving high gain is to use multiple elements in an array excited through a feeding network. This results in a more directive pattern with better half-power beamwidth and gain. The performance of the array depends on its design, radiating element pattern, excitation amplitude, phase, and spacing [2][3].

5. Conclusion

This paper presented the design and simulation of a rectangular microstrip patch antenna optimised for operation at 3 GHz, using the Advanced Design System software. The antenna was implemented on an RO4360 substrate, chosen for its low dielectric loss and suitability for high-frequency applications. An inset-fed microstrip line was employed to achieve proper impedance matching with a 50-ohm input. The simulated antenna demonstrated a resonant frequency of 3.019 GHz, a return loss of −24.735 dB, and a fractional bandwidth of 1.2%. In its current form, the proposed RMPA is well suited for compact, low-cost wireless systems that operate in the 3 GHz frequency band, such as narrowband IoT devices, short-range sensors, or low-power RF transmitters.

While the antenna meets the performance criteria for narrowband wireless applications, it suffers from typical limitations of single patch designs namely, low directivity and restricted bandwidth. These issues suggest the need for further performance enhancement if broader or higher-gain coverage is desired. Future work should focus on integrating multilayer parasitic patches or exploring proximity coupled feeding methods to develop multiband or broadband antennas without significantly increasing fabrication complexity.

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