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Compact and Innovative Microstrip Patch Antenna with Enhanced Microwave Circuit Performance for RFID Applications

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This research article introduces a microstrip patch antenna characterized by its compact dimensions of 60 × 40 × 0.8 mm³ and is minimalistic. This design not only enhances several microwave circuit attributes, such as achieving an optimal gain but also offers a desirable bandwidth. It is designed using low cost FR4 material with a thickness of 0.8 mm and a relative dielectric constant (ε_r) of 4.4 to operate effectively within the frequency range spanning from 0.7 – 1.1 GHz. The ground plane is located beneath the substrate. The proposed antenna design demonstrates its suitability for lower frequencies due to its compact size. Simulation results validate the appropriateness of the antenna model. When compared to conventional patch antennas, the proposed design exhibits improved performance parameters, including a lower reflection coefficient, higher gain, and a lower VSWR. These simulations have been conducted using the CST software, enabling a comprehensive comparative analysis with existing antenna designs. The proposed antenna achieves outstanding impedance matching, indicated by |S11| measuring below – 10 dB, with a VSWR of less than 2 for a broad range of 0.7 to 1.1 GHz. Furthermore, it exhibits a peak gain of 4.49 dBi precisely at 0.915 GHz. Given its resonance at this frequency, the antenna proves to be an optimal selection for RFID applications, providing compatibility, efficiency, and adaptability to cater to a broad spectrum of RFID application scenarios.

Keywords: Antenna, Bandwidth, Gain, Microstrip patch, Radiation Pattern, Radio-Frequency Identification.

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1. INTRODUCTION

Radio-Frequency Identification (RFID) technology has revolutionized the way objects are tracked, identified, and managed across various industries. At the heart of RFID systems lies the crucial element of frequency, which determines the communication range, data transfer rate, and suitability for different applications. This introductory section delves into the diverse frequency ranges utilized in RFID technology, highlighting their significance and applications in the ever-expanding landscape of IoT (Internet of Things) and asset tracking. RFID (Radio-Frequency Identification) technology plays a pivotal role in today's world, with a wide range of applications and impacts across industries and everyday life. RFID is extensively used for tracking and managing goods in the supply chain. It enhances inventory accuracy, reduces errors, minimizes theft, and streamlines the movement of products from manufacturers to consumers. RFID is widely employed for access control systems in offices, hotels, and residential buildings. It ensures secure entry and exit by identifying authorized personnel or residents through RFID cards or key fobs. Hospitals and healthcare facilities use RFID for tracking medical equipment, monitoring patient data, and ensuring the accurate distribution of medications. RFID also helps manage the inventory of pharmaceuticals and medical supplies. Many modern passports and identity cards contain RFID chips for enhanced security and quick verification at border crossings and security checkpoints. Libraries use RFID to automate check-in/check-out processes and track the location of books and other materials. Document management systems use RFID to organize and locate files. RFID-enabled bins and containers help optimize waste collection routes, reduce costs, and promote recycling and sustainability. RFID technology continues to evolve, with ongoing innovations in tag design, reader capabilities, and software applications. Its versatility and efficiency make it a crucial component of the modern interconnected world, contributing to improved efficiency, security, and convenience across a wide range of industries and applications.

2. LITERATURE REVIEW

This study presented in [1] reports a novel rectenna, integrating a dual-band modified quasi-Yagi antenna with dual-band impedance matching and a dual-band rectifier, achieving the desired voltage output, competitive power conversion efficiency, and wide input power range while operating effectively in both the 0.868 GHz and 0.915 GHz ISM bands, making it suitable for indoor wireless power transfer applications within the typical range of 2 m to 10 m. In [2], a cost-effective and flexible hybrid energy harvester, incorporating both solar and electromagnetic energy capture on a PET substrate with an α-Si solar cell, is proposed which operates at 0.915 GHz frequency to efficiently harness and recycle environmental energy, featuring an integrated solar antenna design and an optimized multiband rectifier circuit. In [3], a compact circularly polarized implantable antenna for the Medical Implant Communications Service (MICS) band is proposed. It

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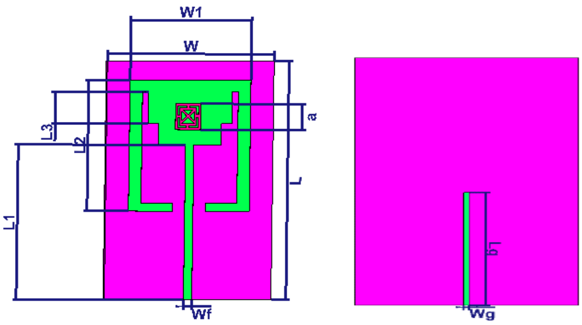
offers a wide impedance matching range and broad axial ratio without the need for a defective ground plane. The compact size and broad AR make it ideal for pacemaker devices in biomedical communication. The article reported in [4] suggests a novel omega-shaped tag antenna utilizing inductively coupled feeding through U-shaped stepped-impedance resonators (SIRs) to enhance RFID antenna performance. It achieves improved impedance matching, and peak gain, with a measured size of $50 \times 55.55 \times 1.6$ mm^3 and a peak gain of 1.8 dBi, demonstrating enhanced performance within the 900 – 940 MHz frequency range as RFID tag antenna. In ref. [5], the exploration of RFID technology in IOT based healthcare system is demonstrated and discussed. The transition from traditional medicine to participatory healthcare, bolstered by the Internet of Things (IoT) and a range of sensors in domestic settings, including RFID technology, is explored in this survey, highlighting its role in personal healthcare within smart environments by monitoring various parameters and complying with regulations. Ref. [6] demonstrates the experimental validation of a miniaturized implantable antenna characterized by circular polarization. It is designed for operation within the ISM band centered at 915 MHz, featuring improved size reduction through slot cutting and a shorting pin to enhance circular polarization purity, meeting safety standards as confirmed through simulations in a skin phantom and measurements in a skin-mimicking solution. In ref. [7], a UHF flexible passive RFID tag antenna operating in the 902 – 928 MHz frequency band is proposed, featuring a compact and slim design on a flexible commercial substrate, The antenna has been optimized using a Genetic Algorithm (GA) with the objective of maximizing its read range, and demonstrating the ability to operate effectively on both flat and curved surfaces, making it suitable for various applications such as industrial asset management, and identifying small objects like hardware tools, tin cans, and cylindrical containers made of PET. The reconfigurable antenna reported in ref. [8] demonstrates the capability to operate in three single-band modes at 0.915 GHz, 1.3 GHz, and 2.25 GHz with good gains while maintaining a compact size of $65.0 \times 25 \times 1.6$ mm^3, addressing the miniaturization requirements of wireless communication systems and antenna multi-functionality. The study conducted in ref. [9] introduces an innovative inductively coupled feed technique to enhance the performance of radio frequency identification (RFID) tag antennas, achieving improved impedance matching, size, and gain within a compact 50.7×01.6 mm^3 design, with a peak gain of 2.5 dBi at its operating frequency and excellent impedance matching characteristics in the 904 – 937 MHz range, as confirmed by comparisons between simulation and measurement results, demonstrating its capacity to boost overall tag antenna performance. In [10], a compact microstrip antenna operating at 915 MHz within the ISM (Industrial, Scientific, and Medical) band is specifically designed for RFID tag applications. It incorporates Defected Ground Structure (DGS) and slot techniques on an FR4 substrate, resulting in a verified antenna that exhibits strong impedance matching spanning from 909 MHz to 921 MHz, a consistent radiation pattern, a return loss of –23.72 dB, a directivity of 1.85 dB, and a gain of 1.21 dBi, all within a small footprint of 49.3×55.57 mm². Some other printed antenna structures operating at the same frequency band (0.9/0.915 GHz) are also reported for RFID applications [11-14] but the overall area occupied by the antenna are larger compared to the RFID antenna proposed in this article.

In this article, the authors are also motivated to design and present a complete analysis of an RFID antenna operating at 0.915 GHz with compact antenna dimensions. The key objective is to enhance operating bandwidth and to offer good impedance and radiation characteristics parameters by maintaining miniaturized antenna dimensions. The proposed designed antenna requires an overall area of 60×40 mm^2 and operates at 0.915 GHz, covering 0.7 to 1.1 GHz frequency spectrum with a peak gain of 4.49 dBi.

3. METHODOLOGY

A novel microstrip patch antenna with a pendulum-shaped design, tailored for RFID applications operating at 0.915 GHz. The recommended antenna design comprises three fundamental components: a pendulum-shaped patch, a segment of ground plane, and a microstrip feed line. The study showcases simulation results demonstrating various antenna attributes, such as a reflection coefficient of less than –10 dB, a VSWR of less than 2, gain, and radiation pattern. In this article, we propose a compact, broadband antenna with a bandwidth exceeding 400 MHz. Furthermore, it exhibits improved gain performance and maintains a stable radiation pattern, which is highly beneficial for RFID applications and ISM applications.

Fig. 1 illustrates the diagram representing the wideband antenna. The first slotting procedure has been conducted on a copper partial ground measuring 1×27.3 mm² in dimensions and having a thickness (t_p) of 0.025 mm. The laminate material possesses a permittivity (ε_r) of 1. Additionally, a pendulum-shaped patch with a length of 33 mm is integrated with a feed transmission line that spans 39 mm. Square-shaped split ring resonators are strategically positioned around the radiating patch to achieve expanded bandwidth and increased gain in the antenna system.



(a) (b)

Fig. 1 – Dimensional parameters of proposed antenna, (a) front view, (b) rear view

Based on the fundamental equations, the mathematical expressions provided in [15] for antenna design can be derived as follows:

1. The operational wavelength of the antenna, denoted as λ_0, is determined using the formula $\lambda_0 = c/fr$, where fr represents the resonant frequency, and c is the speed of light in free space.

2. Wavelength, λ_d, is calculated using the formula,

$$\lambda_d = {\lambda_0}/{\sqrt{\varepsilon_r}}$$

where ε_r is the dielectric constant.

3. The substrate thickness, Ht, is defined as

$$H_t \leq \frac{0.3\times c}{2\pi f_r\sqrt{\varepsilon_r+1}}$$

4. The width of the microstrip feed line, denoted as F_w, is given by

$$F_w = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}}$$

5. The effective dielectric constant, $\varepsilon_{reffective}$, is computed as

$$\varepsilon_{reffective} = \left(\frac{\varepsilon_r+1}{2}\right) + [\left(\frac{\varepsilon_r-1}{2}\right)\left(1+12\frac{h}{w}\right)^{-1/2}]$$

where h is the thickness of the substrate, and w is the width of the microstrip feed line. These formulas provide the necessary mathematical relationships for designing the antenna. The slot-loading methodology is fundamentally congruent with this approach. The proposed antenna configuration has been meticulously designed and rigorously evaluated through simulation using CST software.

Table 1 – Dimensional parameters of the suggested pendulum shaped Wide Band antenna

Parameters	**Dimensions (mm)**
L	60
W	40
W_f	2
L_1	39
L_2	33
L_3	8
W_1	29
L_g	27.3
W_g	1
a	6
b	5
c	4
d	3
e	3.84
g_1	0.7
g_2	0.7

All dimensions relevant to the specifications of the antenna design are detailed in Table 1. It is worth highlighting that the suggested antenna features a compact design that allows for seamless integration into wideband RFID devices. Fig. 2 expounds about the split ring resonator design present on the patch.

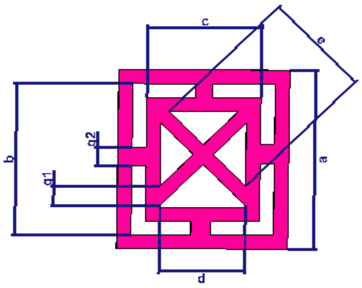


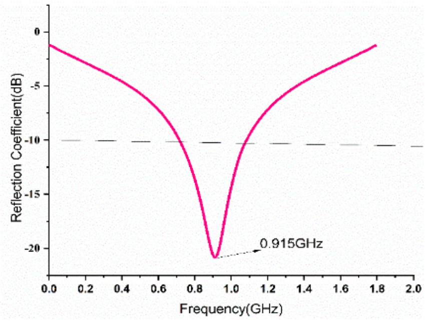
Fig. 2 – Specifications of squared split ring resonator

4. RESULTS

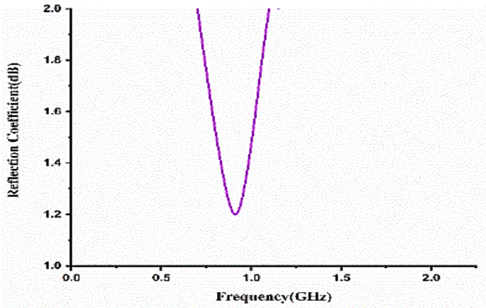
In this section, the CST simulator is employed to conduct a comprehensive evaluation of the proposed antenna's performance. The assessment entails the technical analysis and presentation of essential parameters, which comprise the reflection coefficient (S11), Voltage Standing Wave Ratio (VSWR), bandwidth, gain, and radiation patterns. Fig. 3 visually represents the S-parameter (S11) characteristics of the antenna. In this analysis, it is observed that the antenna demonstrates a resonance peak at 915 MHz, where the reflection coefficient is approximately –22 dB. Furthermore, the antenna exhibits an exceptionally broad bandwidth, as evidenced by the S11 parameter being less than or equal to –10 dB across a substantial frequency range spanning from 0.7 GHz to 1.1 GHz. This extensive bandwidth signifies that the antenna has the capacity to efficiently transmit and receive signals across this expansive frequency range while keeping energy reflection levels relatively low. Fig. 3 presents a graph displaying the Voltage Standing Wave Ratio (VSWR) values. The recommended pendulum-shaped patch antenna exhibits excellent impedance matching at 0.915 GHz, with a VSWR value of 1, well below the threshold of 2.

Fig. 4 illustrates the gain characteristics of the proposed antenna at a frequency of 0.915 GHz. The gain of an antenna quantifies its ability to direct or concentrate electromagnetic radiation in specific directions. In this case, the recommended antenna demonstrates consistent and favorable gain performance across its entire operating frequency band, which spans from 0.7 GHz to 1.1 GHz. Specifically, it maintains a minimum gain of over 3.50 dBi, signifying that the antenna consistently provides better radiation directionality compared to an isotropic radiator throughout this frequency range. The gain characteristics presented in Fig. 4 affirm that the suggested antenna design is well-suited for its intended purposes, as it offers consistently favorable gain levels across the entire operating frequency band.

Fig. 5 presents a graphical depiction of the two-dimensional radiation pattern in both the E-plane and the H-plane for the recommended antenna operating at a frequency of 0.915 *GHz*. In the E-plane, the radiation pattern exhibits a distinctive figure-eight shape. This means that the antenna's electromagnetic radiation is stronger in certain directions and weaker in others. This pattern implies that the antenna has preferential radiation and reception characteristics along specific azimuthal angles, which can be advantageous for applications requiring directional coverage.



(a)



(b)

Fig. 3 – a) s11 parameter results of proposed antenna, (b) VSWR

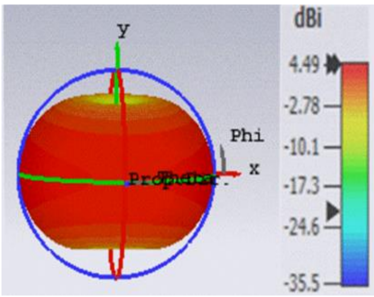


Fig. 4 – Gain obtained at 0.915 GHz frequency

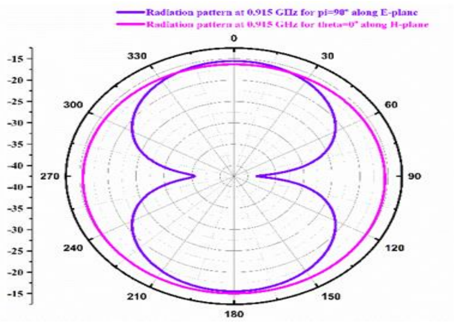
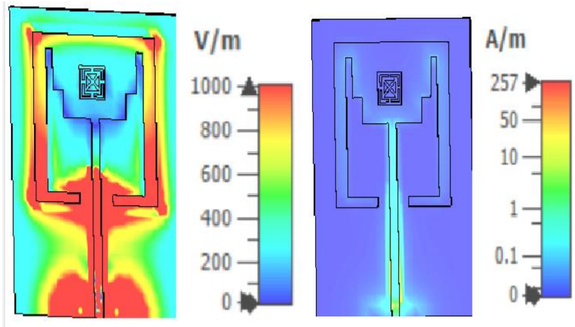


Fig. 5 – Radiation pattern along *E*- and *H*-planes at 0.915 GHz

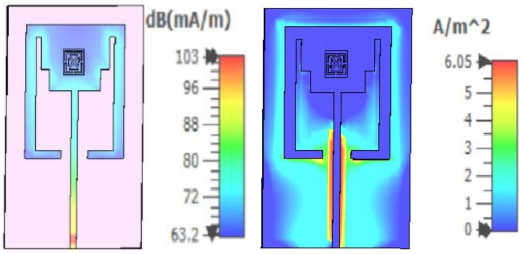
Conversely, in the *H*-plane, the radiation pattern appears nearly omnidirectional. This means that the antenna's radiation is relatively uniform in all directions within this plane, resulting in a nearly spherical coverage pattern when viewed from the side.

Fig. 6 provides an elucidation of the electric field distribution and magnetic field distribution at a frequency of 0.915 GHz. This figure essentially illustrates the spatial variation and intensity patterns of the electric and magnetic fields within the given electromagnetic environment, specifically at the designated frequency of 0.915 GHz. Fig. 7 offers insights into the surface current distribution and current density distribution. Fig. 7 visually represents how electric current flows along the surface and how the current density is distributed across different areas of the surface, providing valuable information about the electromagnetic behavior of the executed antenna under investigation.



(a) (b)

Fig. 6 – (a) Electric field distribution (b) Magnetic field distribution



(a) (b)

Fig. 7 – (a) surface current distribution (b) Current density distribution

5. PERFORMANCE COMPARISON WITH PREVIOUS REPORTED DESIGNS

A comprehensive comparative analysis has been systematically conducted to assess the performance of the proposed antenna design with respect to key technical parameters, including its physical dimensions, material composition, operating frequency range, simulation software employed, and resonator topology. Compared to all the previously analyzed antenna designs as outlined in Table 2, the suggested antenna not only boasts a compact form factor but also fulfills crucial criteria for operating frequency. Furthermore,

Table 2 – Performance comparison table

Ref.	Size (mm³)	Material	Operating frequency (GHz)	Resonator
[1]	58 × 130 × 1.6	FR4	0.9	–
[11]	110 × 60 × 0.787	RO3870 Duroid	0.9	Coupled Rectangular
[12]	55 × 66 × 1.27	Flexible	0.9	Meanderline
[13]	67 × 61 × 1.3	Flexible	0.9	Meanderline
[14]	100 × 100	RT/Duroid 5880	0.915	Nested loop
This Work	60 × 40 × 0.8	FR4	0.915	Squared Ring

the proposed antenna showcases exceptional broadband resonance capabilities and delivers superior gain performance. As a result, the proposed design emerges as the ideal choice for low-frequency RFID and ISM communication systems.

6. CONCLUSION

A novel pendulum-shaped microstrip patch antenna incorporating slot loading techniques has been innovatively designed and evaluated for RFID applications, featuring a compact form factor conducive to seamless integration in confined spaces within microwave electronics. The introduction of a square-shaped split-ring resonator has significantly broadened the antenna's operational bandwidth, while it's optimized dimensions at (60 × 40 × 0.8) mm^3 which furthermore emphasize its compact and uncomplicated design. This design offers distinct advantages over other microstrip antennas, manifesting in reduced radiation loss, minimized dispersion, a unique configuration, and favorable gain characteristics, all achieved without the need for specialized techniques. Notably, the antenna exhibits desirable characteristics, including a VSWR of ≤ 2, a broad bandwidth spanning 0.7 to 1.1 *GHz*, and a satisfactory maximum gain of 4.49 *dBi*. Given its geometric appropriateness and simplicity, the proposed antenna emerges as a promising choice for RFID applications at lower frequencies.

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Компактна та інноваційна мікросмужкова патч-антена з покращеною мікрохвильовою схемою для додатків RFID

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У статті представлена мікросмужкова антена, яка характеризується компактними розмірами 60 × 40 × 0.8 мм³ і є мінімалістичною. Ця конструкція не тільки покращує кілька атрибутів мікрохвильової схеми, наприклад досягнення оптимального підсилення, але також пропонує бажану смугу пропускання. Він розроблений з використанням недорогого матеріалу FR4 товщиною 0,8 мм і відносною діелектричною проникністю (ε_r) 4,4 для ефективної роботи в діапазоні частот від 0,7 до 1,1 ГГц. Площина заземлення розташована під підкладкою. Запропонована конструкція антени демонструє свою придатність для низьких частот завдяки своїм компактним розмірам. Результати моделювання підтверджують відповідність моделі антени. У порівнянні зі звичайними патч-антенами запропонована конструкція демонструє покращені параметри продуктивності, включаючи нижчий коефіцієнт відбиття, вищий коефіцієнт посилення та нижчий КСВН. Це моделювання було проведено за допомогою програмного забезпечення CST, що дає змогу провести комплексний порівняльний аналіз із існуючими конструкціями антен. Запропонована антена забезпечує добре узгодження імпедансу, позначене |S11| вимірювання нижче – 10 дБ, з КСВ менше 2 для широкого діапазону від 0,7 до 1,1 ГГц. Крім того, вона демонструє пікове пыдсилення 4,49 дБі саме на 0,915 ГГц. Враховуючи її резонанс на цій частоті, антена є оптимальним вибором для додатків RFID, забезпечуючи сумісність, ефективність і адаптивність для широкого спектру сценаріїв застосування RFID.

Ключові слова: Антена, Пропускна здатність, Посилення, Мікросмужковий патч, Діаграма спрямованості, Радіочастотна ідентифікація.