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Miniaturized Metal-Mountable U-Shaped Inductive-Coupling-Fed UHF RFID Tag Antenna With Defected Microstrip Surface

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ABSTRACT This study presents a novel miniature ultra-high frequency (UHF) radio frequency identification (RFID) tag for metallic objects. Its arrangement includes a U-shaped feeder, which is inductively coupled to two E-type connected patches. Size reduction is achieved by means of utilizing the U-shaped feeder, and introducing a defection in the connection between the two E-type patches. The defection in the connection area between the patches modifies the current distribution by increasing the electrical length, and the antenna inductance. Furthermore, increasing the length of the U-shaped structure significantly raises the antenna inductance and, consequently, the flexibility of the structure for the impedance matching purpose. Polytetrafluoroethylene (PTFE) is employed for the fabrication of the designed tag. The tag's size is 65 $mm \times 20$ $mm \times 1.5$ mm, and does not require any complex fabrication process such as utilization of metal vias and/or shorting stubs. It is observed that with 4W EIRP, the measured detection distance is 6.9 m when it is attached onto metal sheets (20 $cm \times 20$ cm), and 5.54 m when it is in free space. The measurement results also are in good agreement with the simulated results.

INDEX TERMS Defected microstrip surface, impedance matching, metal mountable tag antenna, miniature UHF tag antenna.

I. INTRODUCTION

Owing to its numerous advantages, the demand for radio frequency identification (RFID) tagging technology has increased significantly, and is being leveraged by the industry for various applications such as inventory management, asset tracking, electronic toll collection, and patient monitoring [1]–[4]. A miniature RFID tag antenna is a suitable candidate for meeting the trending market demands for such applications. However, the tag antenna performance can be affected directly by objects it is mounted on, particularly metallic surfaces [5], [6].

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The dipole antenna has been extensively used for designing metal mountable tag antennas. In [7], a single layer tag antenna, consisting of a folded dipole integrated with outer strip lines, has been designed to achieve increased inductance for impedance matching, but its bandwidth and radiation efficiency were low. The foam-attached tags in [8] and [9] have been constructed from the label-type dipoles with a spacer, in order to reduce the effects of the backing metallic surface. These tags showed otherwise (i.e., in the absence of spacer) a significant deterioration in the radiation performance. An alternative method [10], utilized a ceramic (high permittivity) substrate to realize miniaturization, which resulted in an improvement radiation performance. However, this approach has significantly increased the cost. Furthermore, a folded dipole with the multi-parallel-bar ground was designed by means of a multilayer configuration [11]. The reported structure has an implementation issue due to its bulky size. The design of microstrip patch tags for metal mountable tag antenna has been investigated in [12], yet it is not practical for many applications due to its large footprint. In addition, miniaturization of the patch has been reported by incorporating shorting vias/pins [13]. However, this method requires complex and costly fabrication process, as it involves intricate procedures, whereas the tuning of the operation frequency is sensitive, tedious, and largely affected by the position of the metallic vias [14].

Planar inverted-F antenna (PIFA) [15] has also been utilised in the design of metal mountable tags. However, it employed a vertical feeding approach and shorting elements, which led to complex and expensive fabrication process. Other researchers have proposed a folded-patch antenna with shorting stubs for the purpose of reducing the resonance frequency [16]–[20]. Further miniaturization is achieved by increasing the tag thickness to 3 mm [21], or utilizing three conductor layers, and two foam substrates [22], [23]. However, the tag performance exhibits a significant sensitivity to the position of stubs. Also, it features considerable thickness and a dual-layer structure, therefore, it is not practical for certain applications. In addition, the employment of adhesives to maintain the structure unity is problematic. Moreover, the design of a miniature folded-patch tag antenna poses another difficulty, which is extremely low radiation resistance [23]. This makes realization of matching between the antenna and IC chip a challenging task, whereby the tag's power transmission coefficient (τ) suffers significantly. Other studies proposed the utilization of the electromagnetic bandgap (EBG) structure by etching the ground layer with a periodic arrangement of circles-shaped slots [24] or by employing EBG cells with vias placed around the antenna [25]. Furthermore, the artificial magnetic conductor (AMC) method is used to improve the tag's gain. In [26], a high permittivity AMC substrate contains offset of vias; however, the tag antenna and the AMC substrate are separated by foam spacer. In [27], an air gap spacer for reducing the metallic surface effects had employed between tag and metallic sheets which would significantly affect the antenna gain otherwise. A 3D tag antenna has been suggested in [28] where the tag antenna is attached directly to the reflector surface for long read range. In [23], the tag antenna loaded orthogonally with parasitic substrate for bringing the resonant frequency down. Although the mentioned approaches improve the tag's performance, the cost and structural complexity are considerably increased.

Defected microstrip structure (DMS) has the operative capability to miniaturize the antenna size, control the performance, helps achieving electromagnetic interference noise immunity, and, due to its simple geometry, the ability to be easily integrated within the design structure [29]. The defect in the antenna structure defines the resonance characteristics in the frequency response. Furthermore, it can increase the electrical length and alter the surface current density, which can result in the improvement of the antenna inductance, and, hence, the ability to design a miniature compact ultra-high frequency (UHF) RFID. Other implementations of DMS in the realm of RFID tag antennas include achieving dual-polarization [30], gain improvement [31], and circular-polarization [32]–[34]. By exploiting DMS as a way of increasing the antenna inductance, in this research, we aim to miniaturize the tag antenna size, while keeping its performance upheld.

The utilization of inductively coupled feed in U-shaped feeders was first proposed in [35], to encounter the conjugate matching obstacle. In [31], the U-shaped feeder was utilized to feed the defected patch, in that, the defection was implemented for accomplishing gain improvement. Here, the U-shaped feeder and DMS are integrated in an attempt to design a miniaturized single-layer tag antenna with a simple physical construction in contrast with reported work in [8]–[23], which required complex fabrication, thereby raising the overall cost. Our upfront goal is to design a miniature simple single-layer structure, which is suitable for mass production. It has been ensured that this new structure does not require tedious manufacturing when it is realized as a part of the hardware. The complex manufacturing methods required for the structure reported in the literature works should be avoided, while comparable or better results in terms of antenna performance are to be achieved.

In this study, a metal mountable UHF RFID tag antenna is proposed, which is comprised of a single-layer substrate with the defected surface. The tag antenna is designed using a U-shaped inductive feed, integrated with two E-type patches. The defection has been introduced in the connection area between the two E-type patches. The structure provides flexible tuning mechanism for the resonance frequency. Consequently, the U-shaped feeder has the ability to achieve matching with any IC chip. The designed tag is fabricated on a slab of Polytetrafluoroethylene (PTFE). The structure is cheap and simple to fabricate, unlike previously reported tags, which are associated with costly fabrication procedures, and complex manufacturing. It is observed that the proposed design has acceptable measured read range in comparison with previous studies. The obtained read range on various sizes of metallic surfaces, reading patterns, and realized gain have been presented. The simulation results have been validated through the measurements of the fabricated prototype.

II. ANTENNA DESIGN

A. ANTENNA STRUCTURE

The proposed miniature single layer tag antenna for the on-metal application is displayed in Fig. 1. U-shaped feeder structure based on inductive coupling technique serves the purpose of feeding the patches through transmission lines. The transmission lines are directly integrated with two E-type patches. The copper trace connecting the upper and lower arms of two E-type patches has been etched out in order to introduce defection. This defection reduces the resonance frequency and hence aids in size miniaturization. PTFE has been used for the fabrication of the tag having thickness of 1.5 mm, dielectric constant of 2.55 and loss tangent 0.0015. Higgs 4 strap IC chip has been fixed in the middle of the tag structure as shown in Fig. 1. The input impedance of the selected IC chip is $20.97 - j193.16\ \Omega$ with reading sensitivity of −20.5 dBm. The structure of the Higgs 4 strap has been illustrated in [36], designed precisely via Computer Simulation Technology (CST) simulator. The proposed design has been optimized for operating over UHF band, particularly the North American band (902 − 928 MHz). The tuning of the resonance frequency performed by varying the dimensions of the U-shaped feeder and optimization of the defection area by means of parametrical analysis is presented at later stage in this study.

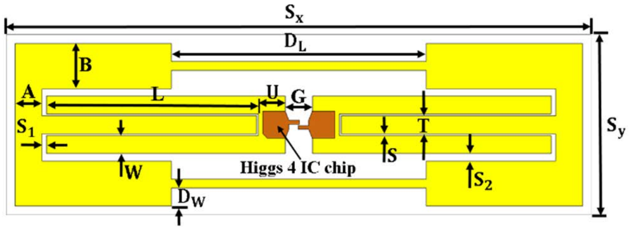

FIGURE 1. Antenna geometry $S_x = 65$, $S_y = 20$, $L = 23.3$, $W = 2$, $S = 0.2$, $U = 3$, $T = 2$, $G = 3$, $S_1 = 0.5$, $S_2 = 0.8$, $A = 3$, $B = 5$, $D_L = 23$, $D_W = 1.5$ (unit: mm).

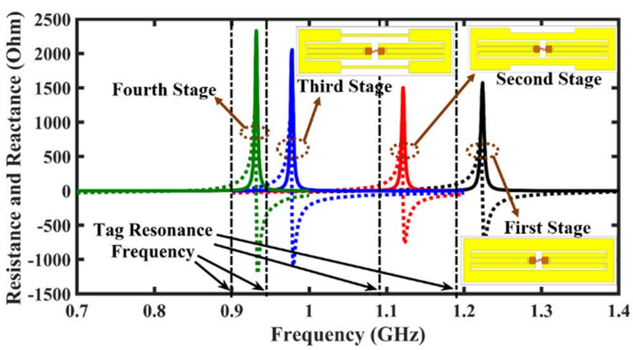

FIGURE 2. The input impedance of the proposed miniature tag antenna at three stages and final tuning.

B. DESIGN PROCEDURE

The CST simulator was utilised to design and optimize the tag antenna dimensions. Since this work focusses over on-metal applications, the tag antenna was designed while being positioned on the top of a perfect electrical conductor (PEC) with a thickness of 1 mm.

Generally, a tag antenna with a size less than 2500 mm^2 possesses a relatively high resonance frequency. Hence, designing a miniaturized tag antenna by reducing its resonance frequency to UHF band is an intricate procedure. In order to attain this, we propose to increase the inductance of the antenna by introducing a defect in the area where the two patches are connected, along with optimization of the U-shaped feeder dimensions.

In the first stage, the U-shaped feeder with two E-type patches was solely simulated, while the Higgs 4 IC chip was attached to the centre of U-shaped feeder. It was observed that the structure resonated at 1.2 GHz, higher than our desired frequency band. In the second stage, the defect was introduced by etching out the outer parts of the area connecting the two E-type patches, as displayed in Fig. 2. This tuned the resonance frequency down to 1.1 GHz. In the third stage, the same area was defected on its inner sides as well, thereby bringing the resonance further down, close to the desired UHF band. Finally, fine tuning of resonance frequency to exact UHF RFID band was achieved by optimizing the U-shaped feeder dimensions and defection area. All these steps are clearly depicted in Fig. 2. Therefore, the defection area can be dominantly attributed to bringing the tag antenna resonance frequency over the UHF band and subsequently attaining the miniature size without utilising any complex structure, which in fact reduces the cost of mass fabrication.

C. PARAMETRIC STUDY

The ultimate performance of the tag antenna could be obtained by impedance matching between antenna and IC chip. This can be achieved by tuning the dimensions of U-shaped structure and modifying the defection area. The strength of inductive coupling is defined by the dimensions of U-shaped feeder (L and W) and the gap between the feeder and transmission line (S). In [35], The antenna's input impedance (Z_{in}) as seen through the centre of the U-shaped structure is given as,

$$Z_{in} = R_{in} + jX_{in} = Z_u + (2\pi f_0 M)^2 / Z_{ant} \tag{1}$$

where Z_{ant} is the antenna's complex impedance, M is the inductive mutual coupling, and Z_u is the U-shaped feeder's impedance which can be expressed as

$$Z_u = 2R_u + j2\pi f_0 (2\,L_u) \tag{2}$$

The antenna input impedance, with the assumption that the effect of the substrate is minimal can be written as

$$Z_{in} = \left[2R_u + (2\pi f_0 M)^2 / R_{ant}\right] + j4\pi f_0 L_u \tag{3}$$

where f_0 is the resonance frequency, M is the inductive mutual coupling, R_{ant} and R_u are the resistance of the antenna and U-shaped feeder; respectively, and L is the U-shaped feeder length.

According to the Z_{in} equation, the reactance of the tag antenna can be determined by the length of the U-shaped (L), while the resistance can be controlled by means of the radiating antenna (M and R_{ant}). Furthermore, the defection was employed to increase the antenna reactance by raising the current density and increasing the electrical length [37]. Therefore, the techniques of U-shaped feeder as well as the defection between two E-type patches, incorporated in the design approach result in a miniature tag antenna with notable performance.

In this section parametric study of the dimensions of U-shaped feeder and defected area is shown to detail the optimization procedure for resonance frequency tuning. Fig. 3 shows the tuning of L and W. Initially L was tuned from 18 mm to 23.5 *mm* while W was fixed at 2 *mm*. As evident from Fig. 3(a), the tag's resonance frequency was shifted down from 1.082 *GHz* to 0.915 *GHz* at the rate 30 *MHz*/1 *mm*. Next, the W was changed from 0.5 *mm* to 2 *mm* and L was fixed at 23.5 *mm*. The tag's resonance frequency tuned down at a rate of 10 *MHz*/0.5 *mm* and is shown in Fig. 3(b).

The tuning of power transmission coefficient with respect to defection area connecting the two E-type patches is shown by parametric analysis in Fig. 4, where the detailed effect of dimensions of defect (D_L and D_W) are studied. Tuning D_L from 4 *mm* to 28.3 *mm* shifted the power transmission coefficient from 1.2 *GHz* to 0.915 *GHz* while the D_W was maintained constant at 1.5 *mm*.

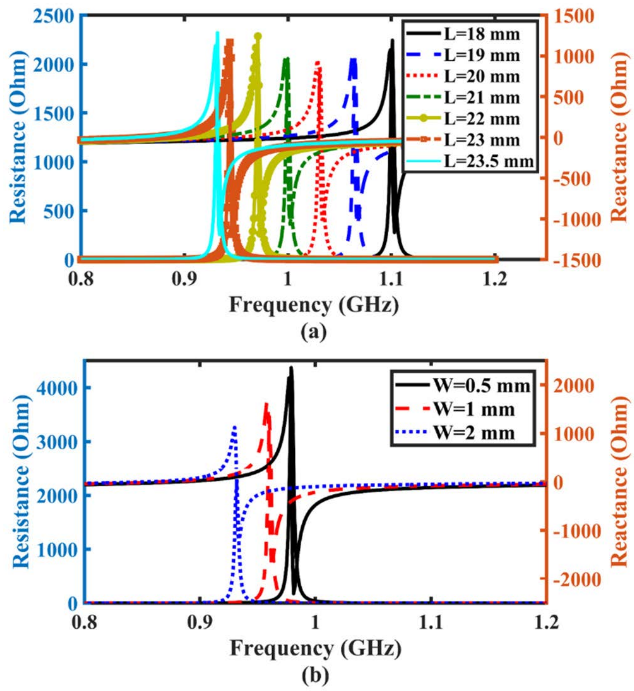

FIGURE 3. The input impedance of the tag while (a) *L* was tuned from 18 mm to 23.5 mm (b) *W* was changed from 0.5 *mm* to 2 *mm*.

This is displayed in Fig. 4(a). Similarly, changing D_W from 0.5 *mm* to 1.5 *mm* brought the power transmission coefficient at the centre of North American band (915 *MHz*) as shown in Fig. 4(b). The optimization of U-shaped feeder and defection area connecting the two E-type patches is attributed to raising the antenna inductance, which resulted in designing a miniature tag antenna having ideal power reflection coefficient ($\tau = 1$), evident in Fig. 4.

D. CURRENT ANALYSIS

The surface current profile of the proposed tag antenna while being attached to the centre of PEC is shown in Fig. 5. The defection in the connecting area of E-type patch has the capability to alter the overall surface current density which also increases the electrical length of the antenna. Thus, miniaturization was achieved as a result of increasing the inductance. It can be seen from Fig. 5 that the surface current density has increased on the strip lines, as an effect of defection. The maximum current surface density has increased from $67A/m$ to $87A/m$. In addition to this, as illustrated in Fig. 3 and Fig. 4, the alteration in the surface current distribution area on antenna also resulted in a significant change in the tag's impedance and resonance frequency [38]. This explains the obtained impedance matching between the antenna and IC chip at the operating frequency.

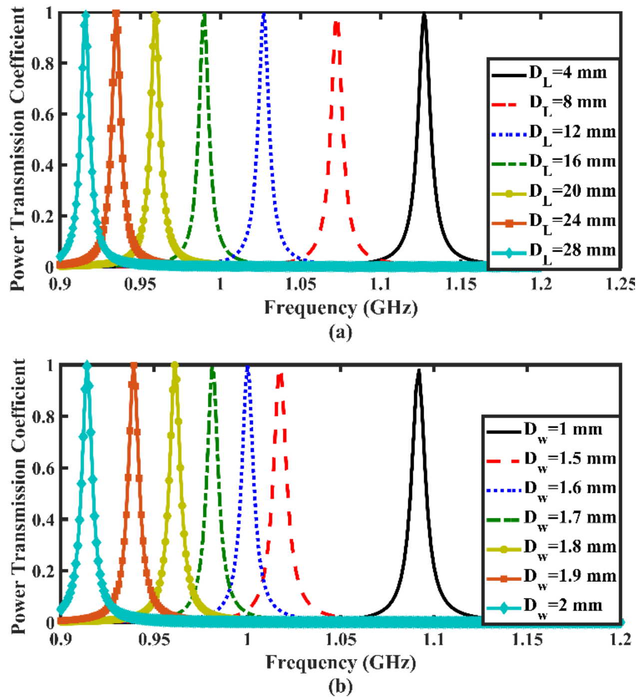

FIGURE 4. The power transmission coefficient of the tag while optimizing the defection area (a) length (b) width.

III. RESULTS AND DISCUSSION

The realized gain (G_r), read range (r), and tag sensitivity (P_{tag}) of the proposed structure has been measured using Voyantic Tagformance Pro measurement system. The experiment setup in anechoic chamber is shown in Fig. 6(b). As can be seen, the tag was placed in the centre of metal plate (20 $cm \times$ 20 cm). The distance between tag antenna and reader was kept at 51 cm. Both were arranged in boresight ($\theta = 0°$) direction from each other. Furthermore, the measured setup supports the matching factor to be equal to one, since the reader and tested antenna were aligned in parallel. The detection distance formula can be derived from Friis formula as given in [37],

$$r = (\lambda/4\pi)\sqrt{(P_{EIRP}/P_{tag})} \quad (4)$$

The results of measured and simulated G_r of the proposed structure is shown in Fig. 6(a). It shows that measured G_r

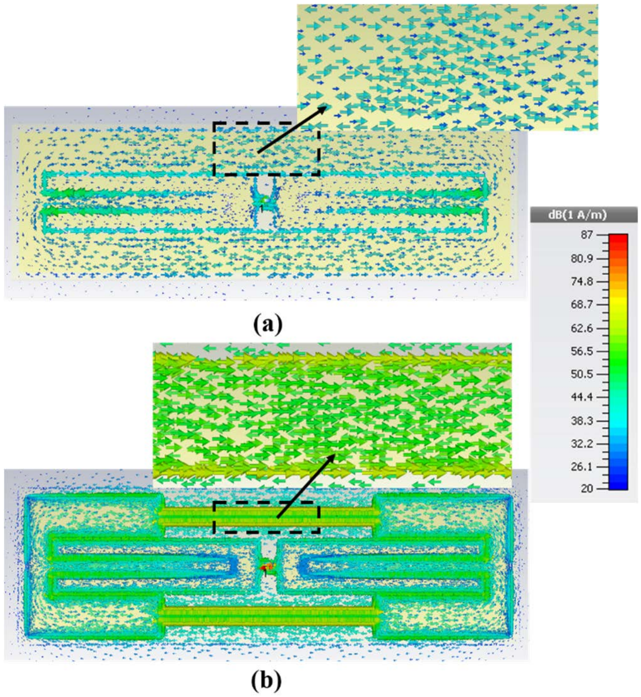

FIGURE 5. **The distribution of the surface current (a) before (b) after defection.**

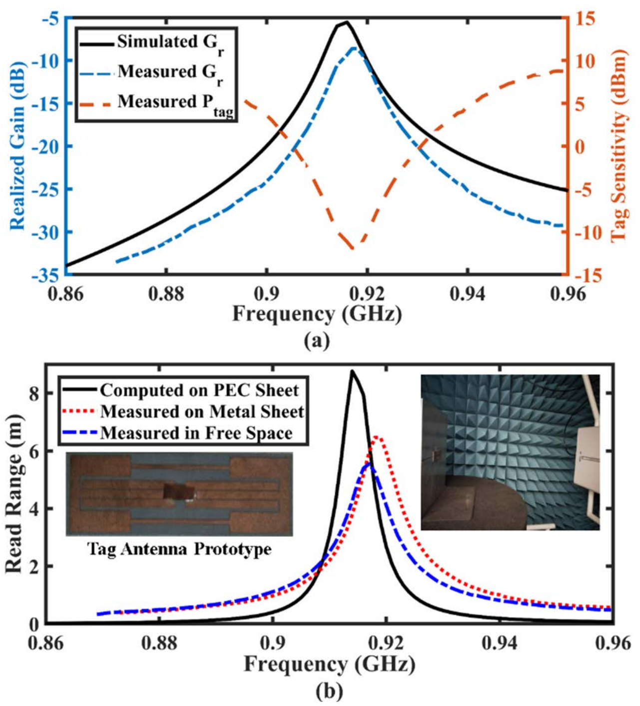

FIGURE 6. **(a) Realized gain and tag sensitivity of the tag (b) read range of the tag on metal and in the free space.**

is obtained as -8 *dB* while the simulated G_r is equal to -5.53 *dB* at resonance frequency. Fig. 6(a) also shows that the measured P_{tag} result (obtained from measured r). It is -12.45 *dBm* at resonance frequency. The compact size of the designed tag and the use of low-profile substrate (1.5 *mm*) justify the value of the radiation efficiency (below 10%). This explains the obtained value of G_r where higher gain required thick substrate [39]. As can be seen, the trend of the measured results correlates well with the simulation results. The slight difference between individual values can be attributed to measurement alignment issues, fabrication defects, IC chip variation, and design tolerance. The measured and simulated detection distance is exhibited in Fig. 6(b). The results show that the measured read range is equal to 6.9 *m* (at 919 *MHz*) when mounted on metal sheet and 5.54 *m* (at 918 *MHz*) in free space. The simulated G_r is -6.78 *dB* in the fee space. The simulated read range on PEC surface is equal to 9.23 *m*. Again, a good correlation among results can be observed.

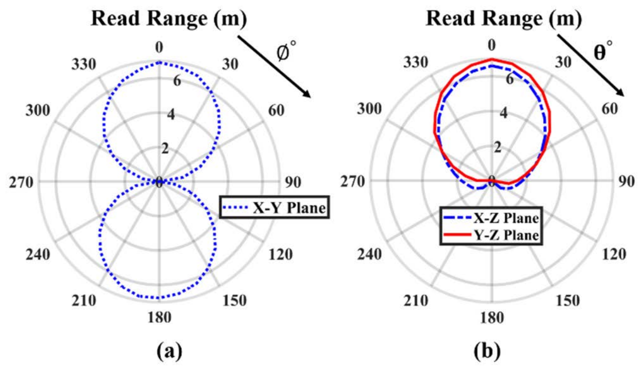

FIGURE 7. **Read pattern of the tag on various planes (a) X-Y plane, (b) X-Z, and Y-Z planes.**

Fig. 7 shows the response of the tag to the reader (read pattern) that defines the graphical representation of the radiation characteristics. In the setup test (Fig. 6(b)), the tag antenna was rotated around its own origin during measurement while the distance between tag antenna and reader was maintained constant. The read pattern for yz, xz, and xy planes are plotted by rotating the tag around x-, y-, and z-axis respectively. The maximum detection distance was observed to be at the boresight. When the tag was rotated beyond $\theta = \pm 90°$, the truncation of the detection of the tag was observed as a result of metal sheet.

The performance of the proposed miniature tag antenna has also been tested for various sizes of metal sheets. The dimensions (Width D and Length C) were varied to study their effect on read range. Initially, the D of the metallic sheet was varied from 10 *cm* to 20 *cm* (for $C = 20$ *cm*). The results in Fig. 8(a) shows that the measured detection distance was decreased to ~3.5 m for $D = 10$ *cm* (simulated $G_r = -9.89$ *dB*), indicating that the performance of metallic sheet as reflector was significantly affected. At the second stage, as shown in Fig. 8(b), the values of C were varied from 10 *cm* to 20 *cm* (for constant $D = 20$ *cm*).

Here, it was observed that the detection distance of the tag in all cases was maintained at 6.9 *m*. This indicates that the function of metal sheet as a reflector was not affected, thereby giving a stable tag performance. From above results, it can be inferred that reducing C to 10 mm does not affect the electrical flux line strength in the boresight. However, reducing the value of D to 10 cm leads to a reduction in electrical flux strength in the boresight and decreases the detection distance to ~3.5 m at D = 10 cm.

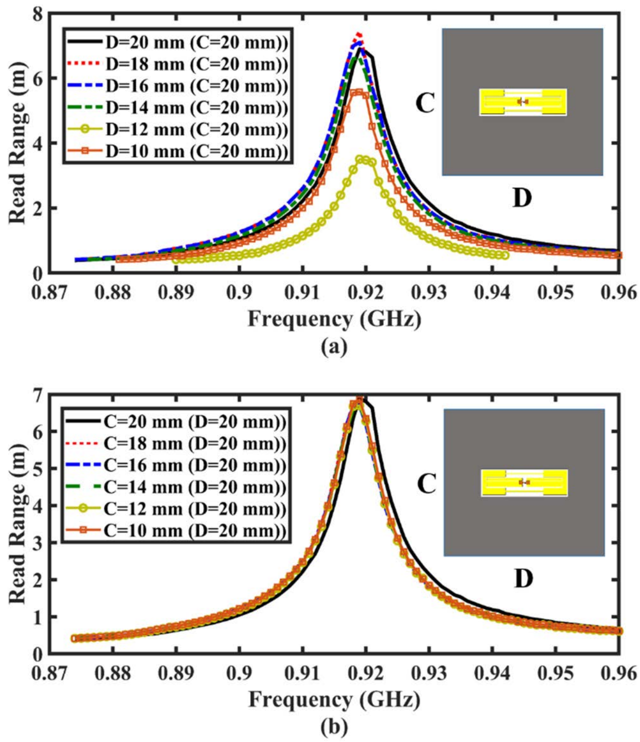

FIGURE 8. Measured read range of the tag at various dimensions (a) ***D*** (b) ***C***.

Next, we compare performances and physical properties of the proposed miniature tag antenna with other similar studies where the tag antenna has been designed for metal mount applications with single layer structure and thickness below 2 mm. The results of these comparisons are given in Table 1. In [7] the tag antenna had a simple structure and did not require complex fabrication process but its detection distance did not exceeded 3.5 m. The reported tag in [10] was comprised of a single layer and attained reading range of 2.65 m. Although the proposed tag was compact, it utilized costly high permittivity substrate. In [27], a read range of 10 m was achieved; however, the design utilized an air gap spacer to reduce the effect of the metallic surface on the performance of the tag. Folded-patch tag antenna with shorting stubs was introduced in [16] and [17] with a reading range of 6.3 m and 5.2 m, respectively. Furthermore, miniaturization was obtained in [37] by loading non-resonating ring underneath the folded-patch, which made fabrication process complex. However, this miniaturized structure achieved a read range of 6.62 m.

In [25], electromagnetic bandgap (EBG) cells were employed around the antenna in order to enhance the radiation efficiency of the tag where its reading range improved 1.2 m. However, it possessed a complex structure where its cost significantly increased because of metallic vias. In [30], a tag antenna with dual polarization was constructed from dual PIFA antennas for metal mountable applications. A read range of 10.2 m was attained. Similar to the above-mentioned study, the fabrication process was complex and costly due to 12 metallic vias. Similarly, metallic vias were introduced in [40] for miniature purpose where its reading range did not exceed 2.5 m. The utilization of metallic vias increased the fabrication cost and complexity. Reported work in [41] utilized a PIFA antenna with 8 metallic vias which also is not suitable for mass production.

In [31], the simple tag antenna comprises U-shaped feeder and defected patch had reported in purpose of gain improvement. The size of the proposed structure in comparison to [31] has shrunk 63% while its performance degradation, in terms of its read range, has only been 18.3%. In contrast to the above works, our proposed design use a simple and compact metal-mountable tag antenna design which composed of a U-shaped feeder and a defect in the connecting area between the two E-type patches. This design does not incorporate any complex fabrication technique, is purely planar with low profile (thickness of 1.5 mm), low in cost, and offers easy design flexibility owing to the U-shaped feeder and the defected structure. Moreover, the performance parameters of the proposed design are comparable to the results of the designs from other works. Owing to these benefits, therefore, our proposed design is extremely suitable for mass production of metal mount tag antenna applications.

TABLE 1. Comparison table of UHF RFID metal mountable tags

Ref.	Shorting Elements	Tag Dimension (mm^3)	Chip Sensitivity (dBm)	r (m)
[7]	No	82.75 × 19.5 × 1.5	−8	3.36
[10]	No	32 × 32 × 1.5	−18	2.65
[27]	No	120 × 60 × 1.9	−18	10
[16]	Stubs	40 × 40 × 1.6	−20	6.3
[17]	Stubs	42 × 50 × 1.6	−20	5.2
[37]	Stubs	20 × 18 × 1.7	−17.8	6.62
[25]	Vias	70 × 70 × 1.6	–	6.1
[30]	Vias	64 × 64 × 2	−17.4	10.2
[40]	Vias	69.5 × 14 × 1.5	−15	2.2
[41]	Vias	60 × 45 × 1.6	–	6.2
[31]	No	57.72 × 60.9 × 1.5	−20.5	8.44
This work	No	65 × 20 × 1.5	−20.5	6.9

IV. CONCLUSION

In this research, a simple miniature low-profile tag with easy design flexibility unlike literature works that demand complex and costly fabrication procedures is suggested. It was fabricated based on the utilization of U-shaped feeder and defection in the connecting area between two E-type patch structures. The flexibility of U-shaped feeder to match any sort of IC chip and the effect of defection on increasing the antenna inductance were the main characteristics of miniaturized tag antenna design. Its performance is notable and the proposed structure is suitable to be mounted on metallic objects. It was observed that the read range of the tag was 6.9 *m* while being mounted onto 20 *cm* × 20 *cm* metal sheet. The proposed tag can be operated over UHF North American band and its radiation efficiency does not exceed 10% due to its compact size and low-profile structure.

REFERENCES

[1] F. Erman, E. Hanafi, E.-H. Lim, W. A. W. M. Mahyiddin, S. W. Harun, M. S. A. Talip, R. Soboh, and H. Umair, ''Low-profile folded dipole UHF RFID tag antenna with outer strip lines for metal mounting application,'' *TURKISH J. Electr. Eng. Comput. Sci.*, vol. 28, no. 5, pp. 2643–2656, Sep. 2020, doi: 10.3906/elk-1912-45.

[2] R. Abdulghafor, S. Turaev, H. Almohamedh, R. Alabdan, B. Almutairi, A. Almutairi, and S. Almotairi, ''Recent advances in passive UHF-RFID tag antenna design for improved read range in product packaging applications: A comprehensive review,'' *IEEE Access*, vol. 9, pp. 63611–63635, 2021, doi: 10.1109/ACCESS.2021.3074339.

[3] M.-T. Nguyen, Y.-F. Lin, C.-H. Chen, C.-H. Chang, and H.-M. Chen, ''Shorted patch antenna with multi slots for a UHF RFID tag attached to a metallic object,'' *IEEE Access*, vol. 9, pp. 111277–111292, 2021, doi: 10.1109/ACCESS.2021.3103177.

[4] F. Erman, A. Ismail, R. S. A. R. Abdullah, A. R. H. Alhawari, A. Shabaneh, and N. Mohamed, ''UHR RFID spilt-ring resonator-based tag antenna with photonic bandgap structure for metallic objects,'' *J. Fundam. Appl. Sci.*, vol. 9, no. 3S, pp. 630–636, 2017.

[5] A. Sharma, A. T. Hoang, F. Nekoogar, F. U. Dowla, and M. S. Reynolds, ''An electrically small, 16.7 m range, ISO18000-6C UHF RFID tag for industrial radiation sources,'' *IEEE J. Radio Freq. Identificat.*, vol. 2, no. 2, pp. 49–54, Jun. 2018, doi: 10.1109/jrfid.2018.2850316.

[6] Y. Yan, J. Ouyang, X. Ma, R. Wang, and A. Sharif, ''Circularly polarized RFID tag antenna design for metallic poles using characteristic mode analysis,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 7, pp. 1327–1331, Jul. 2019, doi: 10.1109/LAWP.2019.2915369.

[7] F. Erman, E. Hanafi, E.-H. Lim, W. A. W. M. Mahyiddin, S. W. Harun, H. Umair, R. Soboh, and M. Z. H. Makmud, ''Miniature compact folded dipole for metal mountable UHF RFID tag antenna,'' *Electronics*, vol. 8, no. 6, p. 713, 2019, doi: 10.3390/electronics8060713.

[8] C. Cho, H. Choo, and I. Park, ''Design of planar RFID tag antenna for metallic objects,'' *Electron. Lett.*, vol. 44, no. 3, pp. 175–177, 2008, doi: 10.1049/el:20083712.

[9] T.-W. Koo, D. Kim, J.-I. Ryu, H.-M. Seo, J.-G. Yook, and J.-C. Kim, ''Design of a label-typed UHF RFID tag antenna for metallic objects,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 1010–1014, 2011, doi: 10.1109/LAWP.2011.2166370.

[10] A. A. Babar, T. Bjorninen, V. A. Bhagavati, L. Sydanheimo, P. Kallio, and L. Ukkonen, ''Small and flexible metal mountable passive UHF RFID tag on high-dielectric polymer-ceramic composite substrate,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 1319–1322, 2012, doi: 10.1109/LAWP.2012.2227291.

[11] A. Hamani, M. C. E. Yagoub, T.-P. Vuong, and R. Touhami, ''A novel broadband antenna design for UHF RFID tags on metallic surface environments,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 91–94, 2017, doi: 10.1109/LAWP.2016.2557778.

[12] T. V. Koskinen, H. Rajagopalan, and Y. Rahmat-Samii, ''A thin multi-slotted dual patch UHF-band metal-mountable RFID tag antenna,'' *Microw. Opt. Technol. Lett.*, vol. 53, no. 1, pp. 40–47, Jan. 2011, doi: 10.1002/mop.25622.

[13] J. Zhang and Y. Long, ''A miniaturized via-patch loaded dual-layer RFID tag antenna for metallic object applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 1184–1187, 2013, doi: 10.1109/LAWP.2013.2281842.

[14] K.-H. Lin, S.-L. Chen, and R. Mittra, ''A looped-bowtie RFID tag antenna design for metallic objects,'' *IEEE Trans. Antennas Propag.*, vol. 61, no. 2, pp. 499–505, Feb. 2013, doi: 10.1109/TAP.2012.2224082.

[15] J. Zhang and Y. Long, ''A dual-layer broadband compact UHF RFID tag antenna for platform tolerant application,'' *IEEE Trans. Antennas Propag.*, vol. 61, no. 9, pp. 4447–4455, Sep. 2010, doi: 10.1109/TAP.2013.2269472.

[16] W.-H. Ng, E.-H. Lim, F.-L. Bong, and B.-K. Chung, ''Folded patch antenna with tunable inductive slots and stubs for UHF tag design,'' *IEEE Trans. Antennas Propag.*, vol. 66, no. 6, pp. 2799–2806, Jun. 2018, doi: 10.1109/TAP.2018.2821702.

[17] S.-R. Lee, E.-H. Lim, F.-L. Bong, and B.-K. Chung, ''Slotted folded patch antenna with double-T-slots for platform-insensitive UHF tag design,'' *IEEE Trans. Antennas Propag.*, vol. 67, no. 1, pp. 670–675, Jan. 2019, doi: 10.1109/TAP.2018.2878346.

[18] S.-R. Lee, E.-H. Lim, F.-L. Bong, and B.-K. Chung, ''High-efficient compact folded-patch antenna fed by T-shaped L-probe for on-metal UHF RFID tag design,'' *IEEE Trans. Antennas Propag.*, vol. 68, no. 1, pp. 152–160, Jan. 2020, doi: 10.1109/tap.2019.2938794.

[19] S.-R. Lee, W.-H. Ng, E.-H. Lim, F.-L. Bong, and B.-K. Chung, ''Compact magnetic loop antenna for omnidirectional on-metal UHF tag design,'' *IEEE Trans. Antennas Propag.*, vol. 68, no. 2, pp. 765–772, Feb. 2020, doi: 10.1109/TAP.2019.2943426.

[20] Y. H. Lee, E. H. Lim, F. L. Bong, and B. K. Chung, ''Compact folded C-shaped antenna for metal-mountable UHF RFID applications,'' *IEEE Trans. Antennas Propag.*, vol. 67, no. 2, pp. 765–773, Feb. 2019, doi: 10.1109/TAP.2018.2879853.

[21] W.-H. Ng, E.-H. Lim, F.-L. Bong, and B.-K. Chung, ''E-shaped folded-patch antenna with multiple tuning parameters for on-metal UHF RFID tag,'' *IEEE Trans. Antennas Propag.*, vol. 67, no. 1, pp. 56–64, Jan. 2019, doi: 10.1109/TAP.2018.2874795.

[22] W.-H. Ng, E.-H. Lim, F.-L. Bong, and B.-K. Chung, ''Compact planar inverted-S antenna with embedded tuning arm for on-metal UHF RFID tag design,'' *IEEE Trans. Antennas Propag.*, vol. 67, no. 6, pp. 4247–4252, Jun. 2019, doi: 10.1109/TAP.2019.2911191.

[23] K. Thirappa, E.-H. Lim, F.-L. Bong, and B.-K. Chung, ''Compact folded-patch with orthogonal tuning slots for on-metal tag design,'' *IEEE Trans. Antennas Propag.*, vol. 67, no. 9, pp. 5833–5842, Sep. 2019, doi: 10.1109/TAP.2019.2920324.

[24] L. Ukkonen, L. Sydänheimo, and M. Kivikoski, ''Effects of metallic plate size on the performance of microstrip patch-type tag antennas for passive RFID,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 4, pp. 410–413, 2005.

[25] P. Kamalvand, G. K. Pandey, M. K. Meshram, and A. Mallahzadeh, ''A single sided dual-antenna structure for UHF RFID tag applications,'' *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 25, no. 7, pp. 619–628, Sep. 2015, doi: 10.1002/mmce.20900.

[26] D. Kim and J. Yeo, ''Low-profile RFID tag antenna using compact AMC substrate for metallic objects,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 7, pp. 718–720, 2008, doi: 10.1109/LAWP.2008.2000813.

[27] Y. F. Lin, M. J. Chang, H. M. Chen, and B. Y. Lai, ''Gain enhancement of ground radiation antenna for RFID tag mounted on metallic plane,'' *IEEE Trans. Antennas Propag.*, vol. 64, no. 4, pp. 1193–1200, Apr. 2016, doi: 10.1109/TAP.2016.2526047.

[28] L. Benmessaoud, T.-P. Vuong, M. C. E. Yagoub, and R. Touhami, ''A novel 3-D tag with improved read range for UHF RFID localization applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 161–164, 2017, doi: 10.1109/LAWP.2016.2565378.

[29] J.-K. Xiao, ''Defected microstrip structure,'' in *Wiley Encyclopedia of Electrical and Electronics Engineering*. Hoboken, NJ, USA: Wiley, 2001, pp. 1–8.

[30] E.-S. Yang and H.-W. Son, ''Dual-polarised metal-mountable UHF RFID tag antenna for polarisation diversity,'' *Electron. Lett.*, vol. 52, no. 7, pp. 496–498, Apr. 2016, doi: 10.1049/el.2016.0076.

[31] F. Erman, E. Hanafi, E.-H. Lim, W. A. W. M. Mahyiddin, S. W. Harun, H. Umair, and R. Soboh, ''U-shaped inductively coupled feed UHF RFID tag antenna with DMS for metal objects,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 19, no. 6, pp. 907–911, Jun. 2020, doi: 10.1109/LAWP.2020.2981960.

[32] H.-D. Chen, C.-Y.-D. Sim, and S.-H. Kuo, ''Compact broadband dual coupling-feed circularly polarized RFID microstrip tag antenna mountable on metallic surface,'' *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 5571–5576, Dec. 2012, doi: 10.1109/TAP.2012.2210273.

[33] H.-D. Chen, S.-H. Kuo, C.-Y.-D. Sim, and C.-H. Tsai, ''Coupling-feed circularly polarized RFID tag antenna mountable on metallic surface,'' *IEEE Trans. Antennas Propag.*, vol. 60, no. 5, pp. 2166–2174, May 2012, doi: 10.1109/TAP.2012.2189702.

[34] H.-D. Chen, S.-H. Kuo, and J.-L. Jheng, ''Design of compact circularly polarized radio frequency identification tag antenna for metallic object application,'' *Microw. Opt. Technol. Lett.*, vol. 55, no. 7, pp. 1481–1485, Jul. 2013, doi: 10.1002/mop.27607.

[35] A. R. H. Alhawari, A. Ismail, A. S. A. Jalal, R. S. A. R. Abudullah, and M. F. A. Rasid, ''U-shaped inductively coupled feed radio frequency identification tag antennas for gain enhancement,'' *Electromagnetics*, vol. 34, no. 6, pp. 487–496, Aug. 2014, doi: 10.1080/02726343.2014.922767.

[36] (2016). *Higgs 4 RFID IC | Alien Technology*. Accessed: Oct. 8, 2018. [Online]. Available: https://www.alientechnology.com/products/ic/higgs-4/

[37] Y.-H. Niew, K.-Y. Lee, E.-H. Lim, F.-L. Bong, and B.-K. Chung, ''Miniature dipolar patch antenna with nonresonating ring for metal-insensitive UHF RFID tag design,'' *IEEE Trans. Antennas Propag.*, vol. 68, no. 3, pp. 2393–2398, Mar. 2020, doi: 10.1109/TAP.2019.2940521.

[38] A. Zhao, J. Zhang, and G. Y. Tian, ''Miniaturization of UHF RFID tag antenna sensors for corrosion characterization,'' *IEEE Sensors J.*, vol. 17, no. 23, pp. 7908–7916, Dec. 2017, doi: 10.1109/JSEN.2017.2751587.

[39] J. Zhang, G. Tian, A. Marindra, A. Sunny, and A. Zhao, ''A review of passive RFID tag antenna-based sensors and systems for structural health monitoring applications,'' *Sensors*, vol. 17, no. 2, p. 265, Jan. 2017.

[40] S. Genovesi and A. Monorchio, ''Low-profile three-arm folded dipole antenna for UHF band RFID tags mountable on metallic objects,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 1225–1228, 2010, doi: 10.1109/LAWP.2010.2103295.

[41] W. Zeng, J. Zhao, B. Ke, and Q. Wu, ''Compact microstrip RFID tag antenna mountable on metallic objects,'' *Proc. Eng.*, vol. 16, pp. 320–324, Jan. 2011, doi: 10.1016/j.proeng.2011.08.1090.

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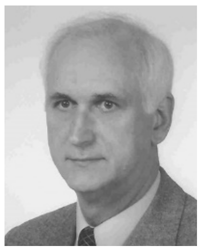

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