Embeddable Miniature UHF RFID Near-Field Antenna for Healthcare Applications

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Abstract—A novel embeddable miniature near-field reader antenna is designed for Ultra-High Frequency (UHF) Radiofrequency Identification (RFID) applications in the healthcare sector. The antenna spans $45\,\text{mm}$(length) $\times\ 20\,\text{mm}$(width) $\times\ 1.6\,\text{mm}$ (thick) in size. The antenna is tuned for UHF RFID region-2 frequencies, 902 to 928 MHz. The antenna's $-15\,\text{dB}$ return loss bandwidth is $140\,\text{MHz}$. The antenna has very low far-field gain, and thus false reads of undesired tags are eliminated. The antenna can read both near-fields, and far-field tags as its magnetic field distribution on its surface are uniform with no dead zones. This miniature, light weight antenna is easy to embed and suitable for niche applications like surgical instrument tracking, dental instrument inventory, etc. The antenna's immunity towards proximity metal assets makes it more suitable for healthcare applications.

1. INTRODUCTION

Radio Frequency Identification (RFID) is a type of Automatic Identification and Data Capture (AIDC) technology that uses electromagnetic fields to identify and track tags that are attached to objects automatically. There are different types of RFID systems that can be broadly classified into active and passive RFID. Active RFID systems require a tag that can transmit and receive signals with the help of a power source. Passive RFID systems use a passive tag that cannot send any signal by itself and require an RFID source to energize them. RFID systems can further be classified based on their frequency of operation. Ultra-High Frequency (UHF) RFID is a type of passive RFID system that operates in the UHF frequency band [1]. A typical UHF RFID system consists of Items/assets, Tags, readers, reader antennas, firmware and software to operate the UHF RFID readers and Network (intranet or internet). The performance of the 'tag Antennas' and the 'reader antennas' determines the read rate, read distance and the read accuracy of an RFID system along with the reader output power, reader's receiving sensitivity and the tag chip's sensitivity. The 'over-the-air-communication' efficiency is critical for a reliable RFID system. Both the tag and the reader antennas in a UHF RFID system are resonant antennas [1]. Tag antennas are typically simple and are multidirectional dipole-like structures, and reader antennas are directional planar antennas. The reader antennas can be radiating far-field antennas or reactive near-field antennas. In the following sections, the concept of near-field antennas, need for miniatured near-field antenna, and its advantages compared to other existing UHF RFID near-field antenna designs are discussed.
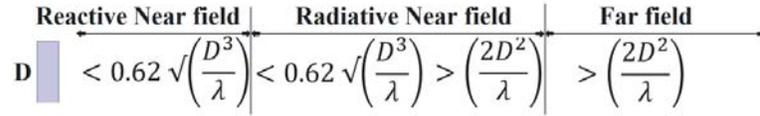
2. UHF RFID NEAR FIELD ANTENNAS

Reader antenna's fields can be broadly classified as the near-field region and far-field region [2]. The near-field region is the region next to the antenna. Near-field region is unpredictable, and thus in general,

Figure 1. Near-field to far-field transition.

no measurements are taken at this region. The near-field can further be classified into the reactive near-field and the radiative near-field. Figure 1 shows the three regions and their zone definition based on the longest length of the antenna 'D' and the antenna's operating wavelength 'λ'. The reactive near-field region lies right next to the antenna, and the governing equation can be found in Figure 1. The region is reactive as the E-field and H-field are 90° out of phase with each other. Propagation does not happen in this region as the E and H fields are out-of-phase. Radiative near-field is the region between the near-field and the far-field. This transitional zone is also known as the 'Fresnel region'. The radiation starts to happen in this region, but it is still immature. The radiation pattern of an antenna will vary with respect to distance in this region. In the far-field region, the E-fields and H-fields are orthogonal to each other and are in-phase. The far-field region is governed by the equation shown in Figure 1. Electromagnetic waves propagate in this region, and a meaningful antenna radiation pattern can be obtained in this region.

The concept of near-field and far-field plays a significant role in UHF RFID applications. Tags can be powered by the far-field electromagnetic fields or by near-field magnetic fields. The far-field electromagnetic fields get absorbed by liquid assets such as pharmaceutical drugs, shampoos, and soaps, while the near-field magnetic fields are not subject to RF absorption. Liquid assets can be efficiently detected when they are tagged using a near-field tag or a hybrid tag that has a dipole-like far-field radiator and a near-field loop. The industry often gets confused between the UHF RFID near-field and NFC (Near-Field Communications). They are two distinct types of passive RFID systems. UHF RFID near-field operates in the UHF frequency range (865–868/902–928 MHz) whereas the NFC operates in 13.56 MHz — same as the High-Frequency RFID. HF RFID and UHF RFID use ISO/IEC 18000-3 and ISO/IEC 18000-6 (or GS1) communication protocols, respectively. HF RFID systems are governed by two more standards viz., ISO/IEC 15693 [3] and ISO/IEC 14443. The former is used in the vicinity (read distance is usually 1 to 1.5 meters) and proximity cards (very close range), and the latter is used for identification cards. The proximity HF cards are sometimes referred to as NFC.

UHF RFID near-field antennas are reader antennas that have proximity read range as opposed to a traditional one whose typical read distance is higher than 8 meters. The proximity read range of a near-field antenna is governed by the sensitivity of the far-field tag and the near-field antenna's reader input power. UHF RFID near-field antennas have dominant magnetic field distribution on their surface. UHF RFID technology offers flexibility in using near-field and far-field antennas for different applications that have different read distance requirements. Besides, the challenges faced by a far-field reader antenna (fields get absorbed by liquid assets) are addressed by the near-field antenna. A higher data rate is offered when using UHF RFID compared to NFC. Multiple tags (almost 1000 tags per second) can be read at once with the UHF RFID near-field antennas whereas only one tag at a time can be read using the NFC technology.

3. RELATED WORKS

Previous works reported in near-field UHF RFID include low gain patch antenna array designs [4, 5], loops and segmented antennas [6–8], segmented dipole in [9], meandered lines in [10], and travelling-wave in [11]. None of these antenna designs is miniature. The antenna designs are very big and are not suitable for embeddable miniature UHF RFID systems. Patch antenna arrays explained in [4] and [5] are not near field antennas. They work for near-field applications, as explained in the previous section within the reactive and radiative near-field zones. The physical dimensions in curved dipole antennas [6] are a function of the operating wavelength. Thus, miniatured antennas in 45×20 mm are not feasible using this design. Circular and square-shaped zero-phase-shift-line (ZPSL) loop antennas proposed in [7] and [8], respectively have a very narrow band and can only work for region-2 UHF RFID

band. These narrow-band antennas are vulnerable to both environmental and proximity asset detuning. The electrically large segmented dipole antenna design reported in [9] cannot be miniatured due to the same reasons explained above. A miniatured antenna will probably resonate at a very high frequency (about 3 GHz). Meandered line near-field antenna design, shown in [10], also has a far-field radiating patch. This is not a true near-field antenna design as opposed to the proposed antenna design. The travelling-wave antenna design in [11] is not miniature, and it is hundred times larger than the proposed design. Moreover, the antenna has very narrow band and has both near-field and far-field components present.

The proposed design is novel because;

1. The antenna is miniature — 45 mm(length) × 20 mm(width) × 1.6 mm (thickness).
2. It is extensively wideband with a 140 MHz, −15 dB return loss bandwidth.
3. The antenna is immune to proximity asset detuning due to its wideband performance and $100\,\Omega$ resistor termination.
4. It is fabricated from low-cost, widely available material.
5. The surface does not have any dead zone with uniform energy distribution.

4. ANTENNA DESIGN

A narrow microstrip line will have more spurious emissions on its surface [11] compared to a wider line. These emissions can be concentrated by arranging the microstrip line in a spiral fashion. The fringe fields tend to couple between the adjacent microstrip lines, enabling uniform energy distribution on the antenna's surface. 1 mm distance of separation is maintained to achieve an efficient coupling. This is the concept behind the proposed antenna design. A 1.6 mm thick FR4 substrate with copper cladded board is used. Very thin microstrip line with higher impedance can be created in FR4 due to its higher dielectric constant ($\varepsilon_r = 4.5$) as opposed to commonly used RF boards such as Rogers 4003C or similar whose ε_r is less than 4.5. Moreover, the FR4 boards are low cost, widely available, and easy to fabricate without the need for special types of machinery. Microstrip line impedances are calculated using the formulae stated in Equations (1) through (4).

If $(\frac{W}{H}) < 1$;

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{reff}}} \ln\left(8\left(\frac{H}{W}\right) + 0.25\left(\frac{W}{H}\right)\right) \tag{1}$$

and

$$\varepsilon_{reff} = \frac{\varepsilon r + 1}{2} + \frac{\varepsilon r - 1}{2}\left[\frac{1}{\sqrt{1 + 12\dfrac{H}{W}}} + 0.04\left(\left(1 - \frac{W}{H}\right)^2\right)\right] \tag{2}$$

If $(\frac{W}{H}) > 1$;

$$Z_0 = \frac{120}{\sqrt{\varepsilon_{reff}\left[\dfrac{W}{H} + 1.393 + \frac{2}{3}\ln\left(\dfrac{W}{H} + 1.444\right)\right]}} \tag{3}$$
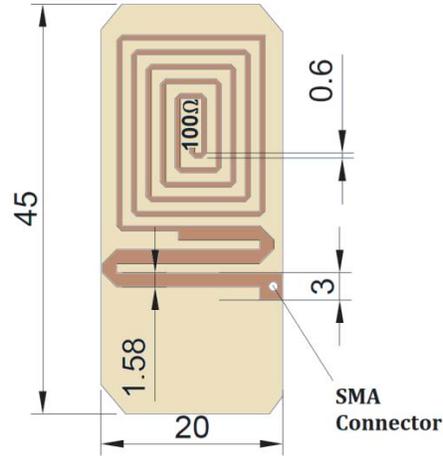
and;

$$\varepsilon_{reff} = \frac{\varepsilon r + 1}{2} + \left[\frac{\varepsilon r - 1}{2\sqrt{1 + 12\dfrac{H}{W}}}\right] \tag{4}$$

where;
  Z_0 is the characteristic impedance ($50\,\Omega$),
  ε_{reff} is the effective dielectric constant,
  W is the width of the microstrip line, and

Figure 2. Miniature near-field antenna design (dimensions in mm).

H is the height of the substrate (1.6 mm).

Figure 2 shows the miniature near-field antenna design. The input impedance of RFID readers is generally 50 Ω, and thus the characteristic impedance is set as 50 Ω. The 50 Ω input impedance is transformed to 100 Ω impedance through a 70.47 Ω quarter-wave impedance transformer. A small 3 mm wide microstrip line is present to connect the 50 Ω connector. The quarter-wave transformer is 1.58 mm wide and spans 46.32 mm long to create 70.47 Ω impedance and 90° phase delay, respectively. The quarter-wave transformer connects the 0.6 mm thick 100 Ω line that is wounded in a spiral fashion and gets terminated with a 100 Ω termination resistor (to match the transformed impedance). The electrical length of the thin line is 450°, i.e., 1.25 wavelengths long for 915 MHz (F_c). The gap between the tracks is maintained as 1 mm.

5. FABRICATION

The near-field antenna is fabricated by routing the microstrip line using a 1 mm router bit to form the antenna pattern shown in Figure 2. Only the top copper layer is removed to leave the FR4 substrate and the back-copper cladding undisturbed. A hole is made using the same router bit in the 50 Ω microstrip line to rear mount the SMA connector. In the centre, the 100 Ω microstrip line is terminated with two 50 Ω surface mount resistors connected in series. The resistor is referenced to the ground plane using a plated hole via. Figure 3(a) shows the antenna pattern with termination resistors, and Figure 3(b) shows the antenna's ground plane with the SMA connector and the solder joint of the ground via. A ruler is put against the antenna to show the miniature antenna footprint.

6. RESULTS AND DISCUSSION

The antenna is tested using a TR-1300 Vector Network Analyzer (VNA) designed by Copper Mountain Technologies. This 2-port VNA can efficiently scan between 300 MHz and 1.3 GHz. The antenna is connected to VNA's port 1 to measure its return loss $|S_{11}|$. Figure 4 shows that the antenna resonates efficiently for the region-2 UHF RFID frequencies, 902 to 928 MHz, in free space. The return loss across the operating frequency band is about −17 dB. This means that only 1.9% of the input power is getting reflected back. It is very important for an RFID antenna to have a good return loss specification to avoid RFID reader damages [1]. The −15 dB return loss bandwidth for this antenna is 140 MHz. Although the operating bandwidth between 902 and 928 MHz is only 26 MHz, this excess bandwidth is important in practical use cases. When a dense asset is loaded on top of the antenna, the antenna fringe fields from the microstrip line travels slower, and thus the antenna resonates at a lower frequency. Since the antenna's best-case return loss is at higher frequencies such as 980 and 1000 MHz, a lower frequency return loss shift will not deteriorate the antenna's performance. Since the antenna is meant to
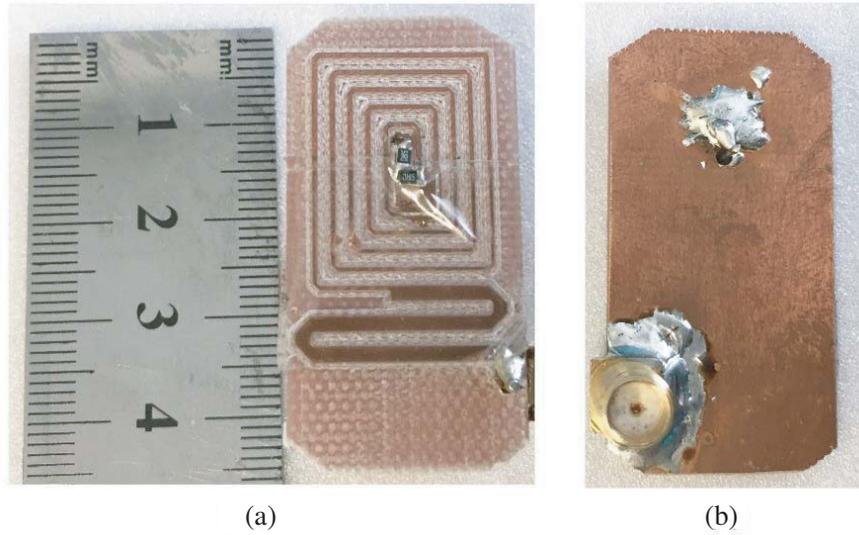
(a)   (b)

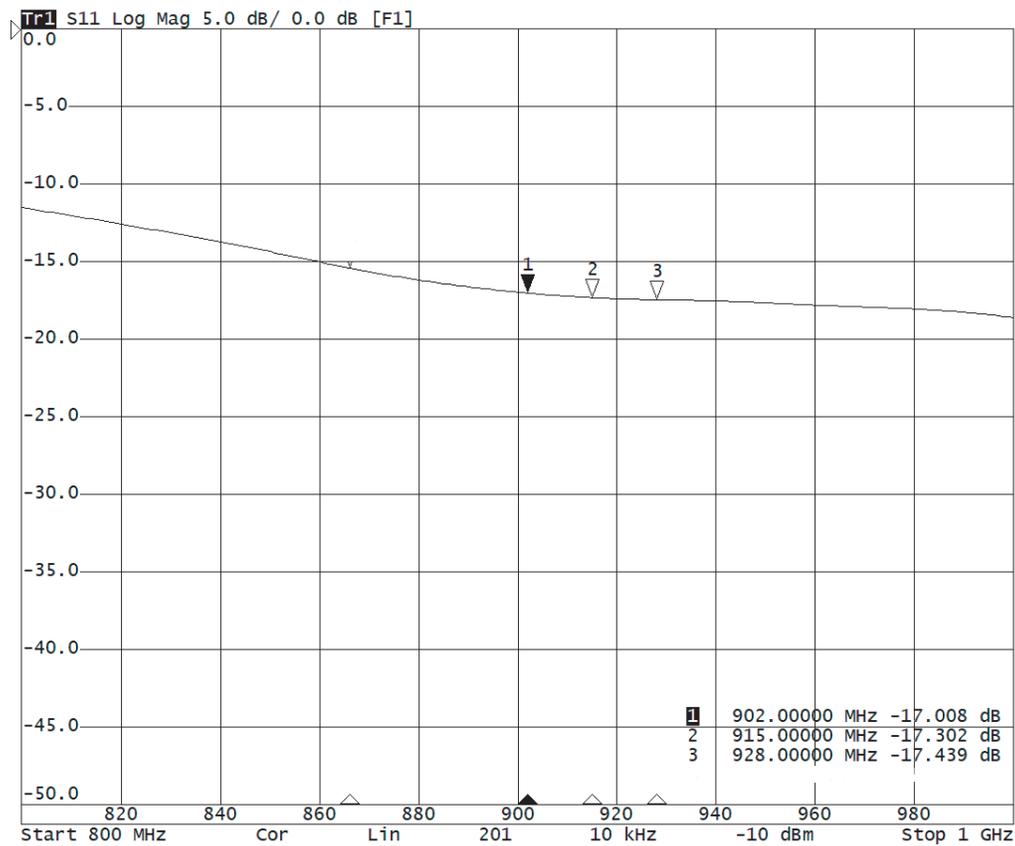**Figure 3.** Fabricated antenna: (a) Front view and (b) rear view.

Figure 4. Return loss $|S_{11}|$.

be embedded in existing medical devices such as surgical instrument sorting trays or dental instrument verification screen, it is highly important to ensure that the antenna can withstand environmental attenuation and detuning effects. The antenna has negligible propagating far-field, it is verified by measuring its radiation. A reference antenna with 0 dBi gain is attached to the VNA's port 2. This

reference antenna is focussed on receiving the radiated power from the near-field antenna under test. The gain of the near-field antenna is measured by the comparative method stated in [12]. The near-field antenna's gain is approximately -36 dBi across the region-2 UHF RFID frequencies (see Figure 5). The antenna's gain is significantly low, and thus it is a 'true near-field antenna'.
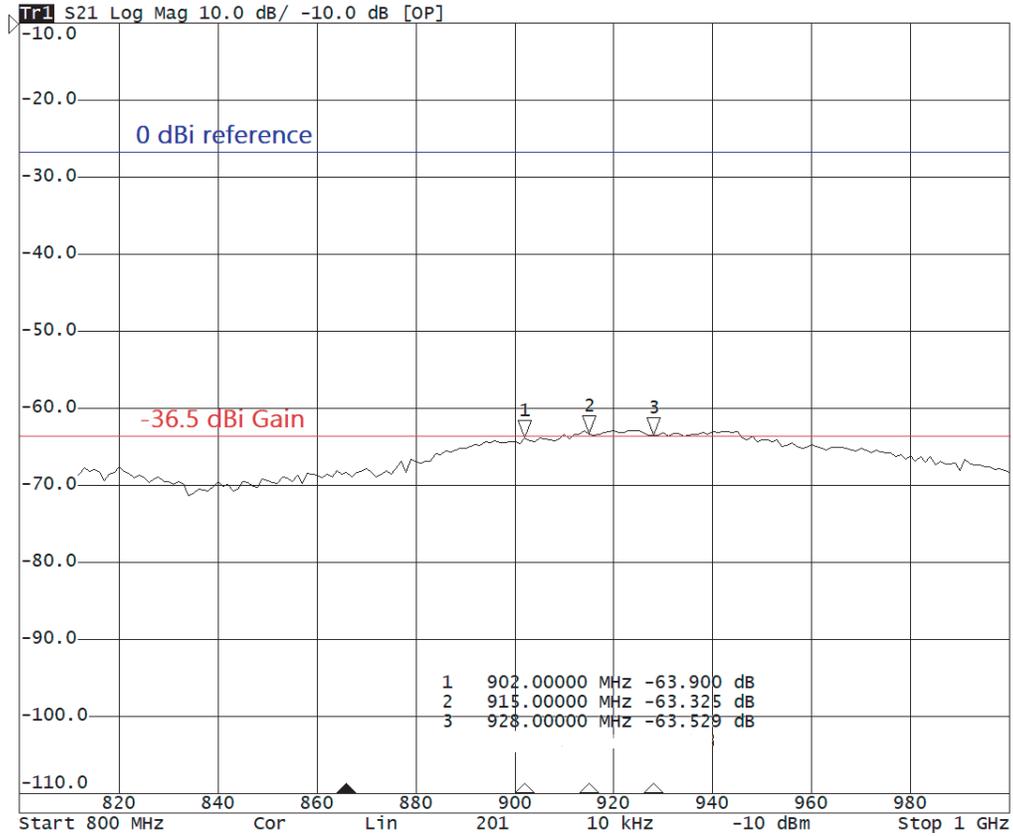

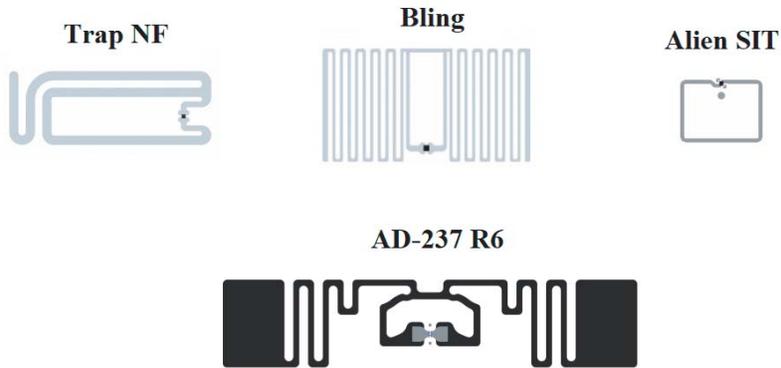**Figure 5.** Path loss $|S_{21}|$ and gain translation.

Figure 6. Different tags used for testing (images not to scale).

7. RFID TESTING

The antenna is tested for UHF RFID performance by testing it with an Impinj R420 RFID reader [13]. Three different tags used for testing are a) Smartrac's 'Trap NF' tag, b) Smartrac's 'Bling' tag, Alien SIT and c) Avery Dennison's '237R6' tag (refer Figure 6) [14–16]. The trap NF tag is a small-sized tag that has a magnetic loop only. Bling is a medium-sized tag that has a wiggled dipole antenna. 237R6 is a big sized tag with a tuned dipole-like antenna. Bigger the tag, higher the sensitivity. Table 1 shows the read ranges and return signal strength for these tags when the antenna is powered at 31 dBm. There were no cable losses involved as the antenna is directly connected to the reader's port (See Figure 7). Figure 8 shows the surface energy distribution with no dead zones. Two different RFID tags were used to test for its return signal strength indication (RSSI) when the antenna was powered at 31 dBm. The tag was moved at a different location to note the RSSI. Trap NF tag measurements were measured at three locations while the SIT tag was measured at six different locations. The former spans 11×25 mm while
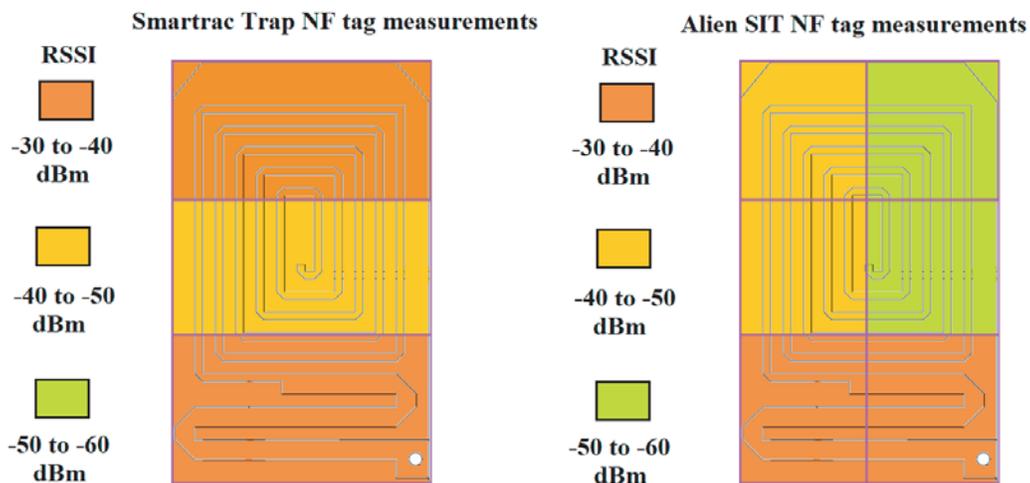

Figure 7. RFID test setup.

Figure 8. Surface field distribution with no dead zones.

Table 1. Read distance measurements.

Tag	Maximum distance	RSSI
Trap NF	13 mm	$-41.5\,\text{dB}$
Bling	43 mm	$-38.6\,\text{dB}$
237R6	90 mm	$-35.8\,\text{dB}$

the latter is $12 \times 9\,\text{mm}$. Testing the near-field distribution using UHF RFID tags is far more accurate as it simulates the real-application. The energy distribution is considered to be uniform as tags can be energized at different locations. There is no dead zones as the RSSI value is not above $-80\,\text{dBm}$. Return signals beyond $-80\,\text{dBm}$ cannot be sensed by RFID readers' limited receiver sensitivity (usually $-82\,\text{dBm}$).

8. CONCLUSION

An embeddable miniature near-field antenna design is proposed for UHF RFID healthcare applications such as surgical instrument tracking and health care professionals' access control. The antenna has a uniform surface energy distribution with no dead zones. The read range is very much confined and does not read unwanted stray tags. The antenna has wideband, and it is immune to environmental and nearby asset detuning. The antenna is in low cost, light weight, and easy to manufacture. As a part of the future work, a miniatured UHF RFID antenna will be created for region-1 UHF RFID frequency band, 865–868 MHz.

ACKNOWLEDGMENT

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