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UHF RFID Antenna Design for Wireless Fault Monitoring System of Threaded Bolts

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***Abstract*—The usage of radio frequency identification technology has improved many aspects of daily life. This research paper introduces a breakthrough in radio frequency identification (RFID) technology, presenting a miniature RFID tag antenna designed for the Wireless Fault Monitoring System of Threaded Bolts. Utilizing a wet-inlay UHF RFID tag, the system accurately detects the status of threaded bolts, distinguishing between tightened and loosened states. The research aims to enhance the current status-detection mechanism, employing the AZ-9654 UHF RFID tag. To achieve a smaller yet more effective RFID tag antenna, we propose a miniaturized meandered UHF RFID tag. With an observed antenna gain of 1.194dBi at 910 MHz, the antenna volume is significantly reduced to 44mm×16mm×0.1mm. Simulation and measurement results obtained from CST Studio 2020 demonstrate the proposed antenna's superior performance in situations with limited space, outperforming the AZ-9654 UHF RFID. The study contrasts results, in terms of S-parameter, antenna impedance, VSWR, accepted power, and 2-D Polar plot, affirming the suggested antenna's suitability for mounting UHF RFID tags on threaded bolts.**

***Index Terms*—radio frequency identification (RFID), RFID tag antenna, ultra-high frequency (UHF), miniature antenna, meandering**

I. Introduction

Radio-frequency identification (RFID) stands at the forefront of technological innovation, utilizing radio frequency signals for the seamless and automated detection of objects at a distance. Even though the first publication on modulated back-scatter, the fundamental concept behind passive RFID was published in 1948, it took a long time before the technology reached its current state [1]. In recent times, RFID has garnered increased attention owing to its expansive read range and cost-effective production. The landscape of RFID is governed by multiple system standards, with ISO, Class 0, Class 1, and Gen 2 emerging as the principal benchmarks [1]. Globally, each region has its allocation of RFID frequency. For instance, the RFID UHF bands in Europe are 866-869 MHz, those in North and South America are 902-928 MHz, and those in Japan and certain other Asian nations are 950-956 MHz [4].

Essential components of an RFID system include RFID tags and readers. An antenna and an application-specific integrated circuit (ASIC) chip make a conventional RFID transponder, often known as an RFID tag. RFID tags are categorized as active or passive (powered by batteries or battery-less respectively) [3]. The power needed to energize the microchip in passive tags comes from the interrogation system itself using back-scatter modulation. When the microchip acts as a switch to match or mismatch its internal load to the antenna, a back-scattering modulation is produced showcasing the complexity and sophistication of RFID technology [1], [3].

The inherent challenge in RFID antenna design lies in the necessity for large antennas to meet high inductive requirements [2]. This challenge prompts the exploration of a novel direction – the development of a small RFID metal tag designed explicitly for threaded bolt fault monitoring systems and adaptable to mounting on metallic objects. The proposed solution involves the introduction of a non-connected conductive layer, allowing the antenna to expand and shift to a low-frequency region for its self-resonant frequency. This innovative approach results in a compact yet highly inductive tag antenna [2].

Direct attachment of the tag to the bolt through a specialized tag holder for the fault monitoring system becomes crucial, especially considering that threaded bolts are predominantly fastened to metallic surfaces. The incident electromagnetic (EM) wave, a central element in RFID functionality, interacts with the metallic surface, influencing the antenna's radiation pattern, input impedance, and resonant frequency. This interaction, marked by complete and phase-reversed reflection, necessitates a meticulous consideration of material, size, and distance in minimizing antenna effectiveness deterioration induced by surrounding metallic objects [2], [4], [8].

Section II of this research paper delves into the recommended primary application of the RFID tag and the specific requirements driving the design of the antenna. Following this, Section III elucidates the intricate configuration and design concepts of the antenna. Section IV meticulously outlines the tag-designing approach, providing a comprehensive understanding of the innovative processes involved. Subsequently, Section V presents the results of the simulated antenna design, offering valuable insights into the performance of the proposed solution. Finally, Section VI draws meaningful conclusions, encapsulating the significance and potential impact of this research on UHF RFID antenna design for wireless fault monitoring systems for threaded bolts.

II. APPLICATION OF THE RFID TAG AND THE REQUIREMENT FOR THE DESIGNED ANTENNA

The designed UHF RFID antenna plays a crucial role in a wireless fault monitoring system tailored for threaded bolts. The system addresses two distinct categories of bolt loosening, rotational and non-rotational loosening [6]. However, the focus is on rotational bolt loosening, and the primary objective is to employ an RFID tag to differentiate between tightened and loosened states of threaded bolts.

In pursuit of this goal, a fault-detecting device is crafted to facilitate the fault monitoring system. Metals such as copper and aluminum terminate radio frequency transmission [7]. In the event of the threaded bolt loosening, the RFID tag is shielded by an aluminum plate, resulting in a complete disconnection between the RFID reader and the tag. To address this, the fault-detecting device is designed to cover the RFID tag with an aluminum plate during loosening and expose it during tightening. This design ensures precise differentiation between the two states when analyzed by an RFID reader.

The fault-detecting device comprises four essential components, as depicted in Fig. 1. A base plate, a tag holder, a cover plate, and a metal plate. These components collaboratively enable the fault-detecting device to effectively respond to the threaded bolt's operational states.

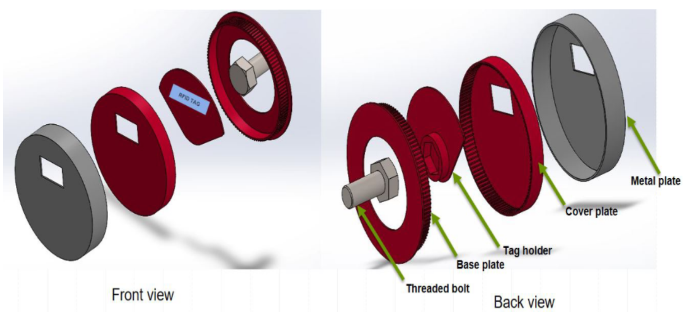


Fig. 1: Components of the fault detecting device for threaded bolts

The radio frequency communication within the fault-detecting device relies on the configuration depicted in Fig. 2. Specifically, the communication is established through a hole in an aluminum plate when the bolt is tightened. Conversely, it is terminated when the aluminum metal plate covers the hole during loosening. The tag holder, affixed to the bolt, hosts the RFID tag, and their alignment with the hole in the metal plate during initial fastening ensures accurate operation. As the bolt rotates, the tag follows suit, rotating away from the hole in a dynamic response to changes in the bolt's operational status. This orchestrated interplay of components and mechanisms forms the foundation of an efficient UHF RFID antenna design for wireless fault monitoring in threaded bolts.

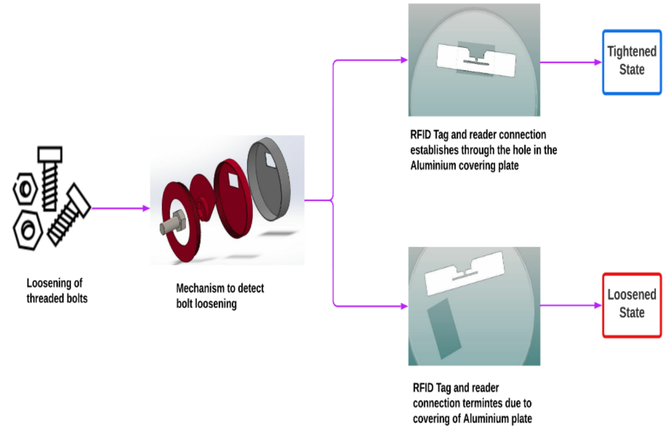


Fig. 2: An explanation of the fundamental function of the fault detecting device

III. THE PROPOSED ANTENNA CONFIGURATION AND DESIGN CONCEPTS

A. Antenna Configuration

The design of the ultra-high frequency (UHF) RFID tag antenna for a wireless fault monitoring system of threaded bolts involves meticulous considerations to optimize its functionality at long reading distances. The primary concerns encompass antenna gain, rectifier efficiency, and chip power consumption [5]. These factors, in conjunction with the microchip's power sensitivity, significantly influence the tag's overall size, read range, and compatibility with tagged items.

a) Key Design Objectives:

- Antenna Volume, Bandwidth, and Gain Enhancement
  The design objective is to minimize the antenna volume while simultaneously expanding its bandwidth and improving gain. This approach aligns with the established budgets for system reliability and resilience.
- Read Range
  The read range, representing the maximum distance at which an RFID reader can detect the tag's back-scattered signal, is a critical performance parameter [3]. The design aims to optimize this parameter for effective fault monitoring.

b) Considerations in Determining RFID Tag Antenna Characteristics [1]:

- Band of Frequencies
  Regulations in the regions where the tag will be deployed dictate the preferred frequency band of operation.
- Size and Shape
  The tag's shape and size must accommodate its placement inside printed labels or its implantation in or affixation to various objects.
- EIRP (Equivalent Isotopically Radiated Power)
  Country-specific laws guide the determination of EIRP, restricting the radiation power from transmitting and receiving antennas.

- Objects
  The performance of the tag varies based on the surface it is applied, requiring adjustments to enhance sensitivity or optimize performance for specific objects.
- Orientation
  The direction of the antenna significantly impacts the read range, necessitating specific directivity patterns for various applications.
- Applications
  Consideration is given to the mobility of the application, determining the required read rate capability and the time the tag spends in the RFID reader's field.
- Cost
  Cost-effectiveness is crucial, imposing limitations on antenna structure and materials. Common conductors include Copper, Aluminum, and silver ink, with dielectric substrates like flexible polyester and rigid PCB substrates (e.g., FR4).
- Dependability
  The RFID tag must withstand environmental changes caused by stress, humidity, and temperature variations, as well as the processes of label insertion, printing, and laminating operations.
- Polarization
  Polarization choice depends on tag orientation—linear for known orientation and circular for unknown orientation. The meandering dipole antenna is chosen for its size, tunability, and ability to operate unidirectionally, perpendicular to the meander's axis, addressing specific application requirements [4].

The proposed antenna configuration and design concepts prioritize efficiency, reliability, and adaptability to diverse operating conditions, ensuring the effectiveness of the UHF RFID tag in the wireless fault monitoring system for threaded bolts.

B. Design Specifications

The UHF antenna designed for a wireless fault monitoring system for threaded bolts is tailored to the specifications of a specific IC, namely the U7/U9 chip, currently available in the market. The design addresses the challenges associated with the significant cost and complexity of new IC design and manufacture [1]. To mitigate cost and fabrication challenges, external matching networks with lumped parts are often impractical for RFID tags. Therefore, the UHF RFID tag antenna is directly matched to ASICs, which have intricate impedances varying with frequency and input power, circumventing these challenges [1].

The design procedure involves a meticulous process of modeling, simulating, and optimizing the tag antenna on a computer. This is crucial for tracking key parameters such as tag read range, antenna gain, and impedance. The prototype antenna is designed and simulated using the full-wave simulator CST Studio 2020, ensuring the verification of the design process [1], [2], [7].

Throughout the design process, various constraints and considerations shape the antenna design, ensuring its effectiveness in the wireless fault monitoring system [1], [2], [7].

a) Key Specifications:

- Wavelength Calculation
  The wavelength (w) is calculated using the formula
  $$w = cf \tag{1}$$
  where c is the free space velocity of electromagnetic signals and f is the operating frequency.
- Impedance Adjustment
  Impedance (z) is calculated using the equation
  $$z = vI \tag{2}$$
  To meet specifications (return loss at -10dB and VSWR value under 2), the impedance is adjusted to 50 Ω.
- Efficiency Target
  $$\eta = \frac{P_{radiated}}{P_{input}} \tag{3}$$
  .
  The targeted efficiency is approximately 50$\%$.
- Intended Directivity
  The intended directivity is set at 40 dBi.
- Antenna Gain Calculation
  Antenna gain is calculated using
  $$Gain = \eta D \tag{4}$$
  , where η is efficiency, and D is directivity.
- Bandwidth
  The bandwidth is established by the operational frequency band of the radio frequency signal, aligned with specific application requirements and frequency ranges provided by the country.
- Polarization
  Depending on the orientation of the tag (known or unknown), linear or circular polarization is employed. Linear polarization suits line-of-sight applications, while circular polarization is utilized in direction-free operational scenarios.

The design specifications ensure that the UHF antenna aligns with the specific requirements of the wireless fault monitoring system for threaded bolts, optimizing its performance and compatibility with the designated IC.

IV. METHODOLOGY

The methodology employed for UHF Antenna Design for a wireless fault monitoring system for threaded bolts involves innovative approaches to enhance read range and performance. The introduction of the concept of miniaturized meandered UHF RFID tags represents a significant advancement in UHF RFID antenna design [11]. The methodology focuses on designing high-intensity, low-dimension RFID tags that surpass the read range of conventional methods, such as Dog-bone RFID tags. The key sections of the miniaturized meandered UHF RFID tag are illustrated in Fig. 3.

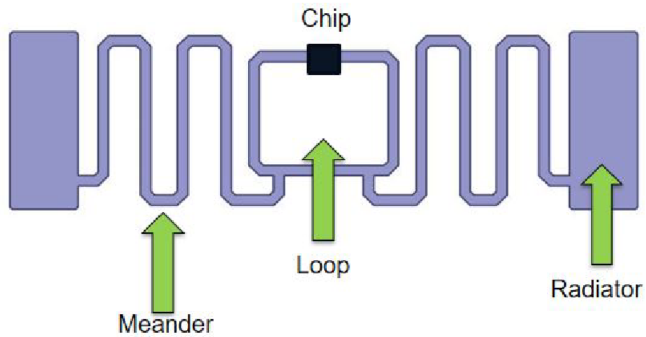


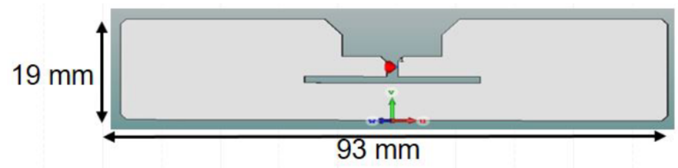
Fig. 3: Sections of a miniaturized meandered UHF RFID

In the design process, several specifications are tuned optimally to achieve the desired performance.

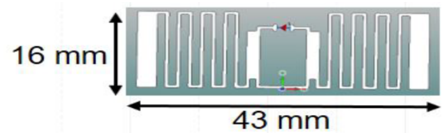
- Size of the Loop
  The size of the loop directly influences the s-parameter (Scattering Parameters), the parameters used to characterize the behavior of the antenna in terms of how it scatters electromagnetic waves at different frequencies, affecting reflected power within the optimal bandwidth. Incrementing the loop size adheres to the required RFID tag dimension limitations, determining the optimal number of meanders based on loop and radiator size.
- Radiator Size
  Adjusting the impedance of the antenna is achieved through the radiator size. Impedance matching with the integrated IC is crucial for proper transmission, and the radiator size is meticulously designed within dimension limitations.
- Number of Meanders
  The impedance of the antenna is adjusted by varying the number of meanders. The S-parameter increases with more meanders but is limited by loop and radiator size. The design goal is to create a tag smaller than the AZ-9654 UHF RFID tag. After numerous iterations, the final design features an antenna with 3 meanders, a radiator size of 7mm×13mm, and a radiator size of 16mm×3mm. Fig. 4a illustrates the suggested RFID metal tag antenna design, with performance measures compared to the AZ-9654 UHF tag shown in Fig. 4b.
  The methodology intricately addresses size, impedance, and meander considerations, resulting in an optimized UHF RFID antenna design for wireless fault monitoring in threaded bolts.

V. RESULTS

Using CST Studio 2020 software, the proposed antenna was meticulously modeled and simulated. A comparative analysis was conducted with the presently employed AZ-9654 UHF tag, simulated with its original dimensions, to assess the performance of the proposed RFID tag. The results were obtained through simulation and encompassed various parameters critical for evaluating antenna efficiency and performance.



(a) Dimensions of AZ-9654 UHF tag



(b) Dimensions of the existing tag and the proposed tag

Fig. 4: 4a depicts the suggested RFID metal tag antenna design. The performance measures of the proposed antenna are compared with the AZ-9654 UHF tag shown in Fig. 4b

A. S-parameter

The S-parameter, or Power Reflection Coefficient (PRC), was employed to calculate the RFID tag antenna's bandwidth in decibels. Fig. 5 illustrates the S-parameter values for both antennas. The current AZ-9654 UHF tag exhibits an optimal bandwidth of 1250-1350MHz, with reflected power ranging from -2.75dB to -3.0dB (Fig. 5a). In contrast, the proposed tag achieves an optimal bandwidth of 970-980MHz with a reflection power surpassing -14dB. This indicates that the proposed tag's optimal bandwidth is not only closer to the RFID reader's operating frequency range (900-930MHz) but also possesses higher reflection power than the current tag.

B. Antenna Impedance

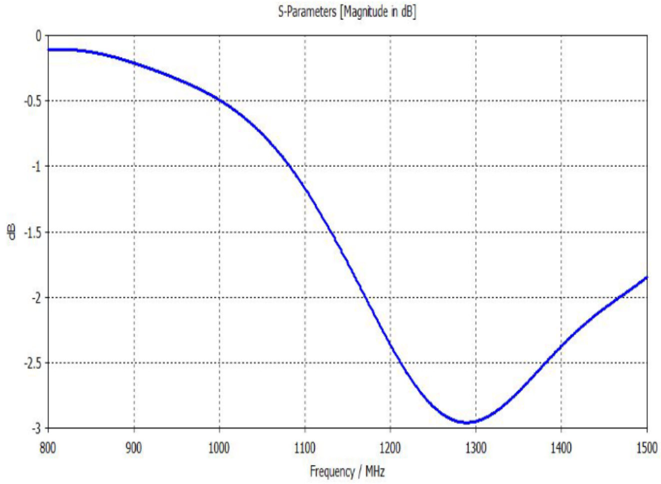
The real component of antenna impedance, representing power radiated or absorbed, was analyzed. Fig. 6 illustrates that both resistance and reactance in the proposed tag are greater than those in the AZ-9654 UHF tag. This suggests that the proposed tag exhibits enhanced near-field characteristics and power reflection, contributing to a better-read range compared to the AZ-9654 UHF tag.

C. VSWR (Voltage Standing Wave Ratio)

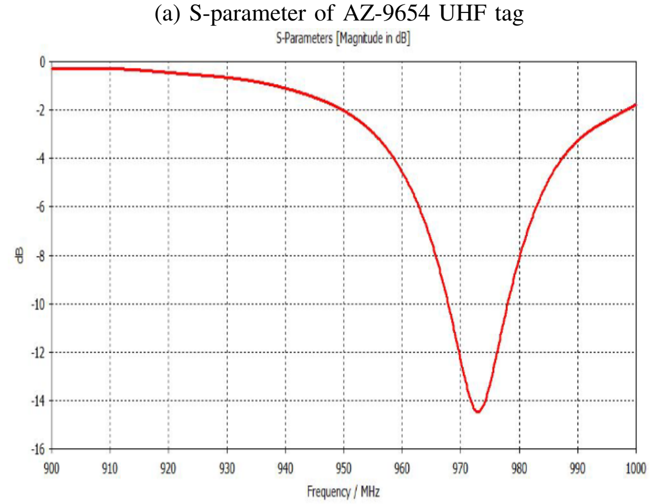
The Voltage Standing Wave Ratio (VSWR) was assessed to evaluate RF power transmission efficiency between the RFID reader and tag. A lower VSWR indicates higher transmission efficiency. In the same operating frequency range (910-930MHz) as the UHF RFID reader, the VSWR range for the AZ-9654 UHF tag is 70-90, while for the proposed tag, it is 28-60. This implies that the transmission efficiency of the proposed tag is superior to that of the AZ-9654 UHF tag.

D. Accepted Power

Antenna efficiency, expressed as the ratio of radiated power to input power, was evaluated through accepted power. Fig. 8 shows that the accepted power for both tags is approximately the same in the 910-930 MHz range, with neither reaching the optimum power level within the RFID reader's operating frequency range.

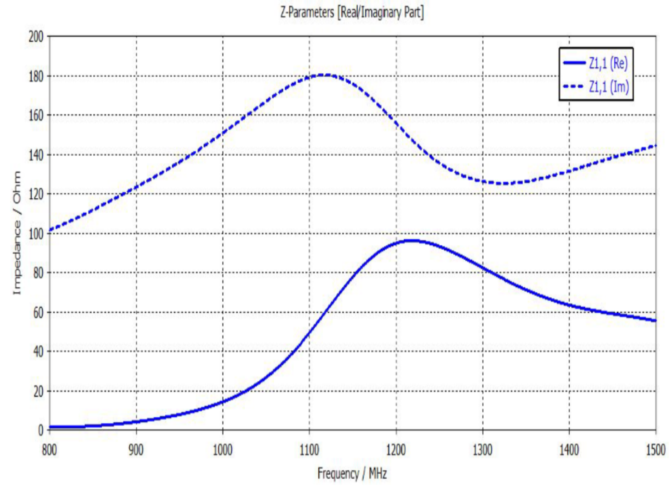


(a) S-parameter of AZ-9654 UHF tag

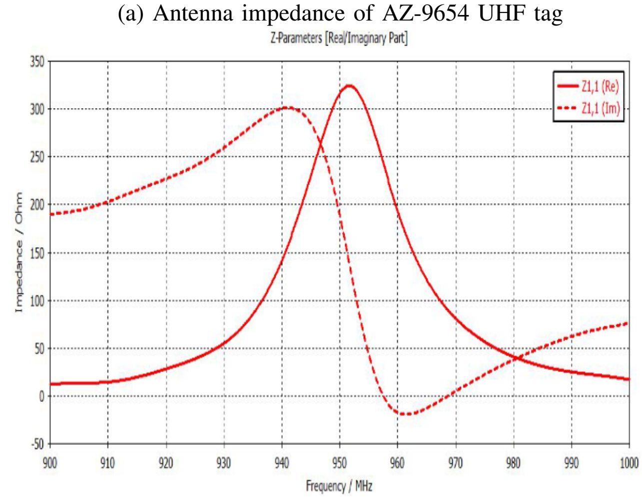


(b) S-parameter of proposed tag

Fig. 5: S-parameter comparison with the existing tag and the proposed tag



(a) Antenna impedance of AZ-9654 UHF tag



(b) Antenna impedance of proposed tag

Fig. 6: Antenna impedance comparison with the existing tag and the proposed tag

E. 2-D Polar Plot

The 2-D polar plot (Fig. 9) illustrates that the AZ-9654 UHF tag possesses a 180° lobe width with a main lobe magnitude of -106dBi. In comparison, the proposed tag has a 178° width with a main lobe magnitude of -109dBi (Fig. 9b). Despite the similarity in values, the proposed antenna outperforms the AZ-9654 UHF tag due to its smaller size, being only half as large.

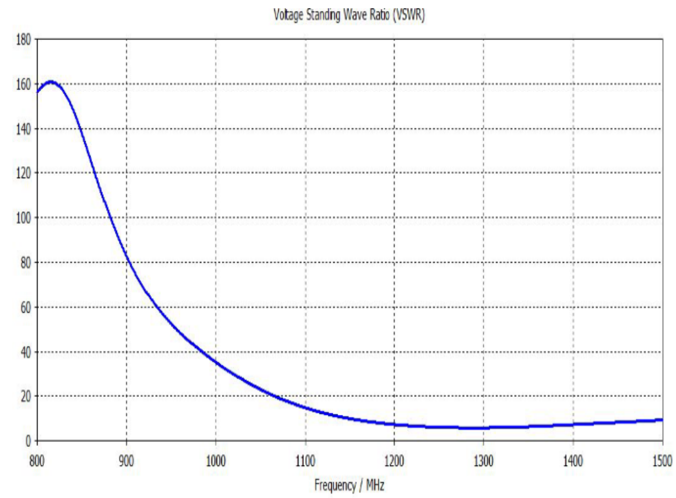
The simulation results demonstrate that the proposed UHF RFID tag exhibits superior performance in terms of optimal bandwidth, impedance, VSWR, accepted power, and 2-D polar plot when compared to the currently used AZ-9654 UHF tag.

VI. CONCLUSION

In this research, we have successfully demonstrated a groundbreaking advancement in the field of wireless fault monitoring systems for threaded bolts—an innovative miniature RFID tag antenna designed specifically for this application. This antenna is intended to be mounted on threaded bolts, offering a compact and efficient solution for fault detection in various industrial settings.

Compared to the currently employed tag antenna for this application, our developed RFID tag antenna stands out for its remarkable reduction in size. The primary design objectives for the ultra-high frequency (UHF) RFID tag antenna included volume reduction, bandwidth expansion, and increased gain. Considerable financial resources were allocated to ensure the reliability and durability of the system, addressing critical concerns in fault monitoring.

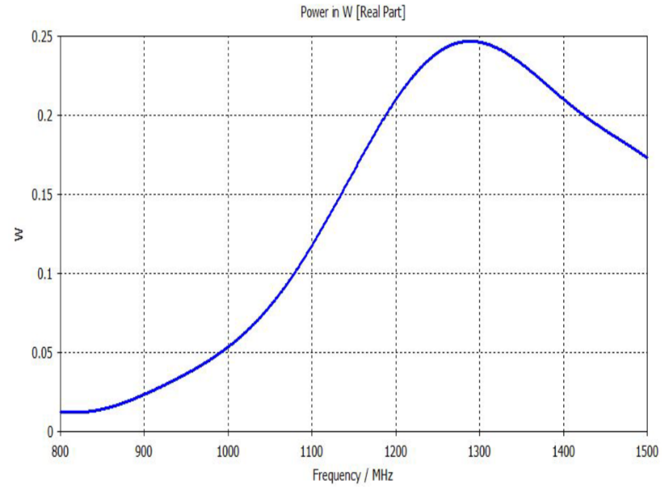
Throughout the research, we delved into the intricate specifications of RFID tag antenna designs tailored for fault monitoring systems, outlining a comprehensive design approach that considered methodologies, antenna configuration, and real-world application-centered design concepts. The culmination of our efforts resulted in a miniature antenna design, supported by detailed modeling and simulation results, which were



(a) VSWR of AZ-9654 UHF tag

(b) VSWR of proposed tag

Fig. 7: VSWR comparison with the existing tag and the proposed tag



(a) Accepted power by AZ-9654 UHF tag

(b) Accepted power by proposed tag

Fig. 8: Accepted power comparison with the existing tag and the proposed tag

rigorously compared with the AZ-9464 RFID tag currently in use for this application.

The introduction of a conductive layer to the antenna structure proved to be a pivotal design choice. This addition raised the capacitive reactance, consequently lowering the antenna's self-resonant frequency and facilitating the achievement of high reactance impedance with a small-size RFID tag antenna. The simulation results unequivocally demonstrated that the proposed RFID tag outperforms the existing tag, particularly in terms of higher reflected power within the RFID reader's operating frequency range of 910-930MHz. Additionally, the proposed RFID tag exhibited comparatively lower Voltage Standing Wave Ratio (VSWR) and higher accepted power, crucial factors for maintaining an extended read range.

Moreover, the proposed tag's adaptability to mass production and its potential application in wireless fault monitoring systems position it as a promising solution to enhance read range while simultaneously reducing the size of fault detection devices. In practical applications where the tag is affixed to metal structures, the incident electromagnetic (EM) wave interactions with metallic surfaces were discussed, emphasizing the impact on radiation patterns, input impedance, and resonant frequency. Insights from studies on meander-line antennas further underscored the significant size reduction potential for antennas in such scenarios.

This research contributes not only to the advancement of RFID technology but also to the efficiency and effectiveness of fault monitoring systems, particularly in industrial settings where threaded bolts play a critical role.

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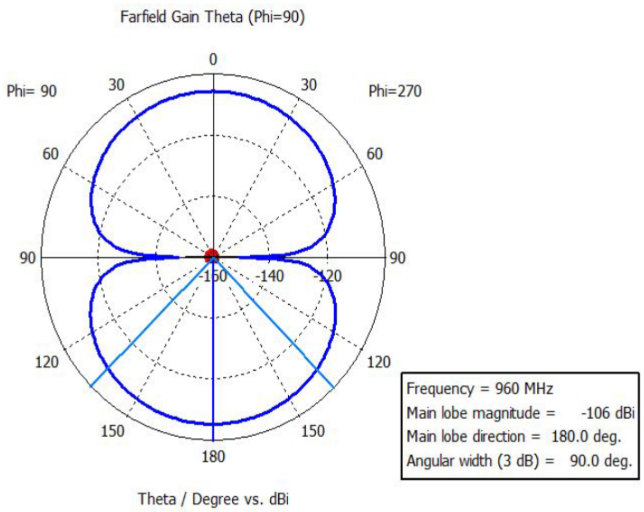
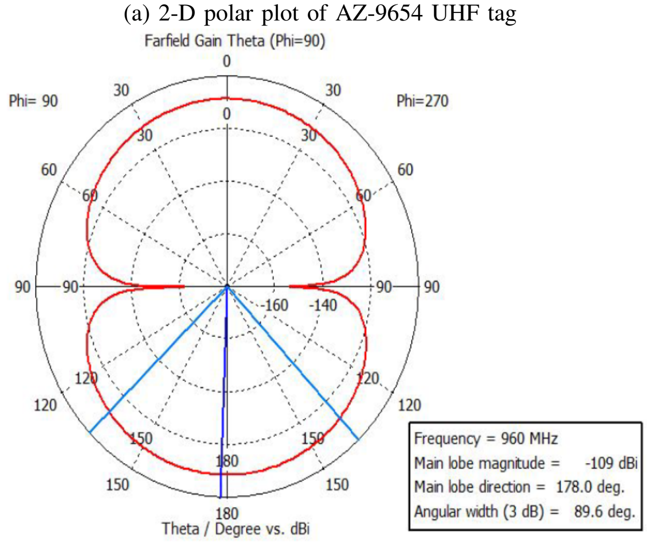


(a) 2-D polar plot of AZ-9654 UHF tag



(b) 2-D polar plot of proposed tag

Fig. 9: 2-D polar plot comparison with the existing tag and the proposed tag

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