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Radiation Beam Pattern Control of UHF RFID Tag Antenna Design for Automotive License Plates †

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Abstract: This paper presents a design of a radio frequency identification (RFID) tag antenna in the ultra-high-frequency (UHF) range, which is applicable to a vehicular license plate attached to a vehicle bumper. The main goals are to first improve the identification ratio by controlling the radiation beam pattern and, second, to control the beam direction. Since every vehicle has a license plate, the available plate structure is used to design the antenna. The shape of the tag is rectangular and has a dimension of 525 mm × 116 mm, which is smaller than the typical size of standard plates, 540 mm × 120 mm, used in Europe and Korea. The fabricated tag antenna, the license plate, and the vehicular bumper are fixed by volt and nut. For vehicle tracking and identification, RFID readers are deployed on the road side. For efficient identification, a long distance passive UHF RFID license plate with a patch antenna is proposed to provide not only line-of-sight identification but also left and right beams. Unlike the general UHF tag antennas, in this paper, the patch antenna is designed to attach to the metal part of the car, the license plate holder. The beam patterns of the RFID tag antenna can be controlled by the patch antenna parameter values. The simulation result demonstrates that the proposed UHF RFID tag antenna has a beam radiation pattern as required at 920 MHz. In addition, the estimated read range of the proposed plate meets the requirement of RFID systems.

Keywords: automotive; license plate tag; UHF RFID tag; long-range RFID tag; radiation pattern

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1. Introduction

With the continuous development of radio frequency identification (RFID) tags, RFID wireless communication is used in various applications to find out information about an object. It is used in the pharmaceutical, automobile, iron and steel, logistics, and alcoholic beverage industries. It has been widely used and applied to the transparency of the distribution process, and it is used in various fields, such as transportation, education and culture, environment, and medicine. RFID systems of various frequency bands are used [1–3].

RFID uses different frequencies according to its application. There are low-frequency (LF), high-frequency (HF) and ultra-high-frequency (UHF) RFID tag antennas. RFID applications are numerous, such as tagging animals, asset tracking, electronic passports, smart cards, shop security, health care, transport management systems, and object logistics. RFID tags are also classified into passive and active tags. Passive tags have no battery and collect energy from nearby RFID readers by interrogating radio waves. Passive tags have smaller memory capacities as compared to active tags due to the absence of a power source. As a result, these tags are much less complex and are less expensive to manufacture. Active tags are RFID tags with onboard transmitters and their own power source, usually a battery. The battery is used to power on the microchip so as to send a signal to a reader. They broadcast signals to RFID readers and power electronic chips. These tags have comparatively larger memories and are much more complex than their passive counterparts. Active tags are able to transmit data and communicate with low-powered RFID readers. Another advantage of using active tags is transmitting signals over relatively long distances, 100 m and above. The complexity, power source, and larger memories make active tags more expensive than passive tags [4–8].

RFID standards specify the operating frequency for the reader. The ISO (International Organization for Standardization) is a worldwide union of national standardization institutions with numerous committees and working groups developing RFID standards.

The ISO 18000 series standard is an international standard that states the air interface for the different RFID frequencies in use around the globe as outlined below. The band below 135 kHz is defined by ISO 18000-2, 13.56 MHz is defined by ISO 18000-3 for the HF band, ISO 18000-7 for the 433 MHz band, ISO 18000-6 for the 840–960 MHz UHF band, and the 2.45 GHz band is specified by ISO 18000-4 [4–7]. Recently, ISO 18000-6C and -6D were added to the ISO standard and 18000-61~18000-64 were specified in the ISO 18000-6:2013 document [9].

In Korea, according to the regulations that changed in 2009, the UHF band is used at 4 W in the 917–920.8 MHz band and 200 mW effective isotropic radiated power (EIRP) in the 920.8–923.5 MHz band. The high-frequency (HF) band utilizes the coupling of the magnetic near field, whereas the UHF band (840 to 960 MHz) uses the electromagnetic wave in the far field; then, backscattering information is conveyed and used for various applications. The most-used RFID frequency bands are UHF RFID from 902 to 928 MHz in North America, from 865.5 to 867.5 MHz in Europe, from 917 to 923.5 in Korea, and from 950 to 956 MHz in Japan, and the wireless bands are at 2.4 GHz and 5.8 GHz.

One of the fields of application is transportation management systems. In recent years, RFID-based license plates have received much attention for use in vehicle identification. Automatic management of an RFID system is more time and cost effective compared to manual management by humans. Many studies of RFID systems for automotive applications have been conducted, and studies on RFID tag position, which is to be attached to the vehicle, have also been considered and studied regarding the long readable range and identification ratio improvement [10–15]. However, the performance of RFID tag antennas is affected depending on where it is attached on the vehicle, such as the conductor of a car body, the bumper, and window glass, which causes the impedance to change. The impedance change affects the tag antenna performance, such as the reading range and identification ratio. Therefore, the tag antenna design needs to consider the surrounding environment where the tag antenna is installed, as well as the part of the car where it is to be attached. A microstrip patch tag antenna [16], a microstrip dipole UHF tag antenna, and a loop-type tag antenna [17,18] have all been placed behind non-metal plates. Since they have been designed for non-metal license plates, the tag antenna installed behind a metal license plate will not operate properly as a tag antenna. A slot-type antenna is proposed to solve this problem with metallic objects [19,20]. An e-plate antenna design to serve as an RFID tag was reported in [21,22], but this method used an active RFID system, where the constraint is the cost of the tag. In [23], a very small RFID antenna was designed for a seal-bolt shape, but, still, the reading distance was limited to 3.5 m, because an antenna, an application-specific integrated circuit (ASIC), and a battery are included in active RFID tags, which was embedded in the e-plate. The proposed tag antenna in [24] is installed as a tag inside a car's side-view mirror for optimum reading. The authors of [25] use an RFID tag as an electronic license plate to localize the vehicles.

This article presents the design of a passive ultra-high-frequency (UHF) radio frequency identification (RFID) tag antenna that is applied to the vehicular license plate and attached to the vehicle bumper. To improve the identification ratio and time, the tag antenna should have a frontal beam pattern. Therefore, a plate-sized passive UHF RFID tag antenna, 525 mm × 116 mm, was designed for the license plate, which faces the bumper rather than the front. The tag has a larger back-lobe radiation pattern since the front side of the tag faces toward the bumper side, which protects the tag antenna from any mechanical damage and dust when the automobile is running. Our UHF RFID tag antenna is closely matched with the conjugate of the Higgs 3 RFID IC chip manufactured by Alien Tech, and the beam pattern can be controlled by a T-matching structure. The antenna was designed using the electromagnetic simulation tool CST. An electro-conductive silver paste is used to attach the RFID chip on the designed antenna. The antenna gain can increase because the license plate is a conductor (made of copper) and is operated as an antenna. Thus, the reading distance range can become longer than that of conventional commercial tag antennas. Furthermore, it has the advantage of an improved identification ratio by controlling the radiation beam pattern in a way that the vehicular license plate tag antenna can easily be detected by readers installed on the road side or toll gates as the vehicle passes through it.

The structure of this article is organized as follows: Section 2 presents our RFID tag antenna design process. Section 3 presents the long-range UHF RFID tag antenna design and results. Finally, Section 4 concludes our work.

2. RFID Tag Antenna Design Process

To design a UHF RFID tag antenna, the impedance (Z_a) of a tag antenna should be the complex conjugate of the impedance of the RFID integrated circuit (IC) of the tag (Z_C). Thus, $Z_a = Z_C{}^*$ and is separated into real and imaginary parts. We have designated the real part $R_a = R_C$ and the imaginary part $X_a = -X_C$. Since the imaginary part of the IC chip impedance is about $-120\,j$, to achieve the high inductive impedance of the tag antenna, the T-matching structure is used.

The total power received by the tag is defined by the Friss Equation (1) [3,26,27]. The parameters involved in the transmitting and receiving system are

$$P_r = P_t \left(\frac{\lambda}{4\pi R} \right)^2 G_t G_r \quad (1)$$

where the parameters are P_t (transmitted power), G_t (transmission antenna gain), P_r (received power), and G_r (gain of tag antenna), and the wavelengths λ and R are the distances between the transmitting and receiving tag antennas.

The read range is calculated with Equations (2) and (3). Equation (2) shows the matching coefficient τ, which determines how well the impedance of a tag antenna and an IC chip are matched to the chip. The reading range is calculated with Equation (3) [3,28]. The threshold power P_{th} is provided by the manufacturer.

$$\tau = \frac{4R_a^2}{|Z_a + Z_C|^2} \quad (2)$$

$$R = \frac{\lambda}{4\pi} \sqrt{\frac{P_t G_t G_r}{P_{th}} \tau} \quad 0 \leq \tau \leq 1, \quad (3)$$

Thus, P_{th} (data sheet) can be expressed in watt as Equation (4) [8]:

$$P_{th} = 10^{\frac{-20.5}{10}} = 8.913\,uW \quad (4)$$

3. Design of UHF RFID Tag Antenna for a License Plate

Figure 1 shows the design structure of the proposed automobile plate with a patch antenna considered for a vehicle bumper made out of plastic. It is composed of copper metal plate similar to a license plate and plate holder, volts and nuts, and a part of the vehicle bumper. The bumper is made of plastic with a dielectric constant of $\varepsilon_r = 3.5$ and loss tangent = 0.015. When general UHF tag antennas are attached to a metal, the reading distance drastically decreases because the impedance of the tag antenna is changed. In this paper, the patch antenna is designed to attach to a metal part of the car, the license plate holder. The antenna is closely matched with the conjugate of the Higgs 3 RFID IC chip

(Z_C = 11.7 − j132 Ω). The T-matching method was used to match the input impedance of the tag antenna to the conjugate of the impedance of the RFID chip.

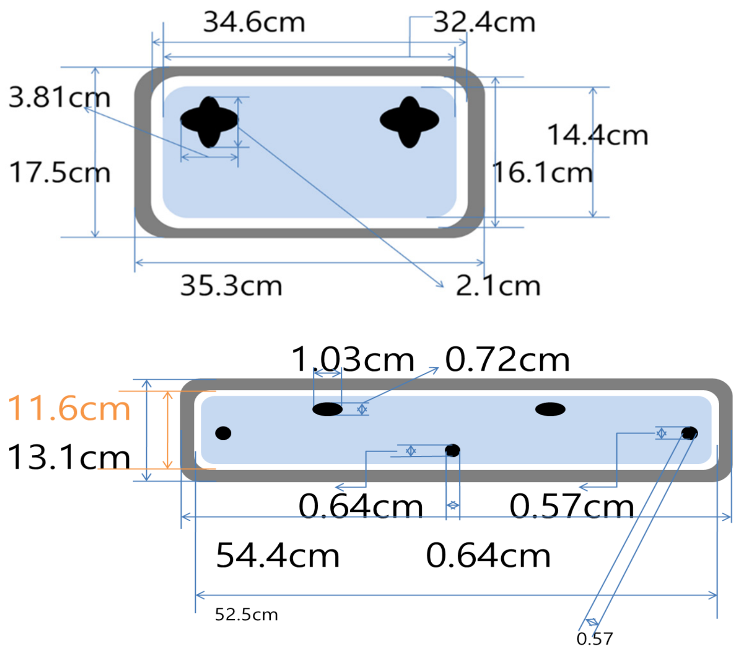


Figure 1. Size of a typical license plate holder. [26].

According to the Korean license plate standard, there are two commonly used plates. One is the size of 335 mm × 115 mm and the other is 520 mm × 110 mm as shown in Figure 1. The standard plate size of 520 mm × 110 mm is used in our design.

The proposed antenna was simulated using CST simulation software; here, a discrete port was used to represent the RFID tag terminal. There is a gap of 2 mm between the two edges of the discrete port. The simulated results of the proposed antenna are expected to give acceptable performances at a center frequency of a 920 MHz band for UHF RFID application.

Figures 2 and 3 show the structure of the proposed automobile plate for a plastic vehicle bumper and tag antenna. It is composed of a metal plate similar to a license plate and plate holder, bolts and nuts, and a part of the vehicle bumper. The bumper is made out of plastic with a dielectric constant of ε_r = 3.2. In this design, the tag antenna is designed to attach to a metal part of the license plate holder. Figure 2 shows the proposed tag antenna attached next to the standard plate holder, which is shown in Figure 1. The loop-shape tag antenna facing the bumper is placed on the side of the license plate to have a frontal pattern. The tag antenna has a rectangular shape with a dimension of 130 mm× 50 mm and is attached next to the license plate holder as shown in Figure 2. The tag facing the bumper side in Figure 2 is enlarged and drawn in Figure 3 with the detailed parameters of the antenna. This tag antenna uses the back-lobe pattern to be recognized by readers since it faces the bumper side.

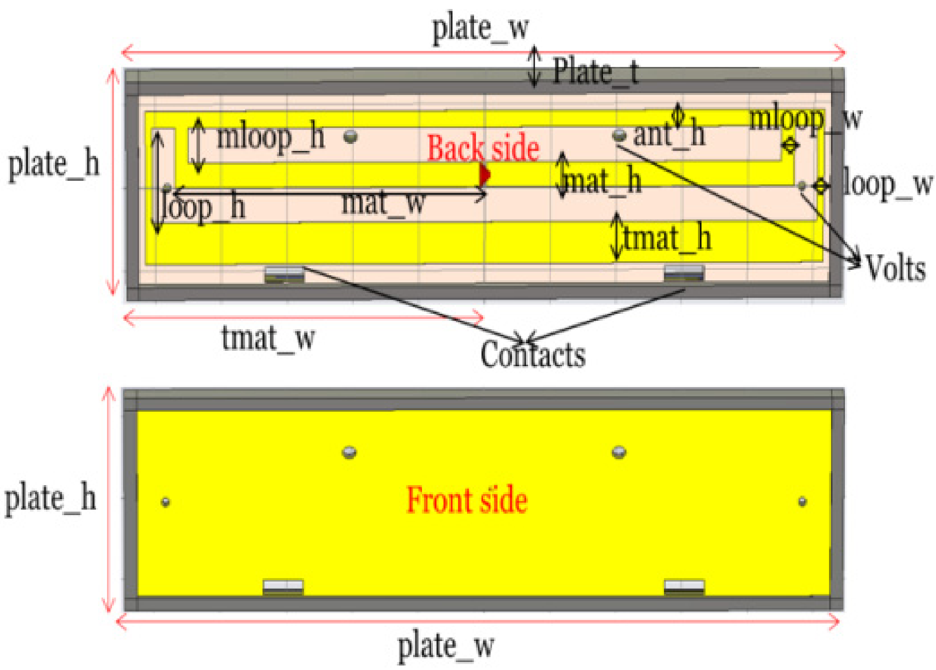


Figure 2. Parameters and design structure of the RFID tag antenna without bumper.

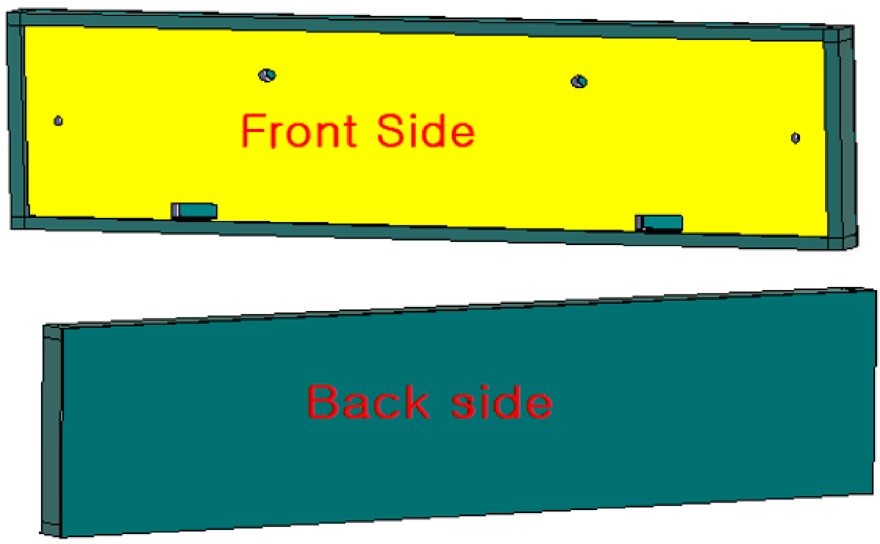


Figure 3. Front and back side of license plate RFID tag antenna with bumper.

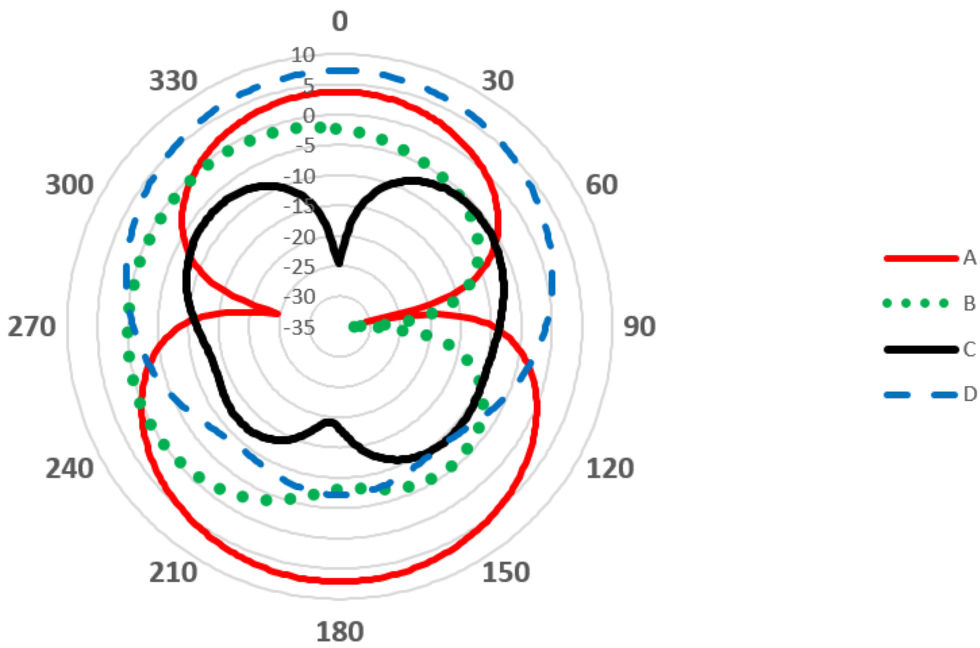
The proposed tag antenna is designed to operate at 920 MHz. The geometric parameters defined in Figure 2 were designed and optimized by parameter sweeping. The results of the optimized values are shown in Table 1.

Table 1. Optimized parameter values.

Para.	Dimension (mm)	Parameter	Dimension (mm)
Plate_w	525	Mat_w	235
Tmat_h	25	mat_h	15
Ant_h	10	Loop_w	5
Tmat_w	257.5	Mloop_w	10
Plate_h	116		

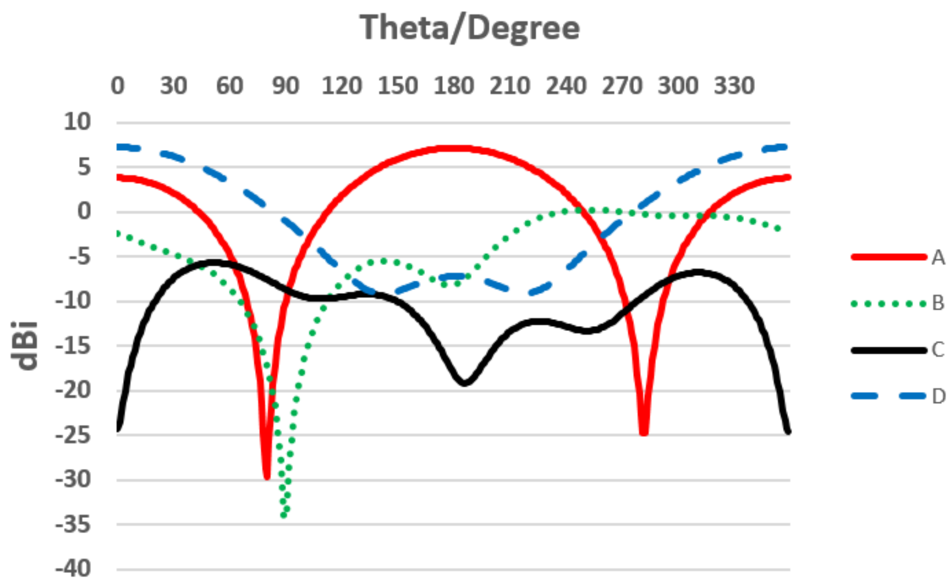
The signal radiating toward the bumper cannot be identified by the reader, only the signal radiating toward the front side of the car is readable by the reader. So, we need a strong signal radiating toward the front. The 0 degrees in Figure 3 indicates the back direction that the tag antenna and the reader antenna stand, which is opposite to each other. Moreover, the 180 degrees indicates the front direction with respect to the above back direction. Since the readers are deployed along the road side, we can see that there is a strong signal radiating toward the right and left directions. Since the readers are deployed along the road side, the reader antenna is facing the backside of the tag antenna. Therefore, the beam pattern is carefully controlled and managed. This is achieved by controlling the parameter values of the patch antenna.

By controlling the antenna parameter value, the radiation pattern can be controlled in any direction according to the specific application. The parameters are mat_w, mloop_w, and mat_h. Upon changing one of the parameters, the center frequency and the gain will change slightly. The parameters are modified to adjust the center frequency at 920 MHz. Figure 4 shows polar and rectangular radiation patterns at the selected degrees of 0 degree, 60 degrees, 180 degrees, 210 degrees and 270 degrees as shown in Table 2. We can see that there is a strong signal radiating in every radiating angle. We simulate and obtain a good radiation pattern shifting its main beam direction as the main parameter value changes. This is achieved by controlling the parameter values of the tag antenna. The radiation pattern meets the requirement for the deployment of RFID readers along the road. For example, if the reader is placed on the roadside, the beam emanating from the tag antenna will allow the license plate and the reader to communicate with each other very well.



(**a**) Polar Plot

Figure 4. *Cont.*



(**b**) Rectangular Plot

Figure 4. Radiation pattern of tag antenna.

Table 2. Beam angle vs. parameters.

Main Parameters/ Beam Angle (Deg)	mat_w (mm)	mloop_w (mm)	mat_h (mm)	Patterns Figure 4
0	25	5	6	D
60,300	235	10	15	C
180	25	17	5	A
270	240	5	4	B

The above radiation pattern meets the requirement of the deployment of RFID readers in the management of vehicles, such as intelligent transportation systems (ITS). For example, if the reader can be placed on a lamppost on the roadside, the beam emanating from the tag antenna will allow the license plate and the reader to communicate with each other very well. The 3D radiation pattern in Figure 5 shows that there is a strong signal radiating from the plate toward the left and right side of the road, where the readers are deployed. There is no doubt that the volts and nuts and the vehicle's body, where the license plate is mounted, will influence the performance of the antenna, so all these conditions are included in our numerical simulation.

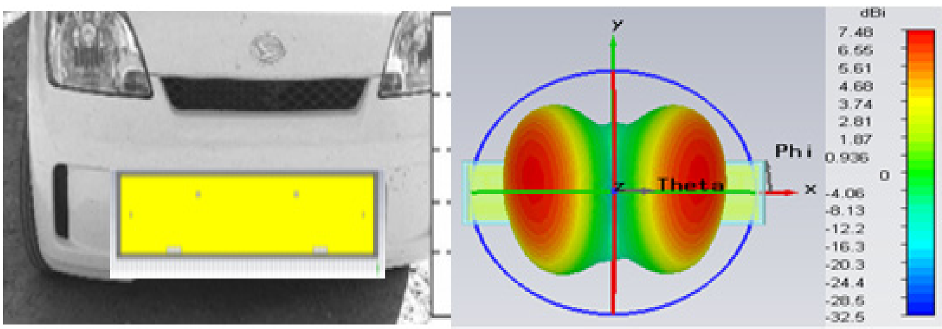


Figure 5. The three-dimensional radiation pattern of the tag antenna at 920 MHz.

The simulated return loss of the proposed tag antenna is shown in Figure 6a. The results of the CST simulation show that the proposed tag antenna has a reflection coefficient of −24 dB at 920 MHz. Figure 6b shows the surface current distribution on the tag antenna at 920 MHz. The current is flowing in almost the entire patch.

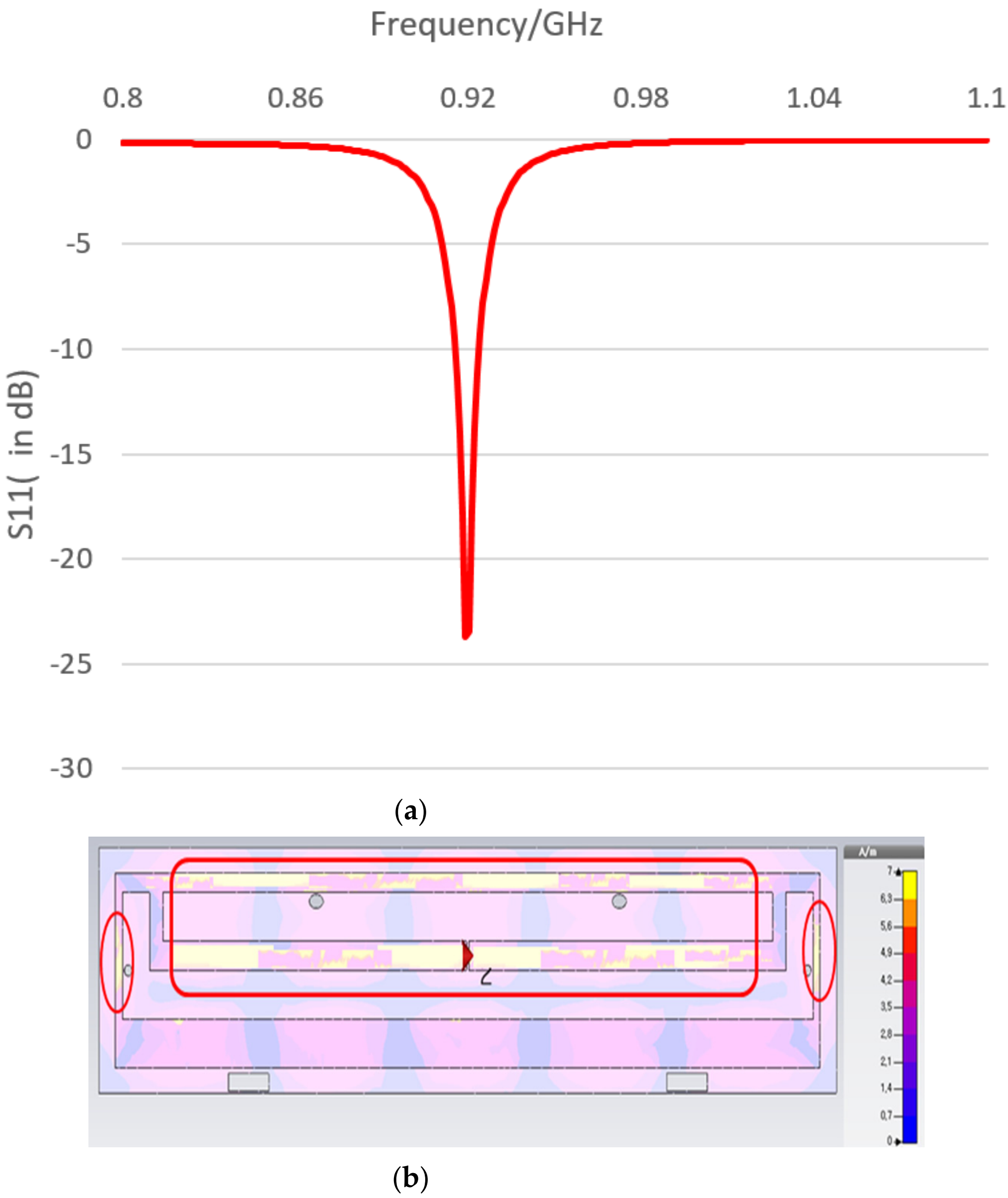


Figure 6. (**a**) Simulated return loss of tag antenna at 920 MHz. (**b**) Current density of the tag antenna at 920 MHz.

In order to achieve the optimum value during the simulation stage of the proposed antenna, parametric studies were conducted. Parameter sweeps were used for the optimization of the parameter elements. Figure 7 shows the simulation result using parametric sweeping with the center frequency of 920 MHz.

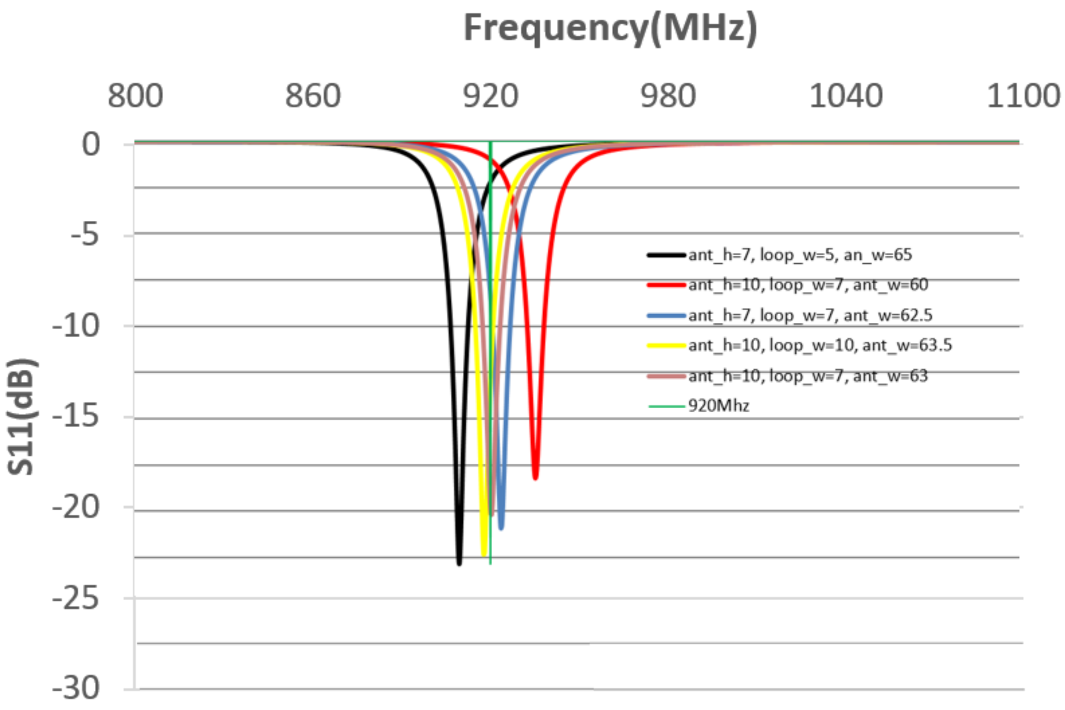


Figure 7. Optimization using parameter sweep S11 (dB) vs. frequency (GHz).

4. Conclusions

In this article, a passive automobile plate with a patch antenna is designed and demonstrated by positioning the patch antenna on the back side of a plate holder (i.e., toward the bumper of the vehicle). The plate dimensions are according to the standard license plate. The RFID metal tag has approximately the return loss −24 dB in the 920 MHz frequency, and used Higgs-3 chip with T-matching structure. The performance analysis of the proposed license plate indicates that the proposed plate meets the requirements for on-road vehicle identification when RFID readers are deployed on the roadside lampposts. The beam patterns of the RFID tag antenna are controlled by the patch antenna parameter values.

Author Contributions: T.H.B. conducted the simulation, fabrication, and measurement. Conceptualization, idea development, investment, and verification were carried out by Y.C. All authors have read and agreed to the published version of the manuscript.

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