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Design and performance evaluation of a high-efficiency circular microstrip patch antenna for RFID applications at 900 MHz

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ABSTRACT

This study presents a high-efficiency circular microstrip patch antenna designed for radio frequency identification (RFID) applications simulation results illustrate the performance of a circular microstrip patch antenna operating at 900 MHz. Microstrip antennas are renowned for their ability to meet the requirements of compact, lightweight designs, ensuring compatibility, and ease of integration. This research focuses on the development of a circular microstrip antenna, formed as a circular patch on a 0.035 mm thick FR-4 substrate. The design was realized using a substrate with a relative permittivity (εr) of 4.3, a loss tangent (tan δ) of 0.021 and a substrate height (h) of 1.6 mm. The antenna dimensions are small, measuring 58×45 mm, with a circular patch radius of 17 mm. The antenna operates over a frequency range from 0.5 GHz to 2 GHz. Key performance parameters include a return loss of -49.8 dB, a wide bandwidth of 150 MHz, a voltage standing wave ratio (VSWR) of 1.009, a gain of 2.161 dB, and a directivity of 2.200 dBi. Antenna design and simulation were carried out using computer simulation technology (CST) Studio Suite Software, specifically adapted to RFID applications.

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1. INTRODUCTION

Radio frequency identification (RFID) technology has revolutionized the way we identify, track, and manage objects, living beings, and locations [1], [2]. Central to the functionality of RFID systems is the antenna, a critical component that ensures efficient communication between the RFID reader and the tags [3]. Designing antennas for RFID applications involves addressing unique challenges to optimize performance across various environments and applications [4]. Antennas in RFID systems must be designed to operate efficiently within specific frequency ranges, such as low frequency (LF), high frequency (HF), and ultra-high frequency (UHF), each offering distinct advantages and applications [5].

The design process must consider factors like impedance matching, radiation pattern, polarization, and physical size to ensure optimal signal transmission and reception [6]. The performance of an RFID system heavily relies on the antenna's ability to transmit power to the RFID tag and receive the return signal. One of the primary challenges in RFID systems at 900 MHz is the need for antennas that are compact, lightweight, and efficient while providing adequate bandwidth and gain to maintain reliable communication over varying distances. High efficiency is critical to ensure optimal energy transmission and minimize power losses, which directly impact the reading range and performance of the system [7]. Additionally, the antenna must be designed to handle the impedance matching constraints imposed by the RFID chip and reader, further complicating the design process. Traditional microstrip patch antennas, though widely used for their low-profile design and ease of fabrication, often suffer from narrow bandwidth and suboptimal efficiency, which limit their effectiveness in RFID applications, especially in environments with variable conditions or multi-object tracking [8], [9].

This makes parameters such as gain, bandwidth, and efficiency crucial in the design process. Additionally, environmental factors, including the presence of metal objects, water, and varying tag orientations, pose significant challenges that must be addressed through innovative antenna design strategies [10]. In this context, the development of RFID antennas involves a multidisciplinary approach, combining principles from electromagnetics [11], materials science, and electrical engineering. By leveraging advanced simulation tools and experimental validation, designers can create antennas that meet the stringent requirements of modern RFID applications [12], ranging from supply chain management and inventory tracking to contactless payments and access control. Various frequency bands of the electromagnetic spectrum, including 130 kHz LF, 13.5 MHz HF, 900 MHz UHF, and 2.4 (microwave frequency) are used in RFID technology [13], [14]. Recently, several antenna designs with unique characteristics have been reported for RFID applications [15].

One such design is a closely-spaced loop antenna microstrip monopole with directional radiation patterns, proposed to operate at 900 MHz [16]. One widely used frequency is 900 MHz. In recent years, numerous antennas have been developed to meet the requirements of this frequency, with the microstrip antenna being a notable example. A microstrip antenna consists of a dielectric substrate sandwiched between a ground plane and a patch Microstrip antennas offer numerous advantages, including a thin cross-sectional area, ease of fabrication, compact size, and lightweight design [17], making them suitable for integration with existing wireless communication devices [18].

Their use in base stations is particularly beneficial due to their favorable physical and mechanical properties, such as their lightweight and thin profile [19]. The core factors required to evaluate an antenna's performance include the radiation pattern, gain, impedance bandwidth, and polarization. Compact printed monopole antennas are essential for RFID applications [20], [21].

In addition to their small size, these antennas should be low cost, lightweight, durable, and have a low profile. The design method should also be straightforward. This paper presents a novel high-efficiency circular microstrip patch antenna tailored for RFID applications at 900 MHz. The design focuses on optimizing both efficiency and bandwidth, while maintaining a compact form factor conducive to RFID tag integration. By employing a circular patch structure, along with a modified ground plane and advanced impedance matching techniques, this study addresses the limitations of traditional designs, aiming to significantly improve the performance of RFID systems.

2. METHOD

In this section, we present a monopole circular patch antenna with a modified ground plane. The antenna design is implemented using computer simulation technology (CST). The initial step in the antenna design process involves applying specific formulas to calculate the antenna dimensions [22]. This includes determining the length and width of the antenna using prescribed equations. Subsequently, microstrip patch antennas are designed and simulated, focusing particularly on achieving a frequency requirement of 900 MHz. Table 1 presents detailed operational specifications for the design, which employs FR-4 substrate with a thickness of 0.035 mm [23].

Table 1. Dimensions of the antenna

Parameters	Values (mm)
W	45
L	58
W_f	6
L_f	40
RP	17
w_g	45
L_g	20
t	0.035
h	1.6

The design process utilizes a substrate featuring a relative permittivity (εr) of 4.3, a loss tangent ($tan\ \delta$) of 0.021, and a substrate height (h) of 1.6 mm, which helps in minimizing signal losses and improving overall efficiency. The thickness of the substrate is 1.6 mm, providing a balance between mechanical rigidity and electrical performance. The circular patch geometry was chosen due to its compact size and ability to achieve good omnidirectional radiation patterns, which are essential for RFID systems.

The radius of the patch is calculated using the following equation derived from transmission line theory to ensure resonance at 900 MHz.

The configuration includes an internal microstrip line to feed the patches. As shown in Figure 1, copper annular features are incorporated into the ground plane, along with circular patches [24]. Designing a circular microstrip antenna requires careful consideration of parameters such as the radius of the circular patch, the thickness of the patch and ground, and dimensions of the substrate in terms of width, length, and radius of the circular patch. These parameters are calculated using specified equations [25].

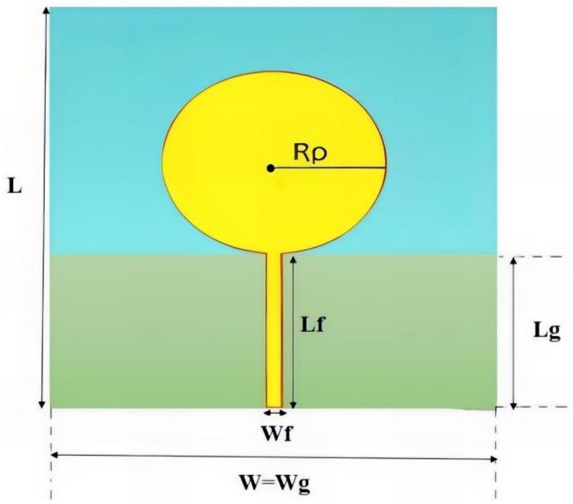

Figure 1. Microstrip patch antenna

The formulas used to size the microstrip antenna according to the literature are [26]:

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

$$L = \frac{c}{2f\sqrt{\mathcal{E}_{reff}}} - 2\Delta l \tag{2}$$

$$\mathcal{E}_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{w}\right]^{-\frac{1}{2}} \tag{3}$$

$$\frac{\Delta l}{h} = 0.412\frac{(\mathcal{E}_{reff}+0.3)(\frac{W}{h}+0.264)}{(\mathcal{E}_{reff}+0.258)(\frac{W}{h}+0.8)} \tag{4}$$

where, W is the width, L is the actual length, L_{eff} is the effective length, $\mathcal{E}_{reff}$ is the effective dielectric constant, and ΔL is the fringe length. The radius of a circular patch is determined using (5) and (6) [27]:

$$r = \frac{F}{\left[1+\frac{2h}{\pi F\varepsilon_r}\left(\ln\left\{\frac{\pi F}{2h}\right\}+1.7726\right)\right]^{0.5}} \tag{5}$$

where,

$$F = \frac{8.791\times10^9}{f_r\sqrt{\varepsilon_r}} \tag{6}$$

3. RESULTS AND DISCUSSION

In this study, was designed and simulated a circular microstrip patch antenna. This research seeks to minimize antenna size while maximizing performance. A systematic approach was adopted to achieve optimal results. Comprehensive performance evaluation encompassed key parameters including return loss, bandwidth, voltage standing wave ratio (VSWR), gain, directivity, and efficiency. The simulation was conducted with a fixed inset length, as the design is intended to operate at a resonant frequency of 900 MHz.

The simulations were performed using CST Studio Suite Learning Edition Software. The goal of this investigation was to evaluate the impact of varying the width of the partial ground plane on the antenna's performance. Specifically, the width of the partial ground plane was varied between 17 mm and 20 mm to determine the optimal width for the antenna. It was observed that the antenna's properties varied significantly with the change in ground plane width. After repeatedly adjusting the width of the partial ground plane, we were able to achieve the desired results.

3.1. Efficiency

Figure 2 highlights the antenna's excellent efficiency at 900 MHz, emphasizing its critical importance in wireless communication system design. Antenna efficiency, a key metric in antenna theory, measures the conversion of received power into radiated power. Efficiency is calculated as the gain-to-directivity ratio with a remarkable 98% efficiency, a gain of 2.161 dB, and a directivity of 2.200 dBi, the antenna demonstrates exceptional performance, making it well-suited for RFID applications.

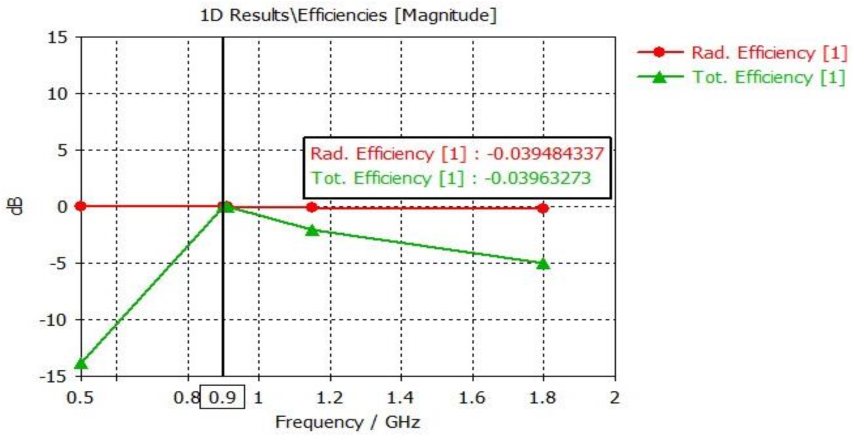

Figure 2. Radiation efficiency

3.2. The return loss, or S-parameter

The reflection coefficient, or return loss (S-parameter), quantifies the electromagnetic power reflected from a circular microstrip patch antenna. This metric is crucial for optimal impedance matching between the antenna and the connected system. Figure 3 illustrates the return loss (S11) of the proposed antenna. The antenna demonstrates an exceptionally low return loss of −49.8 dB at the resonant frequency of 900 MHz, indicating superior impedance matching. Generally, a return loss below -10 dB is considered satisfactory, but a value of -49.8 dB reflects outstanding performance. This enhanced impedance matching minimizes power losses, significantly improving the antenna's efficiency and overall performance, making it highly suitable for real-time data transmission and reception in RFID applications. The x-axis shows the frequency, while the y-axis represents the corresponding return loss.

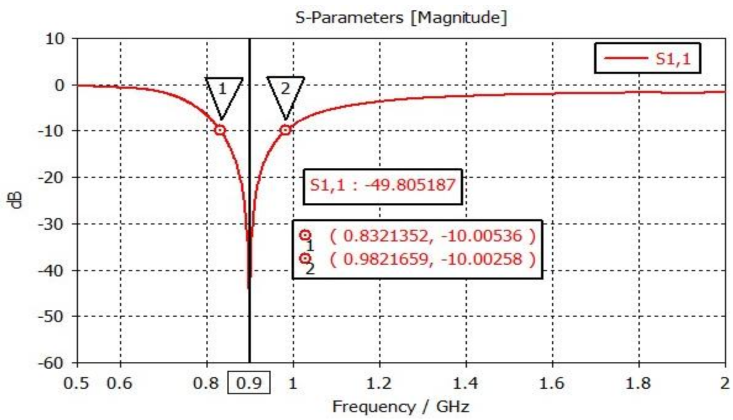

Figure 3. S-parameters of antenna patch in CST

3.3. Voltage standing wave ratio

Figure 4 illustrates the VSWR for the proposed antenna. The antenna achieves a VSWR of 1.009 at the resonant frequency of 900 MHz, indicating perfect impedance matching between the antenna and the transmission line. A VSWR value of 1 represents ideal matching, meaning that all power is efficiently transferred from the source to the load with minimal reflection. The value of 1.009, being extremely close to 1, confirms that the proposed antenna is well-matched at 900 MHz, ensuring efficient power transfer and minimal signal loss. Maintaining a VSWR close to 1 is crucial for optimal antenna performance, as higher values lead to poor matching, which can result in signal degradation and reflections. This near-perfect impedance matching not only enhances system efficiency but also preserves signal integrity, making the antenna highly suitable for its intended applications.

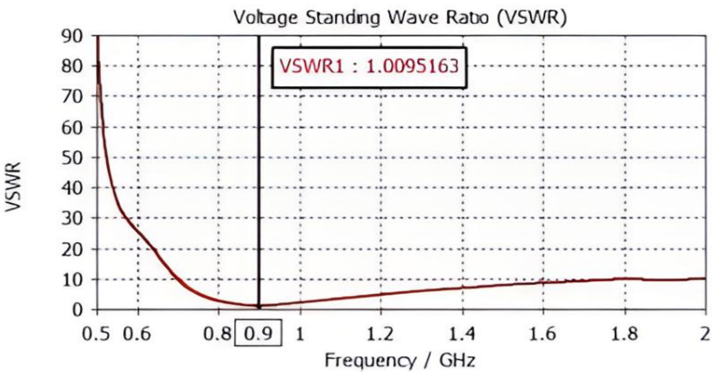

Figure 4. VSWR of antenna patch in CST

3.4. The gain

The radiation pattern is a pivotal factor in determining data transmission accuracy and ensuring wave propagation aligns with system requirements while preserving data integrity. It directly influences the directional behavior and effectiveness of the antenna. Similarly, gain is a critical performance indicator, representing the ratio of the antenna's radiated field strength to that of a reference antenna. This metric is essential for evaluating how well the antenna can focus energy in a given direction. As shown in Figure 5, the proposed antenna achieves an effective gain of 2.161 dB at 900 MHz, making it highly suitable for RFID applications where consistent performance and signal clarity are vital.

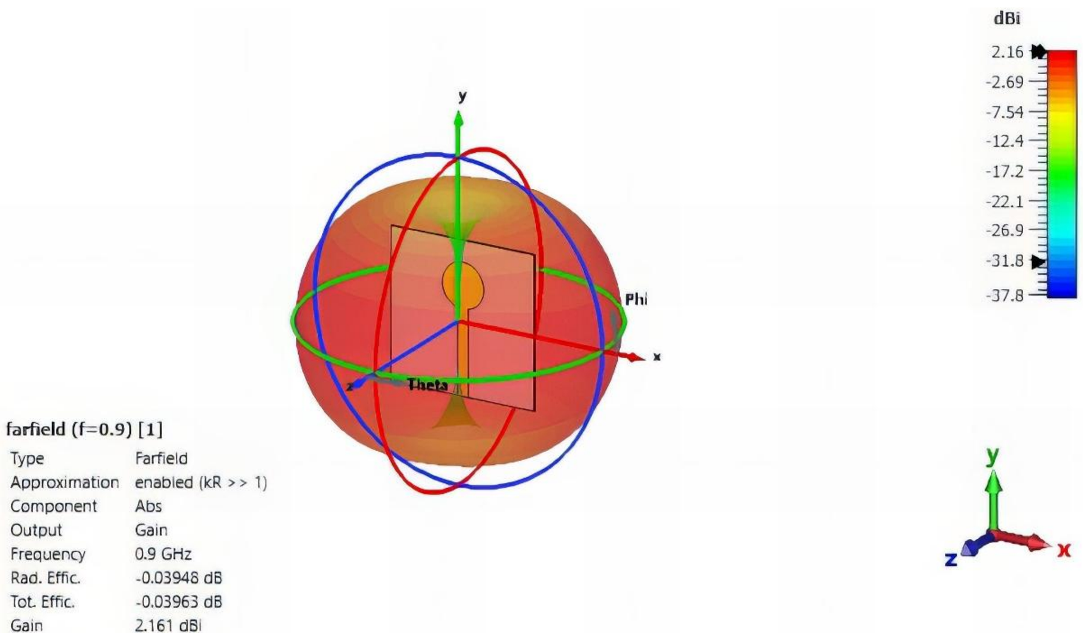

Figure 5. 3D Fairfield gain simulation in CST

3.5. The directivity

Directivity quantifies the ability of an antenna or optical system to concentrate its radiated energy in a specific direction, a key attribute for applications requiring targeted or directional transmission. This parameter is particularly important in systems where focused signal delivery improves efficiency and reduces interference. As illustrated in Figure 6, the proposed antenna demonstrates an impressive directivity of 2.200 dBi at the operating frequency of 900 MHz, ensuring optimal directional performance. Such a high directivity makes this antenna well-suited for RFID applications, where precise signal targeting is essential for enhancing communication reliability and range.

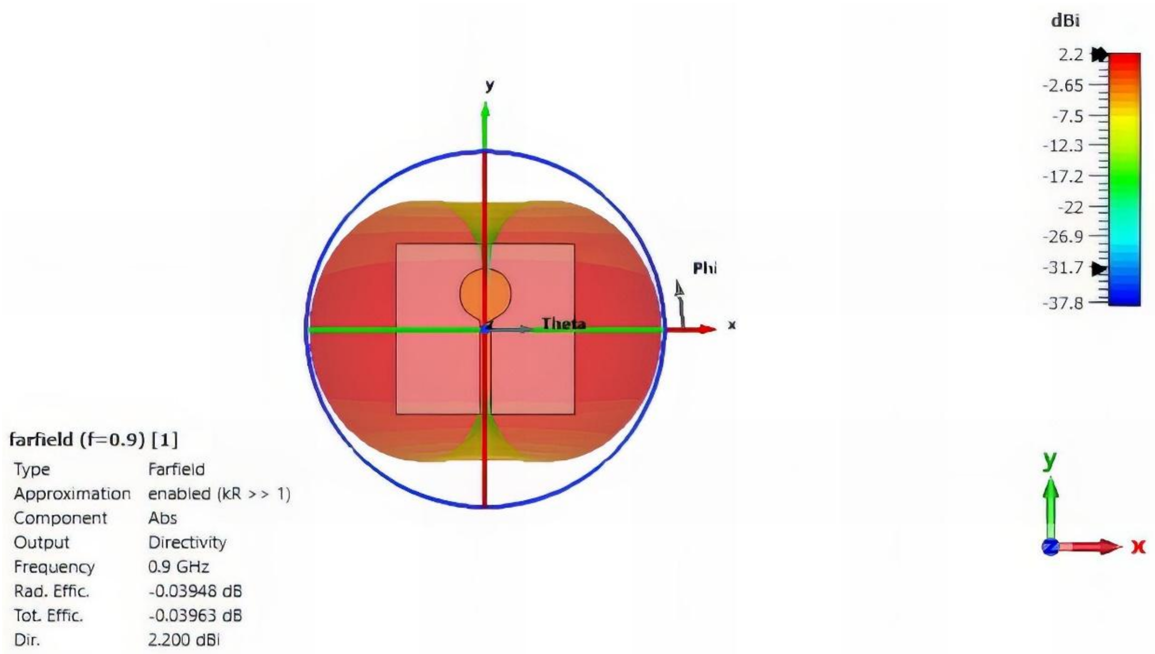

Figure 6. 3D Fairfield directivity simulation in CST

A detailed comparative analysis of the proposed antenna and similar types reported in the literature is presented in Table 2. As can be observed from the table, the RFID antenna proposed in this paper exhibits several advantages over its counterparts, including S-parameters (dB), VSWR, substrate material, efficiency (%), and applications.

Table 2. Comparison of proposed antenna design with similar designs

Ref	S-parameters (dB)	VSWR	Substrate material	Efficiency (%)	Applications
[28]	-39	-	FR-epoxy	93	RFID
[29]	-43	1.01	FR-epoxy	60	RFID
This work	-49.8	1.009	FR-4	98	RFID

4. CONCLUSION

In this study, we have developed and optimized a compact circular microstrip antenna tailored for RFID applications, operating within a broad frequency range from 0.5 to 2 GHz, with a specific focus on the resonant frequency of 900 MHz. Through the use of CST simulation, the antenna has demonstrated exceptional performance metrics, including high gain, minimal return loss, low reflection coefficient, and optimal VSWR. These characteristics are critical for ensuring reliable RFID functionality, where efficient data transmission and energy harvesting are essential. The high performance of the antenna, particularly its wide bandwidth of 150 MHz, reflection loss of -49.8 dB, gain of 2.161 dB, directivity of 2.200 dBi, and efficiency nearing 98%, indicates its suitability for integration into various RFID systems. These results suggest that the proposed design could significantly enhance the efficiency and accuracy of RFID tags, making it particularly useful in environments requiring high data throughput, these figures confirm the suitability of the circular antenna for RFID applications.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Mohamed Habibi	✓	✓		✓	✓				✓			✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The dataset on which the results of this study are based is publicly available in Table 1. The data includes the parameter values used to obtain the results from the CST. Researchers can access the dataset listed in Table 1 and use it for further studies.

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