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Design and Fabrication of Long-range UHF RFID Reader Antenna with Protection Cover

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ABSTRACT

This research introduces a circularly polarized, long-range UHF RFID reader antenna featuring a protective cover. The antenna's truncated patch structure, designed using an air-substrate patch antenna, ensures circular polarization. Experimental results demonstrate that the antenna achieves 840–890 MHz of impedance bandwidth with a Voltage Standing Wave Ratio (VSWR) of less than two. Additionally, the Axial Ratio (AR) remains below 3dB within the 860-870 MHz bandwidth. The simulation results reveal that the antenna achieves an Axial Ratio (AR) bandwidth ranging from 860 to 870 MHz at 3 dB, along with an impedance bandwidth spanning from 830 to 900 MHz. Notably, the antenna consistently maintains an average gain of 9.2 dBi throughout the entire 3-dB AR bandwidth. Measuring 260×260×20 mm, the antenna is both compact and lightweight. CST Microwave Studio is employed to analyze the aluminum sheet metal antenna design, operating at 865-868 MHz. Inexpensive, lightweight, and simple to construct, the antenna's cover is fabricated via 3D printing, offering protection from environmental factors such as moisture and dust. The antenna's performance is evaluated using various materials for the cover, with PETG material being selected for optimal frequency tuning. The experimental and simulated results show a significant correlation, which makes the suggested antenna a perfect option for long-range UHF RFID applications.

Keywords: UHF RFID, Truncated patch, Circularly-polarized, ThingMagic M6e, Polyethylene Terephthalate Glycol.

1. INTRODUCTION

The ability of RFID technology to quickly and accurately identify objects without requiring physical contact has made it more and more popular in recent years. Diverse industries, such as healthcare, retail, logistics, and manufacturing, have embraced this technology, integrating it into their operations [1-4].

Ultra-High Frequency Radio Frequency Identification technology operates at frequencies typically ranging from 860 MHz to 960 MHz and has a typical read range of several meters. A radio signal is sent by the reader to an RFID tag when it is in range. This allows the tag to be powered and broadcast its unique identification back to the reader. For a dependable link between the tag and the reader, a circularly polarized antenna is needed because the placement of the linearly polarized tag is random.

Designing high-performance RFID reader antennas that can operate over a wide frequency range, maintain high gain and high efficiency, and accommodate various manufacturing processes is crucial for the success of RFID systems.

To address the challenges in RFID antenna design, researchers have developed innovative techniques to overcome the limitations of conventional antenna designs. These techniques include:

- Wide-band antenna design using parasitic patches [5-10].
- Compact antenna design using a minimized overall antenna size and advanced structures [11-19]. However, as the antenna size decreases, the gain tends to decrease.
- Low-cost antenna design using printed antennas on low-cost substrates [20-24].
- High-gain antenna design by using array techniques [25-27].
- Stability of the antenna and immunity from external mechanical movements and environmental parameters by using protection shields, which are used in many existing commercial antennas [28-30].

A circularly polarized reader antenna design is presented in this study. that is suitable for outdoor environments and includes a 3D-printed protective cover. The antenna is designed to work outdoors for long-range detection that is compatible with the two port +30 dBm reader (ThingMagic M6e Micro) [31]. Circularly polarized features are obtained by using an air-substrate trimmed patch antenna. [32-35]. Using a 3D printed cover as a prototype has several advantages over traditional manufacturing processes, including cost savings, faster production time, and more design flexibility. The structure is simple, compact, and high gain. It is fabricated using a laser cutting technique [36].

This is how the other part of the paper is structured: In section 2, a detailed design of antenna configuration is presented. Section 3 presents the simulation and measured results of the antenna without a protection cover. In section 4, a protection cover for the antenna is added. Section 5 draws the conclusion.

2. DESIGN AND CONFIGURATION OF ANTENNA

Utilizing a rectangular patch antenna is the foundation of the suggested antenna's concept. The antenna consists of the radiator and the reflector elements that are fabricated from an aluminum sheet with a thickness of 1 mm and 2 mm respectively. The reflector acts as a ground plane and the back side of the case of the antenna. The initial design commences with calculating the patch width which ensures efficient radiation [37]. This calculation uses the formula:

$$W = \frac{c}{2F_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \qquad (1)$$

where c represents the speed of light in free space, Fr signifies the desired resonant frequency, and εr denotes the dielectric constant of the substrate. Considering that air is the material between the conducting patch and ground in this case, εr is unity, resulting in an effective dielectric constant, εreff, of unity as well. Upon obtaining W, the actual patch length can be calculated using the following formula:

$$L = \frac{c}{2F_r\sqrt{\varepsilon_{reff}}} - 2\Delta L \qquad (2)$$

where

$$\Delta L = 0.412\text{h}\,\frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{L}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{L}+0.8\right)} \qquad (3)$$

where h is the substrate thickness.

Figure 1 shows the geometry and dimensions of the proposed antenna. H1 is the radiator thickness, H2 is the air-substrate thickness and H3 is the reflector thickness. Three Teflon spacers are used to fix the radiator element. The feeding structure used is a single-probe feeding arrangement. The location of the feed point has a big impact on the axial ratio (AR). [38]. A connector of a 50 ohms N type feeds the antenna. The extension of the coaxial connector's core is connected to the radiating element, while the connector's Teflon and inner core are extended and joined to the rear side of the radiator element. During this process, it is crucial to prevent any short circuits from occurring between the inner core and the ground. The N-type connector's base is then soldered to the reflector element. The overall dimensions of the proposed antenna are (260 × 260 × 20) mm. Table 1 summarizes all the parameters that were optimized through simulation and tuning to the optimum dimensions in millimeters.

Figure 2 illustrates the suggested antenna design's prototype. High mechanical strength and great efficiency are achieved by the proposed antenna because of its all-metal construction. The antenna is simple and inexpensive to manufacture because all the pieces are readily available and only require a simple cutting technique (laser cutting - metal stamping). With the aid of computer simulation technology (CST), the suggested antenna was modeled and simulated.

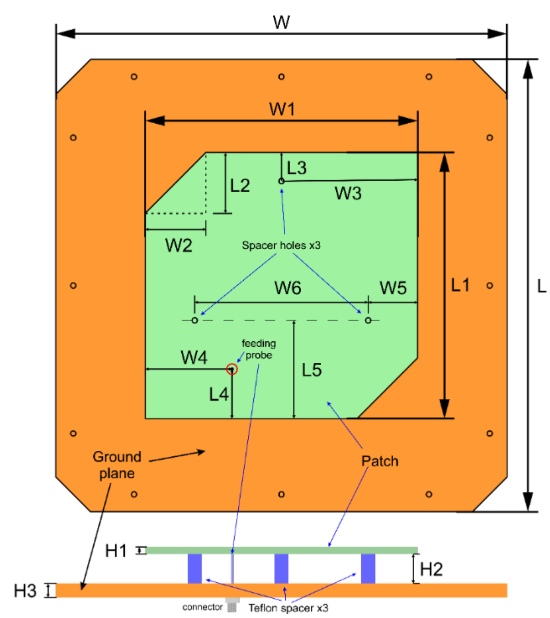

Figure 1: Antenna's dimensions and geometry

Table 1. Antenna dimensions without cover

symbols	Dimensions (mm)	symbols	Dimensions (mm)
W	260	L1	153
W1	157	L2	35
W2	35	L3	56
W3	79	L4	28
W4	50	L5	56
W5	28	H1	1
W6	100	H2	17
L	260	H3	2

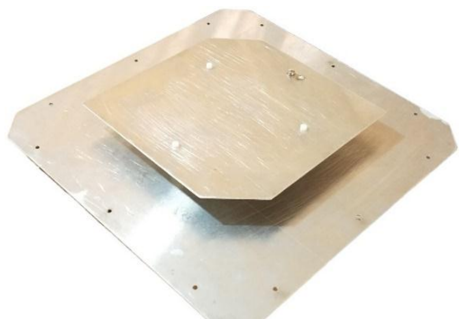

Figure 2:Photo of the fabricated RFID reader antenna

3. ANTENNA WITHOUT PROTECTION COVER - SIMULATION & MEASURED RESULTS

To assess the antenna's return loss performance, a Rhode & Schwarz ZVL-network analyzer (VNA) was employed, as depicted in Fig. 3. The comparison of measured and simulated return loss figures, illustrated in Fig. 4, demonstrates a strong correlation between measurements and simulation. Upon excitation at 860 MHz, the proposed antenna demonstrates a 10-dB impedance bandwidth spanning 50 MHz, ranging from 840 MHz to 890 MHz. Both simulation and testing reveal a peak return loss of 45 dB at the resonant frequency of 860 MHz.

The Voltage Standing Wave Ratio (VSWR), a crucial parameter in RF transmission systems, represents the ratio of maximum to minimum power in a wave. High VSWR can significantly diminish power delivery to an antenna or system. As a real and positive number, VSWR has a minimum value of 1, with values below 1.5 considered optimal. Fig. 5 illustrates the simulated VSWR, revealing a bandwidth of 850-880 MHz with a VSWR under 1.5.

A further important metric for evaluating the effectiveness of circularly polarized antennas is the axial ratio (AR). An important step in evaluating the system requirements' suitability for circular polarization is figuring out the axial ratio. The axial ratio is a key parameter in antenna design, particularly in applications requiring circularly polarized electromagnetic waves. It is defined as the ratio of the major to the minor axes of the polarization ellipse and is a measure of the ellipticity of the polarized wave. A low axial ratio indicates that the antenna's radiation pattern is more circularly polarized, which is beneficial for minimizing signal distortion and maximizing signal reception in communication systems. High axial ratios can result in signal degradation and reduced performance while low axial ratios are an indication for optimal circular polarization performance. Precise measurement and control of the axial ratio are essential for ensuring an efficient and reliable antenna. Figure 6 illustrates the attainment of good circular polarization properties in the 860-870 MHz region, with an AR bandwidth of less than 3 dB.

Antenna efficiency plays a fundamental role in the performance of electromagnetic communication systems by directly impacting the amount of power effectively radiated into the surrounding environment.

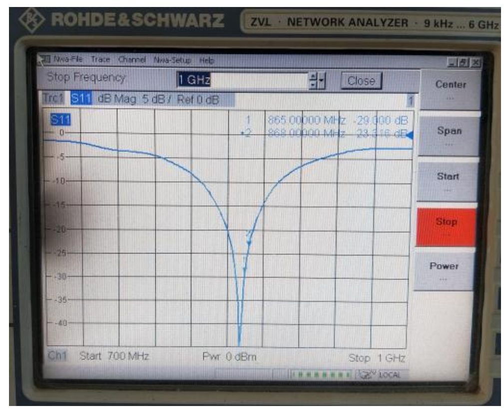

Figure 3: S-parameter measurement of the circularly polarized antenna using VNA

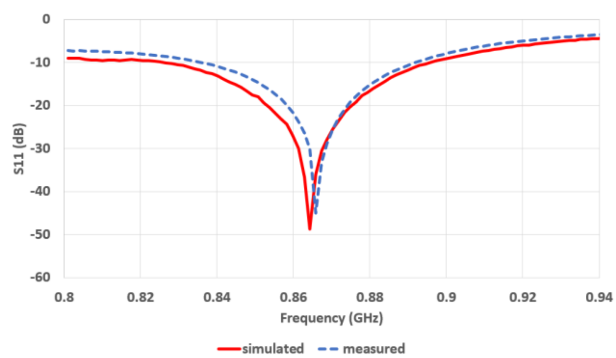

Figure 4: Simulated and measured return losses

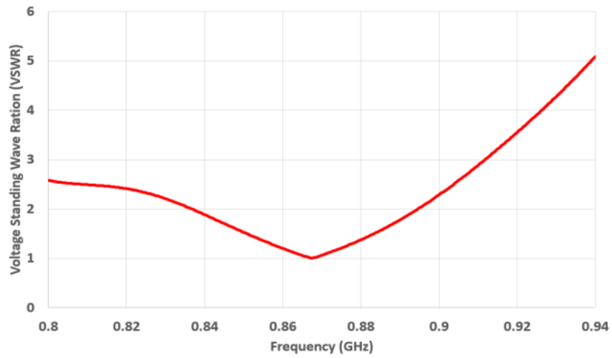

Figure 5: Simulated Voltage Standing Wave Ratio (VSWR)

It is defined as the ratio of the power radiated by an antenna to the total input power supplied to it. In a perfect scenario, where all power supplied to the antenna is radiated without losses, the efficiency would be 100%. However, in real-world applications, various factors contribute to energy losses, such as conduction losses, radiation losses, and dielectric losses. Maximizing antenna efficiency is crucial for maximizing the range and reliability of communication systems while minimizing power consumption. Figure 7 demonstrates the simulated antenna efficiency. The proposed antenna achieves 98% efficiency.

When compared to an isotropic source, antenna gain indicates the power delivered in the direction of maximum radiation, considering both directivity and effective performance. As shown in Fig. 8, the proposed antenna exhibits a gain exceeding 9 dBi.

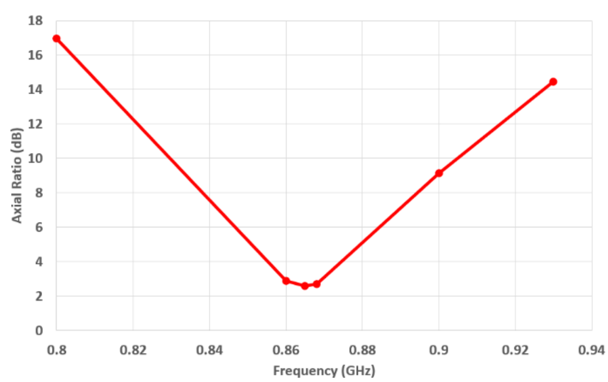

Figure 6: Simulated Axial Ratio (AR)

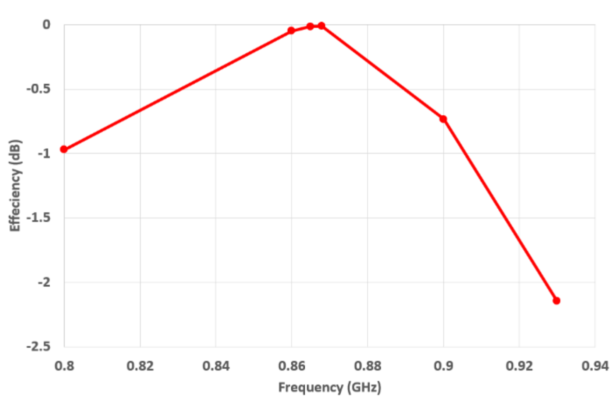

Figure 7: Simulated antenna efficiency.

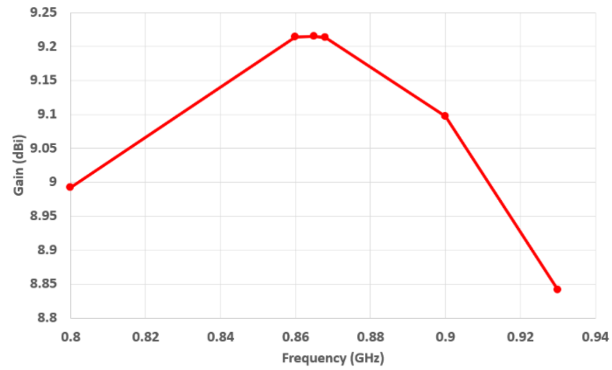

Figure 8: Simulated maximum antenna gain

Figures 9 and 10 show the 3D and 2D simulated radiation patterns, respectively, at 865 MHz. Figures demonstrate that the 3D radiation pattern has a symmetrical shape and that the directivity calculated using CST is approximately 9 dBi.

The surface current distribution analysis of the proposed antenna, presented in Fig. 11 at 0°, 90°, 180°, and 270°, reveals that it exhibits left-hand circular polarization at 865 MHz.

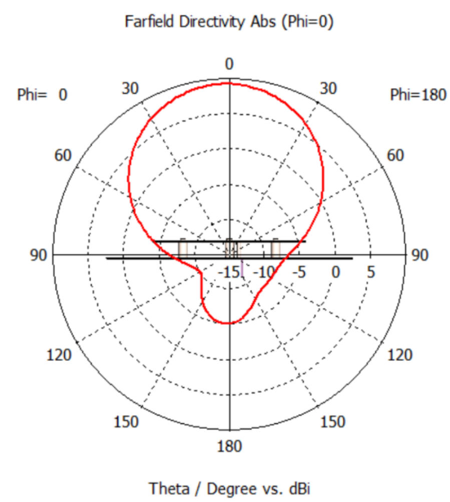

Figure 9:Simulated 2D radiation pattern at 865 MHz

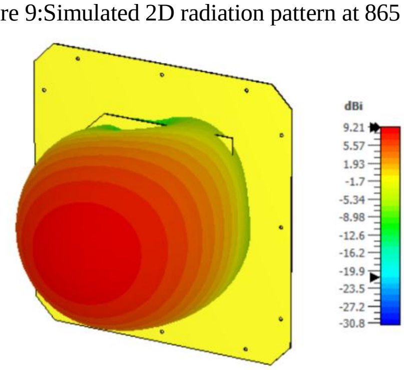

Figure 10:Simulated 3D radiation pattern at 865 MHz.

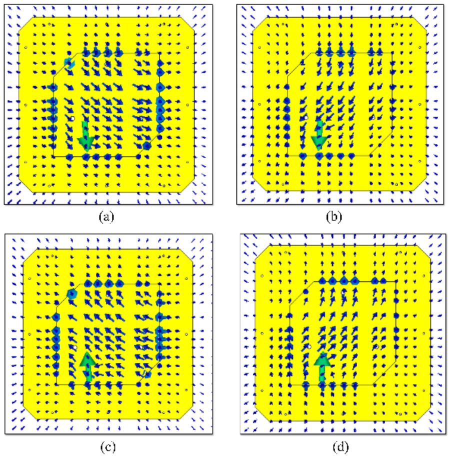

Figure 11: Surface current distribution at 865 MHz with four phase angles (a) 0°, (b) 90°, (c) 180°, and (d) 270°.

4. ANTENNA WITH PROTECTION COVER - SIMULATION & MEASURED RESULTS

In the case of outdoor usage, it is important to consider the environmental factors. So, a cover was designed and fabricated to protect the antenna from UV radiation, heat, and weather. With 3D printing technology, designs become easier and more accessible than ever before. A large variety of materials are available for use with the 3D printing technology. The most common materials used for 3D printing filaments are thermoplastics such as PLA, ABS, PETG, Nylon, and TPU. Selecting the appropriate filament material is contingent upon the specific characteristics desired in the final product, which may include factors such as tensile strength, pliability, longevity, and thermal stability.

The 3D model and the dimensions of the protection cover are shown in Fig. 12. The 3D model of the cover and the antenna are attached to simulate them together with different cover materials (PETG – ABS – PLA) as shown in Fig. 13. There is a frequency shift occurred due to the effects of the protection cover. A PETG material was selected to fabricate the cover which is a popular choice for 3D printing outdoor devices because of its great strength and ability to withstand weather conditions like UV radiation, heat, and weather [39, 40]. Figure 14 shows a Photo of the fabricated antenna with a PETG cover. The AR was affected badly as shown in Fig. 15. So, we will tune the parameters to obtain the desired return loss and the best axial ratio.

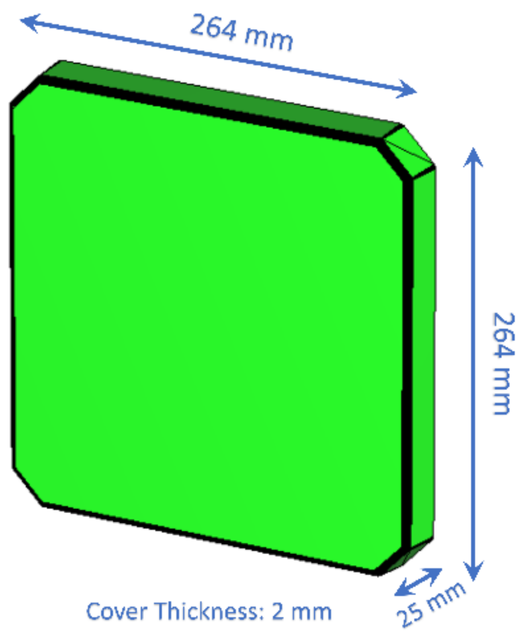

Figure 12: Dimensions of the 3D cover model.

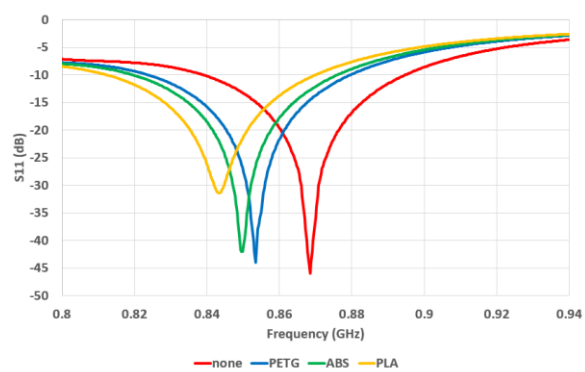

Figure 13: Simulated reflection coefficient of the antenna w/o protection cover using different materials.

Figure 14:Photo of the fabricated antenna with a PETG cover.

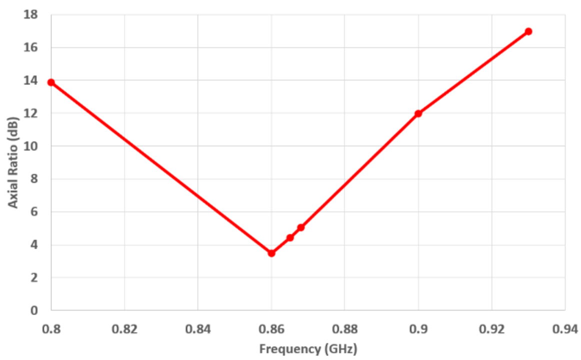

Figure 15: The effect of the PETG cover on the Axial ratio result.

Table 2 shows the newly tuned parameters. Fig. 16 shows a comparison of the antenna's measured and simulated performance with a PETG cover. The figure shows that the measured and simulated return loss agree fairly. The circular polarization attained with an AR bandwidth of 860–870 MHz below 3 dB is displayed in Fig. 17. After adjusting all parameters as given in Table 2.

Figures 18 and 19 show the simulated 2D and 3D radiation patterns respectively at a frequency of 865 MHz. The 3D radiation pattern has a symmetrical shape and the directivity calculated is approximately 9 dBi.

The simulated surface current distribution of the antenna with a PETG cover at a frequency of 865 MHz is shown in Fig.20. To verify the effectiveness of the suggested antenna, a testing scenario is implemented, as illustrated in Fig. 21. One important component that has a big impact on the test result is the surrounding environment. As a result, certain considerations were made when arranging the testing locations to guarantee measurement accuracy. To prevent Fresnel zone reflection, the tag and reader antenna are positioned 80 centimeters above the ground. The reader antenna and the tag are positioned in the same horizontal plane. ThingMagic M6E-Nano, a UHF RFID reader system with a maximum output power of +30 dBm, was utilized in this test. The reader system can detect the tag in the range of up to 8 meters in line of sight using a commercial UHF RFID tag (RRUHFT05) [41].

Table 2. Antenna dimensions with PETG cover.

Symbols	Dimensions (mm)	Symbols	Dimensions (mm)
W	260	L1	153
W1	157	L2	35
W2	41.71	L3	56
W3	79	L4	25.5
W4	45	L5	56
W5	28	H1	1
W6	100	H2	17
L	260	H3	2

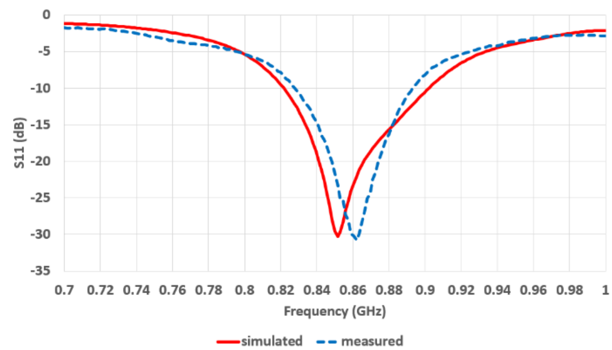

Figure 16: Simulated and measured return losses with a PETG cover.

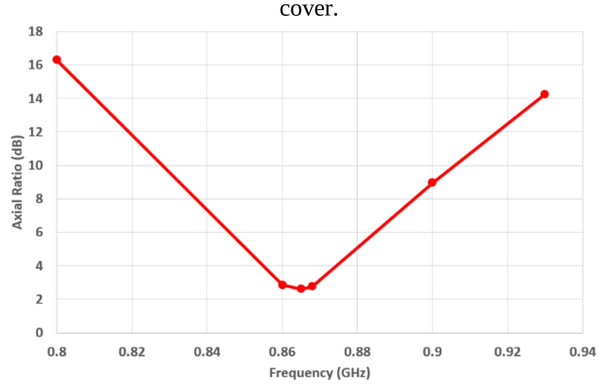

Figure 17: Simulated axial ratio with PETG cover.

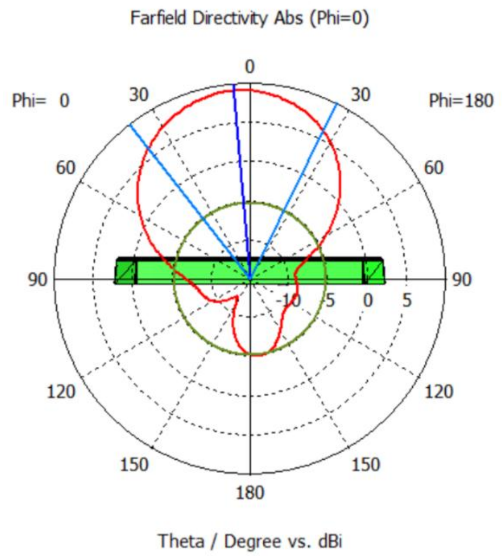

Figure 18: Simulated 2D radiation patterns at 865 MHz with PETG cover.

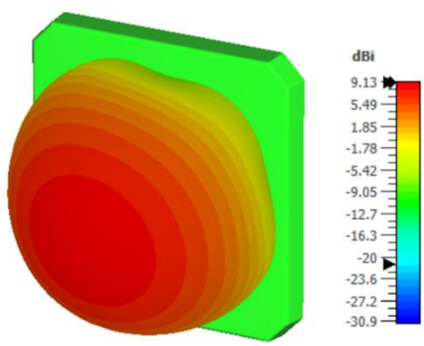

Figure 19: Simulated 3D radiation patterns at 865 MHz with PETG cover.

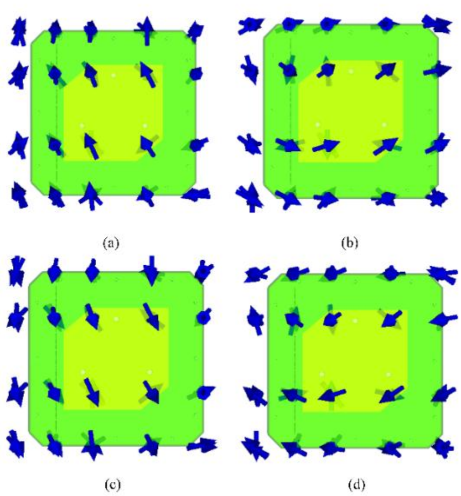

Figure 20: Distribution of the surface current at 865 MHz with four phase angles (a) 0°, (b) 90°, (c) 180°, and (d) 270°.

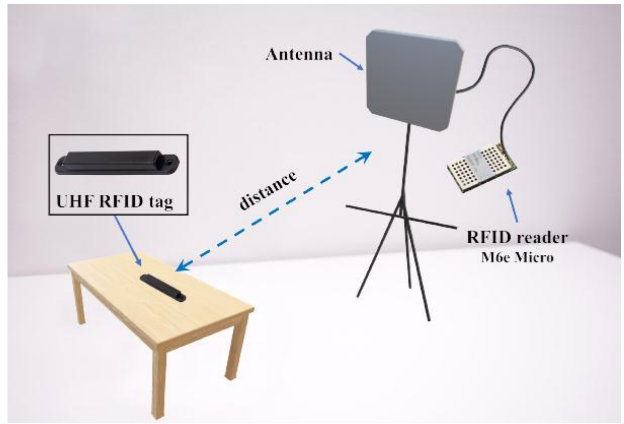

Figure 21: Experiment environment setup.

5. CONCLUSION

This study introduces a circularly polarized RFID reader antenna featuring a 3D printed protective cover made of PETG filament, achieving circular polarization using an air-substrate trimmed patch antenna. Analysis of the surface current distribution of the proposed antenna indicates left-hand circular polarization at 865 MHz. The antenna demonstrates a frequency range of 830 to 890 MHz for both computed and measured impedance, a 3 dB AR bandwidth between 860 and 870 MHz, and a gain exceeding 9 dBi. The antenna size with the cover is 264×264×25 mm. Different cover materials were tested, and PETG was selected for fabrication. The protective cover induces a frequency shift, necessitating parameter adjustments to achieve the desired return loss and optimal axial ratio. Tested performance shows the antenna can achieve a maximum reading distance of up to 8 meters line of sight when powered with +30 dBm input from the UHF RFID reader.

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