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Research Article

A Novel RFID Sensing System Using Enhanced Surface Wave Technology for Battery Exchange Stations

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This paper presents a novel radio-frequency identification (RFID) sensing system using enhanced surface wave technology for battery exchange stations (BESs) of electric motorcycles. Ultrahigh-frequency (UHF) RFID technology is utilized to automatically track and manage battery and user information without manual operation. The system includes readers, enhanced surface wave leaky cable antennas (ESWLCAs), coupling cable lines (CCLs), and small radiation patches (SRPs). The RFID sensing system overcomes the electromagnetic interference in the metallic environment of a BES cabinet. The developed RFID sensing system can effectively increase the efficiency of BES operation and promote the development of electric vehicles which solve the problem of air pollution as well as protect the environment of the Earth.

1. Introduction

Air pollution, especially CO, HC, and NO_x, generated by vehicles, such as motorcycles and cars, is a very serious problem in many countries. The quantity per year of polluted air exhausted by vehicles continues to reach record highs. Therefore, the replacement of traditional petroleum vehicles with electric vehicles is becoming a global trend. However, batteries and cost are the most important challenges for electric motorcycles and cars. A rechargeable battery is a low cost solution for electric vehicles. As far as the electric motorcycles are concerned, battery exchange stations (BESs) or rapid-charging batteries are required [1, 2].

Battery information is of critical importance for the management of the BES. A barcode attached to a battery is one approach to identify each battery in the BES; however, it consumes manpower and time to gather the battery information.

In recent years, radio-frequency identification (RFID) technology [3–15] has been widely used in different applications because of the contactless, long reading distance and multiread characteristics [16–26]. RFID applications include asset management, health care, logistics, security, and so on [27–38]. During long-distance RFID signal transmission, signal interference might occur and result in erroneous or missed readings. In the metallic environment of a BES, electromagnetic radiation is disturbed in a small space. The traditional antenna of an RFID reader radiates far-field electromagnetic waves and occupies a large area. These features are not suitable for a BES which has a closed and small space.

Leaky cable antennas (LCAs) [39–46] have attracted much attention in regard to communication applications. The conventional LCA is widely used for the mobile communications in subways and tunnels.

In this paper, a novel ultrahigh-frequency (UHF) RFID sensing system integrating a flexible enhanced surface wave leaky cable antenna (ESWLCA) with a coupling cable line (CCL) and a small radiation patch (SRP) is proposed incorporating the enhanced surface wave technology in order to overcome the narrow metallic environment of the BES and to lower the manufacturing cost. The ESWLCA has been successfully implemented in a UHF RFID sensing system for the BESs of electric motorcycles.

Figure 1: BES.

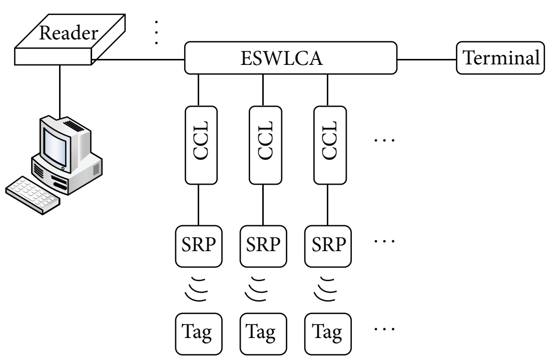

Figure 2: System structure of RFID sensing system.

Figure 3: RFID sensing system with ESWLCA, CCL, and SRP for BES.

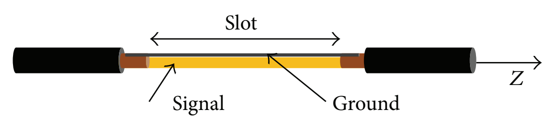

Figure 4: Structure of ESWLCA.

2. System Structure

Rechargeable batteries for electric motorcycles are installed in a BES, as shown in Figure 1. A BES is a closed metallic cabinet, in which a large number of dense metal brackets and wires disturb far-field electromagnetic radiation. In addition, the electromagnetic noise reflected by the metallic BES cabinet might cause the saturation and malfunction of the receiver of a reader.

The system structure of the proposed RFID sensing system is shown in Figure 2. The system includes readers, ESWLCAs, CCLs, SRPs, and tags. The ESWLCA transmits the enhanced surface wave through the CCL to the SRP which is close to the tag. The SRP at the end of the CCL radiates the electromagnetic wave to activate the RFID tag attached to the battery. The physical picture of the RFID sensing system with an ESWLCA, a CCL, and an SRP for the BES is shown in Figure 3. The ESWLCA has several advantages, such as flexibility, a slim form factor, and low radiation, to avoid interference in the metal-rich environment and to be easily placed in suitable positions for detecting tags. Figure 4 shows the structure of the ESWLCA. There is an open slot on the ESWLCA.

The operation of the system is described as follows. First, one of the ESWLCA ports is connected to the output port of the UHF reader and the other port is terminated with 50 ohms. When the reader turns on the RF power, the RF signal will be fed into the ESWLCA. Some signals will radiate into the air from the slot aperture and some will flow through the cable surface from the slot aperture to produce surface waves along the cable.

Then, at suitable positions of the ESWLCA, the CCL will be connected to the ESWLCA by wiring, so that some surface waves will flow into the CCL from the ESWLCA.

Finally, the surface waves on the CCL will be fed into the port of the radiation patch and the RF energy will be transferred to the RFID tag. As the RF energy is higher than the threshold energy of the RFID tag, communication between the reader and the tag will happen.

3. System Theorem

An LCA has the functions of transmission and radiation of electromagnetic waves. When the electromagnetic waves pass the open slot of the LCA, some electromagnetic waves will

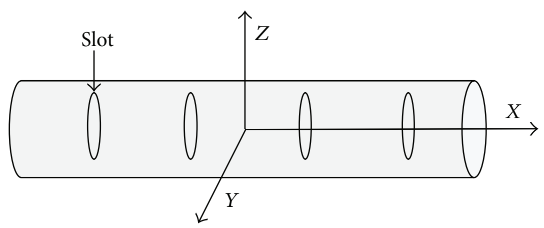

Figure 5: Conventional LCA.

leak through the open slot. The LCA has the advantages of wide operation frequency band, large sensing range, easy deployment, and low cost. Figure 5 shows the conventional LCA. The electric field within the area of the radius r of the LCA is determined by

$$E(r,\varphi,x_d) = M(\eta,r,\varphi)\,Z(x_d)\,e^{j\beta x_d}e^{-\alpha x_d}, \quad (1)$$

where φ is the current density, x_d is the distance along the x-axis, η is the magnetic flux density, β is the propagation constant of the electromagnetic wave, α is the attenuation constant of the electromagnetic wave, and $M(\eta,r,\varphi)$ represents the integration of electromagnetic field for specific boundaries.

The refection coefficient Γ, the voltage $U(x_d)$, and the current $I(x_d)$ along the x-axis can be represented, respectively, by

$$\Gamma(x_d) = \frac{Z_L - Z_0}{Z_L + Z_0}e^{-j2\beta x_d},$$
$$U(x_d) = U_{i0}e^{j\beta x_d}\left[1+\Gamma(x_d)\right], \quad (2)$$
$$I(x_d) = \frac{U_{i0}e^{j\beta x_d}}{Z_0}\left[1-\Gamma(x_d)\right],$$

where U_{i0} is the amplitude of the incident wave at $x_d = 0$, which is the results of the addition of the characteristic impedance Z_0 and load impedance Z_L.

The theorems of the impedance, voltage, and current of the ESWLCA follow those of the conventional LCA. The ESWLCA along the z-axis does not need to consider the radiation of the electromagnetic waves. The surface electric field of the ESWLCA, $E_p(r,\phi,z)$, is a simplified periodic function of Z, as follows:

$$E(r,\phi,z) = E_p(r,\phi,z)\,e^{-jk_z z}, \quad (3)$$

$$-mf_1 < f < -mf_2, \quad m < 0, \quad (4)$$

$$f_1 = \frac{c}{P\left(\sqrt{\varepsilon_r}+1\right)}, \quad (5)$$

$$f_2 = \frac{c}{P\left(\sqrt{\varepsilon_r}-1\right)}, \quad (6)$$

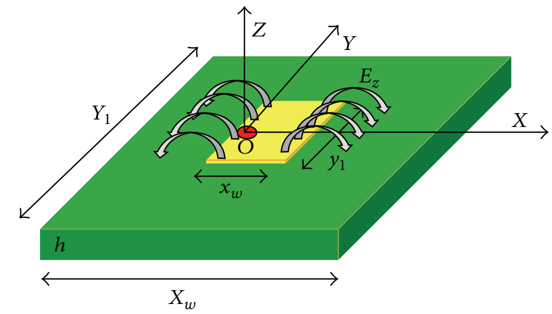

Figure 6: SRP structure.

where c is the velocity of light in free space, ε_r is the dielectric constant, and P is the period of slots. If the frequency conditions (4)–(6) are satisfied, the leaky cable produces radiation waves. Otherwise, the leaky cable generates surface waves. The suitable length of P and slot size will optimize the composition of radiation and surface waves for the desired applications.

Figure 6 shows the SRP structure. The substrate material is the FR4 circuit board with the dielectric constant ε_r of 4.4 and thickness h of 1 mm. The dimensions are $X_w = 50$ mm, $Y_l = 50$ mm, $x_w = 10$ mm, and $y_l = 20$ mm. The signals are fed into the SRP at position O, as indicated in Figure 6.

The electric field as a function of the position is as follows:

$$E_z = E_o\cos\left(\frac{\pi x}{x}\right). \quad (7)$$

The magnetic flow density on the patch of the SRP is

$$J = -e_n \cdot e_z \cdot E_z. \quad (8)$$

The minimum electric field required to activate the tag, E_r, is derived as follows:

$$E_r = \left[P_r\cdot\left(4\cdot\frac{\pi}{\lambda^2}\right)\cdot\left(\frac{377}{G_r}\right)\cdot\left(\frac{1}{\tau}\right)\right]^{0.5}, \quad (9)$$

$$S = \frac{G_t P_t}{4\pi R^2} = \frac{E^2}{377}, \quad (10)$$

$$\tau = \frac{4\cdot R_{\text{ic}}\cdot R_{\text{ant}}}{\left|Z_{\text{ant}}+Z_{\text{ic}}\right|^2}, \quad (11)$$

where P_r is the received power of the tag at a distance from the antenna of the reader, λ is the operation wavelength, G_r is the tag antenna gain, S is the electric field obtained per unit area, G_t is the reader antenna gain, P_t is the output power of the reader, R is the distance from reader antenna, E is the electric field, τ is the power transfer efficiency from the antenna of the RFID tag to the radio-frequency integrated circuit (RFIC) of the RFID tag, R_{ic} is the real RFIC impedance, R_{ant} is the real antenna impedance, Z_{ant} is the antenna impedance, and Z_{ic} is the RFIC impedance.

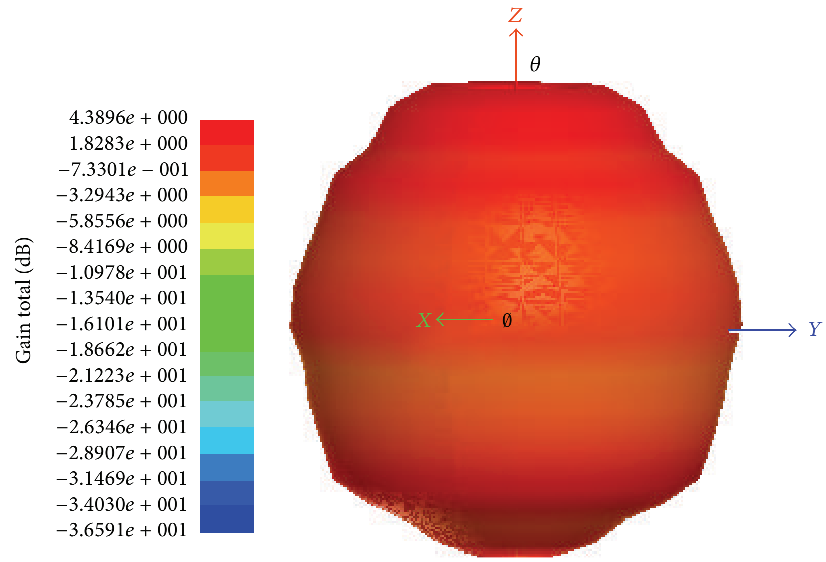

Figure 7: 3D electromagnetic model of ESWLCA.

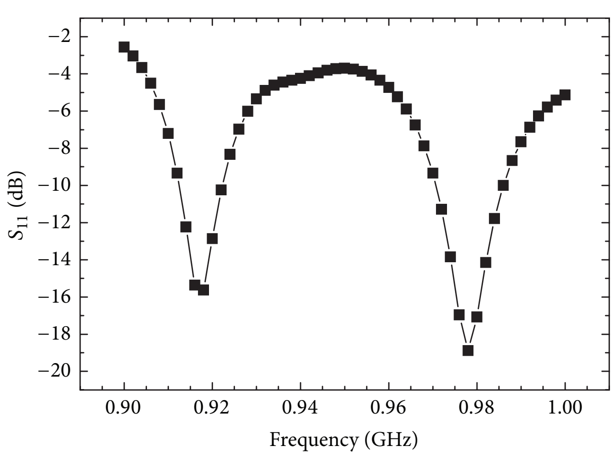

Figure 8: S_{11} return loss characteristics of ESWLCA.

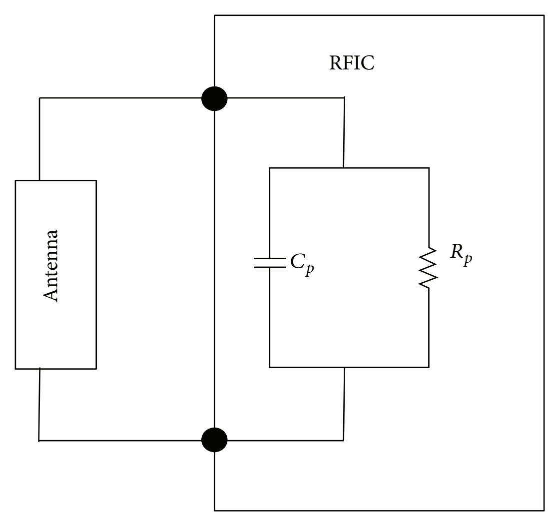

Figure 9: RFIC equivalent circuit.

4. System Design

The design of the RFID sensing system is based on a full-wave electromagnetic simulator, Ansoft HFSS. The system is designed to be operated at a UHF frequency band of 860–960 MHz. The output power of the RFID reader is 30 dBm. According to (9), the minimum electric field required to activate the RFID tag is 4.8 V/m. Figure 7 shows the three-dimensional (3D) electromagnetic model of the ESWLCA. Figure 8 shows the return loss characteristics of the ESWLCA.

Figure 9 is the equivalent circuit of the Alien Higgs-3 RFIC, in which the parallel capacitance C_p is 1.3 pF and the parallel resistance R_p is 1.5 kohms. The RFIC impedance Z_{ic} can be determined by

$$Z_{ic} = \frac{R_p}{1+\omega^2 C_p^2 R_p^2} - \frac{j\omega C_p R_p^2}{1+\omega^2 C_p^2 R_p^2}. \tag{12}$$

The impedance of the Higgs-3 RFIC at 920 MHz is $31 - j216$ ohms.

The back-radiation power of the RFID tag of the battery, P_{back}, is

$$P_{back} = \frac{P_{th}}{\tau} \cdot G_r \cdot \left|\frac{Z_{ic} - Z_{ant}}{Z_{ic} + Z_{ant}}\right|^2, \tag{13}$$

where P_{th} is the threshold power to activate the RFIC.

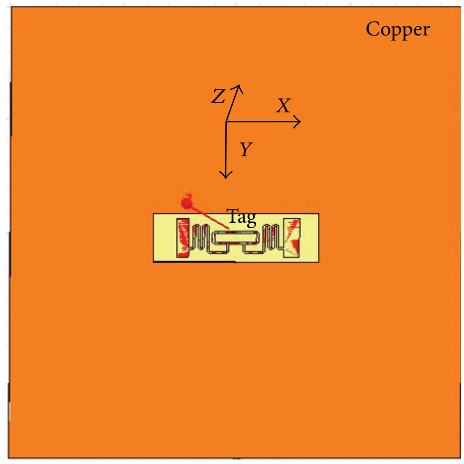

FIGURE 10: Environment of RFID tag of battery.

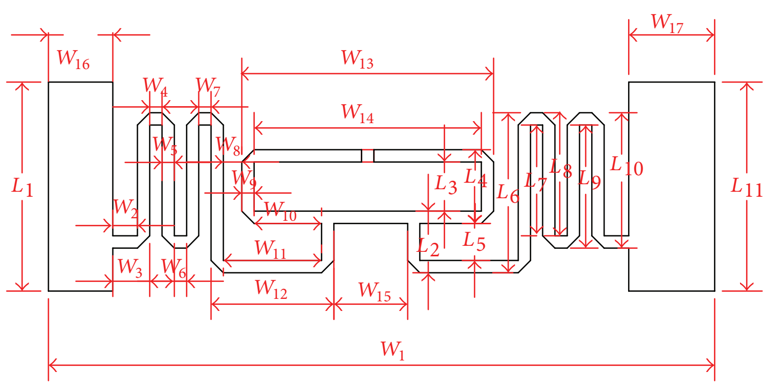

FIGURE 11: Design diagram of RFID tag.

The radar cross-section of the antenna of the tag, σ, is

$$\begin{aligned}\sigma &= \frac{P_{\text{back}}}{(P_t \cdot G_t)/4\pi R^2} \\ &= \left(\left(\left((P_t \cdot G_t)/4\pi R^2\right) \cdot \lambda/4\pi \cdot G_r\right)\right. \\ &\qquad \left. \cdot G_r \cdot \left|(Z_{\text{ic}} - Z_{\text{ant}})/(Z_{\text{ic}} + Z_{\text{ant}})\right|^2\right) \\ &\quad \times \left((P_t \cdot G_t)/4\pi R^2\right)^{-1}.\end{aligned} \tag{14}$$

5. Results and Discussion

Figure 10 shows the environment of the RFID tag of the battery. A copper metal object with the size of 200 × 200 × 1 mm^3 is 2 mm below the RFID tag.

Figure 11 shows the design diagram of the RFID tag with the dimensions of L_1 = 17 mm, L_2 = 5 mm, L_3 = 4 mm, L_4 = 6 mm, L_5 = 3 mm, L_6 = 13 mm, L_7 = 9 mm, L_8 = 10 mm, L_9 = 10 mm, L_{10} = 11 mm, L_{11} = 17 mm, W_1 = 54.25 mm, W_2 = 2 mm, W_3 = 3 mm, W_4 = 1 mm, W_5 = 1 mm, W_6 = 1 mm, W_7 = 1 mm, W_8 = 1.5 mm, W_9 = 1 mm, W_{10} = 5.5 mm, W_{11} = 8 mm, W_{12} = 10 mm, W_{13} = 20.5 mm, W_{14} = 18.5 mm, W_{15} = 6 mm, W_{16} = 5.25 mm, and W_{17} = 7 mm.

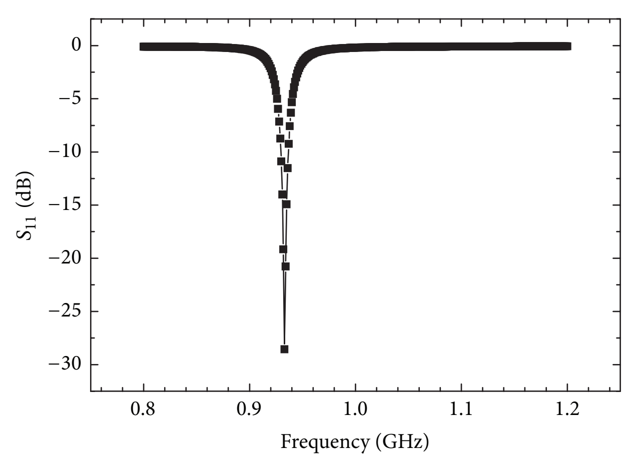

FIGURE 12: S_{11} return loss characteristics of RFID tag of battery.

Figure 12 shows the S_{11} return loss characteristics of the RFID tag of the battery. The tag is suitable for objects with metal surfaces. The S_{11} is −28.6 dB at 930 MHz. The antenna impedance is $Z_{\text{ant}} = 19 + j186$ ohms. Figure 13 shows the 3D pattern of the RFID tag of the battery. The Alien Higgs-3 turn on power sensitivity is −18 dBm.

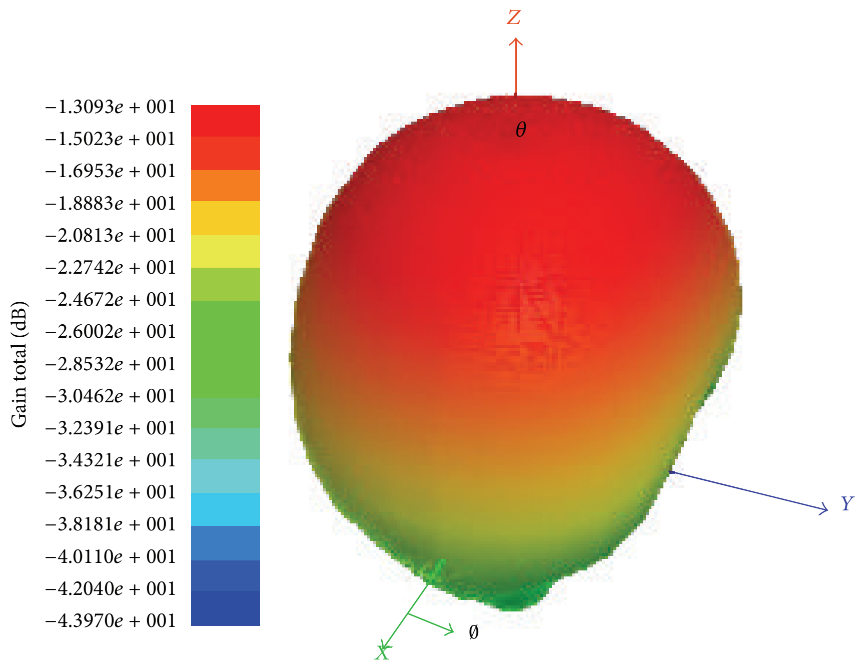

Figure 13: 3D pattern of RFID tag of battery.

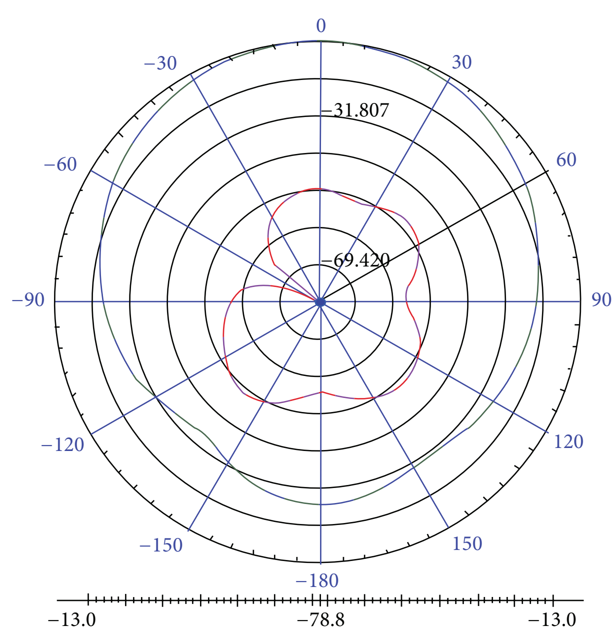

Figure 14: 2D pattern of RFID tag of battery.

Figure 14 shows the two-dimensional (2D) pattern of the RFID tag of the battery. The maximum gain of the antenna of the RFID tag of the battery G_r is −13 dBm. According to (11), the power transfer efficiency from the antenna of the RFID tag of the battery to the Higgs-3 RFIC is $\tau = 0.6$.

The surface electric field distribution of the ESWLCA is analyzed as the RFID reader feeds 30 dBm output power into the ESWLCA. Figure 15 shows the surface electric field distribution of the ESWLCA at the location of 1 mm from the ESWLCA. The maximum electric field E_{max} is greater than 100 V/m and the minimum electric field E_{min} is 80 V/m. The RFID tag requires the minimum electric field of 4.8 V/m for operation.

Figures 16, 17, and 18 illustrate the electric field distribution at a distance H from the ESWLCA. Figure 16 shows the

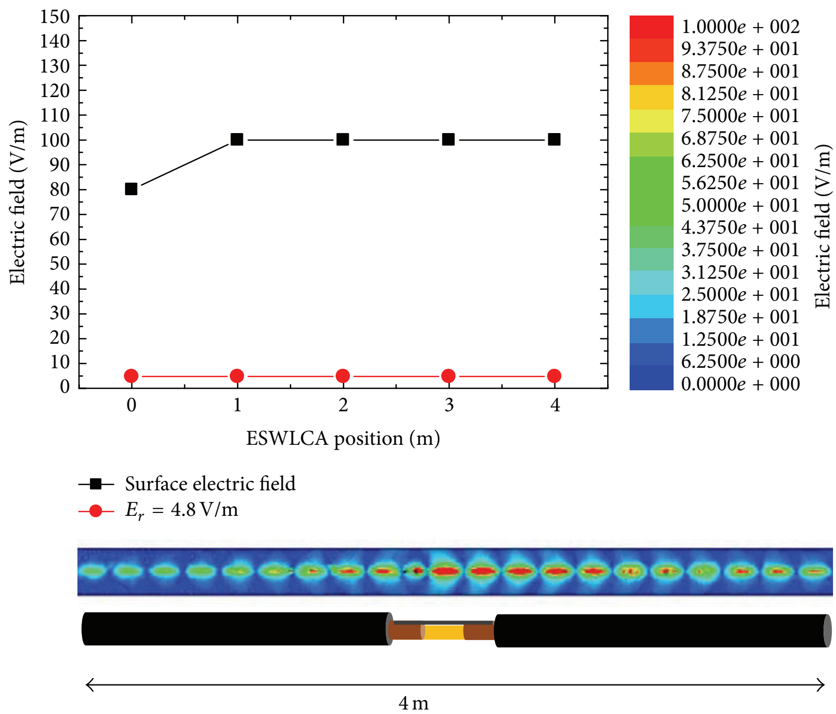

FIGURE 15: Surface electric field distribution of ESWLCA.

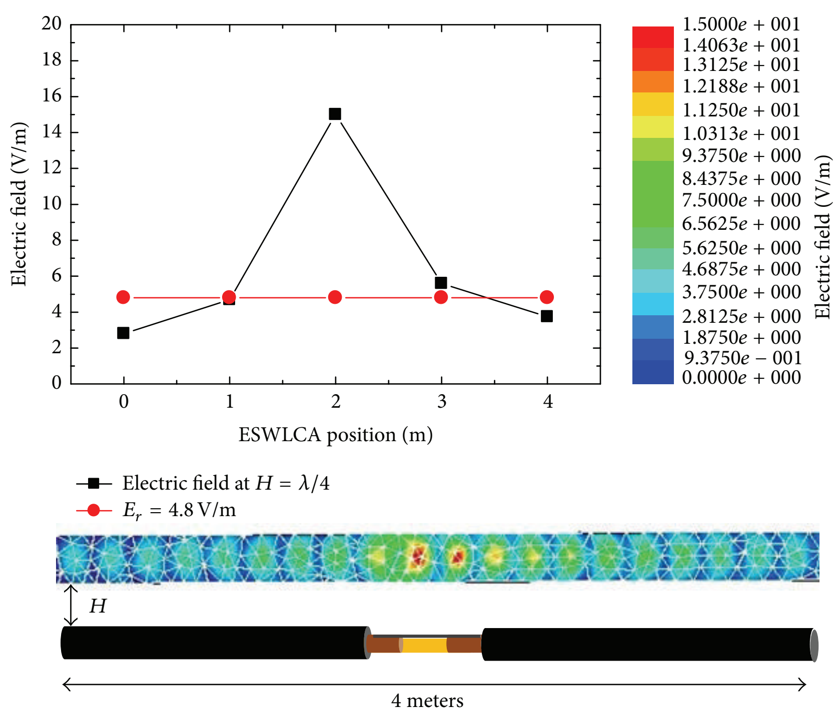

FIGURE 16: Electric field distribution of ESWLCA at $H = \lambda/4$.

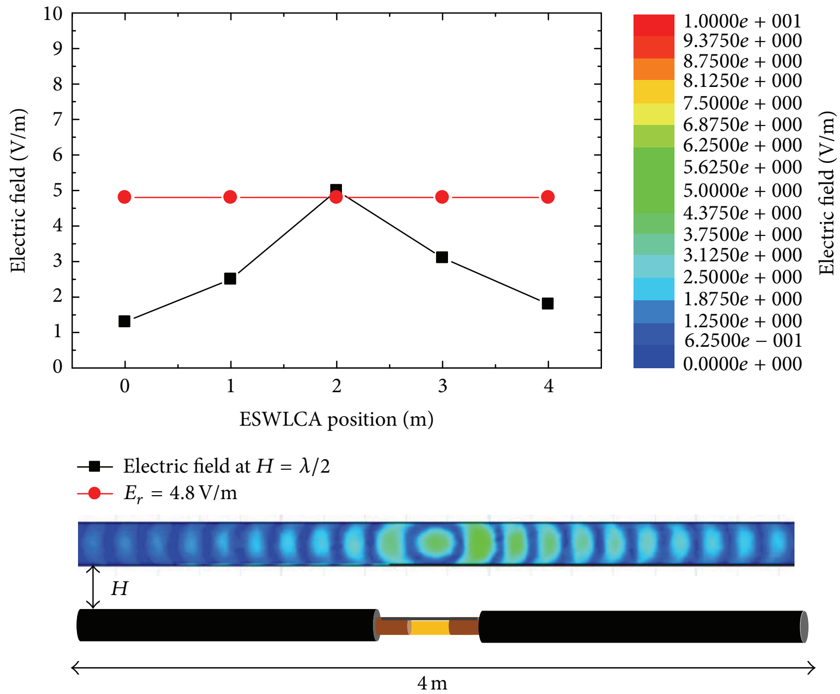

Figure 17: Electric field distribution of ESWLCA at $H = \lambda/2$.

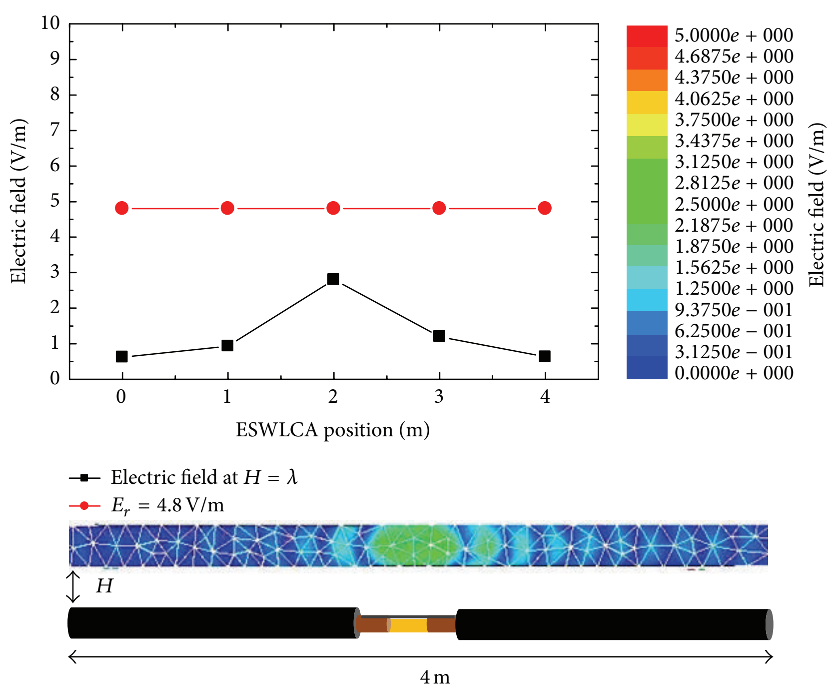

Figure 18: Electric field distribution of ESWLCA at $H = \lambda$.

electric field distribution of the ESWLCA at a quarter of a wavelength from the ESWLCA ($H = \lambda/4$). The maximum electric field E_{max} is 15 V/m and the minimum electric field E_{min} is 2.8 V/m.

Figure 17 shows the electric field distribution of the ESWLCA at half a wavelength from the ESWLCA ($H = \lambda/2$). The maximum electric field E_{max} is 5 V/m and the minimum electric field E_{min} is 1.3 V/m.

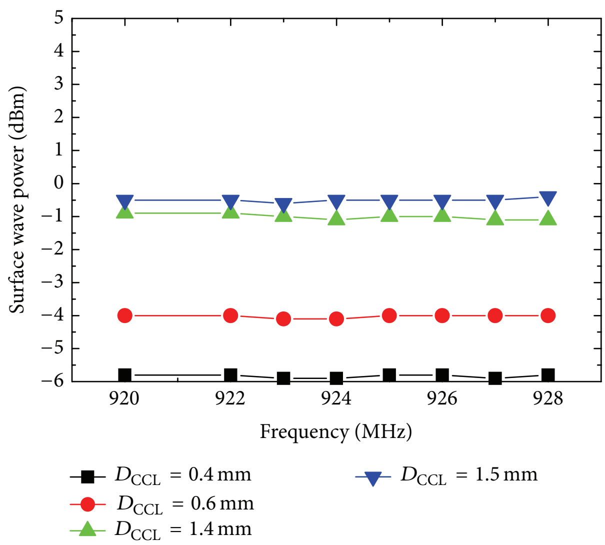

FIGURE 19: Measurement characteristics of surface wave power.

FIGURE 20: Completed RFID sensing system for BES.

Figure 18 shows the electric field distribution of the ESWLCA at a full wavelength from the ESWLCA ($H = \lambda$). The maximum electric field E_{max} is 2.8 V/m and the minimum electric field E_{min} is 0.62 V/m.

Figure 19 shows the measurement characteristics of the surface wave power as a function of the diameter of the CCL (D_{CCL}) at a source power of 0 dBm. The surface wave power increases with the increasing D_{CCL}.

Figure 20 shows the completed sensing system for the BES. The ESWLCA is suitable for the BES which is a small space in a metallic cabinet. The leaky wave is radiated from the open slot in the transmission line of the ESWLCA. The electromagnetic wave propagates along the surface of the transmission line and transmits to the SRP through the bendable CCL. The CCL can still easily transmit the electromagnetic wave even in a closed metallic environment where the barcode approach is not applicable.

6. Conclusion

The state-of-the-art UHF RFID sensing system for the BES of electric motorcycles has been developed. The ESWLCA, CCL, and SRP are designed to overcome the metallic environment in a BES cabinet. The RFID sensing system demonstrates excellent characteristics and shows great potential for the modern BES of electric vehicles.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

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