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Gain Enhancement of E-Shaped Microstrip Patch Antenna for Underground RFID Reader Application

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Abstract

Radio Frequency Identification or (RFID) is a wireless communication technology that uses radio waves and consists of a reader, tag, and antenna. This paper introduces an innovative concept: an E-shaped microstrip patch antenna utilizing an air gap substrate. The proposed design is tailored for the specific application of underground RFID readers, aiming to optimize the antenna's performance within this unique context. The study encompassed the execution of a parameter analysis to thoroughly explore and optimize the impact of alterations in the antenna dimension on the performance of S11. The antenna design uses coaxial probe feeding technique with aluminum patch. Then, the performance of the final antenna design is analyzed and evaluated. The gain obtained for the proposed design is 9.329 dBi, while the S11 value at the desired resonant frequency 921 MHz is -12.39 dB. The simulation is performed with CST suite software.

1. Introduction

Radio Frequency Identification is a wireless communication technology that uses radio waves to capture data, which automatically identify people or objects from different identification such as barcode, serial number, or character recognition. The RFID system consists of three major components: transceiver (RFID reader), transponder (RFID tag) and RFID antenna. The combination of RFID reader and RFID tag are for identification purpose while RFID antenna is an extensive of reader that used for transmitting and receiving Radio Frequency (RF) signals between reader and tags. RFID reader is an interrogator that sends and receives Radio Frequency data from RFID tag via antenna at certain frequency. The RFID tag will be activated by the reader in the form of radio waves. Once the tag is activated, it will transmit the data signal through radio waves that will be stored in a centralized database such as a CPU. This RFID Operation between RFID reader and RFID tag are performed through a backscattering electromagnetic radio waves where the input impedance in tag is switched and presents a certain radar cross section as stated by Nikitin and [1]. As for the RFID tag or also known as transponder, it consists of microchip and antenna. The microchip is used to store the data information related to the object that it is attached to, and the antenna is used to transmit the data to the reader via radio waves. RFID system is not a new technology in this era since lots of companies have used this system for inventory management, logistics, monitoring, tracking system and speed test system.

Antenna plays an important role in transmitting and receiving signals between reader and tags. An effective and efficient wireless antenna network will help them operate properly. The performance of antenna could be different depending on their applications. Many efforts have been directed towards enhancing antenna design performance. Researchers strive to develop antennas that are compact, cost-effective, and high-performing. To improve antenna gain, various design techniques have been applied. [2]–[4] used the array technique in designing the antenna. From [2], the author proposed a high gain antenna based on a quasi-Yagi structure for frequency-coded chip less radio frequency identification (RFID) handheld readers. The result shows that the impedance bandwidth is 1.7 to 5.53 GHz and broadside gain and FBR are over 3.7 to 5.3dBi and 4.8 to 16.8dBi respectively. The advantage of the proposed design is it will improve the bandwidth of the antenna and enhance the gain.

[3] has proposed a novel structure of antenna array that consists of H-shaped patch antennas with slot and parasitic elements. The proposed antenna will be operated in the frequency band centre at 2.45Hz. The results show S11 parameter is in order -30dB at 2.45GHz and the gain reaches a value of 6.6 dB at the range of 2 to 3GHz. The proposed design shows that the design can create a high gain main lobe of the antenna which direction could be modified by the excitation phase of antenna. However, high gain side lobes are also produced in different directions. These side lobes reduce the main lobe's gain and produce a parasitic radiation in direction. While [4] proposed an RFID reader antenna array design for vehicle identification in a defined area The maximum gain and directivity obtained are both 7.1933 dB and 11.996 dB respectively. The metamaterial techniques of high gain antenna design were used by [5], [6]. However, the gain obtained is an average ranging from 1.3 dBi to 4.6 dBi. [7] proposed an eccentric annular slotted patch antenna for UHF-RFID reader antenna. The technique used to achieve a better circular polarized bandwidth is a parasitic arc-shaped element besides the radiating patch. The simulated gain across 880 to 960MHz, is 7.8 to 8 dBic while the measured ones are slightly lower which is 7.61 to 7.97 dBi. However, using a parasitic element will impact the axial ratio as the Circular Polarized frequency at 912MHz is shifted lower than the original one which is at 898MHz.

A Circularly Polarized Microstrip Patch Antenna (CPMPA) miniaturization with parasitic elements for UHF RFID systems is proposed by [8]. The proposed antenna has two side corners that has been truncated to achieve better impedance matching across the operating bands and it operates at the frequency band of 915 MHz. The gain obtained is 5.1 dB at 915 MHz and the return loss of -40 dB. However, the miniaturized CPMPA technique will affect the bandwidth to degrade because of size reduction. The same techniques were used by [9] to design antenna for frequency 5.7 GHz to 6 GHz. The design is linearly polarized and acts as the main radiator and the inverted C-shaped patch acts as a parasitic element. The results show that the gain obtained is 5.1 dBi at the resonance frequency of 5.82 GHz. The shorting pin technique are used by [10], [11] to design an antenna. The measured gain obtained from [10] is 8 dBi at 886 to 950 MHz while the simulated one is 8.2 dBi. The proposed design achieves the desired performance which has good gain value, good field test range and well fits the budget plan. In [11], the results show that the peak gain obtained is 5.55 dB at 0.9 GHz and 8.65 dB at 2.45 GHz respectively. The proposed design has a low profile and is compact, thus it could reduce the overall gain.

Authors in [12] proposed a simple circular patch antenna with slots on the patch and slits on the ground plane. The proposed antenna will operate at two frequency bands which are at 915 MHz and 2.45 GHz. The maximum simulated gain achieved at 915 MHz and 2.45 GHz is 0.62 dBi and 7.1 dBi respectively. The reason why the gain is lower at UHF RFID is due to high loss tangent of FR-4 substrate that gives very low simulated radiation efficiency. The problem can be improved by using a substrate with low loss tangent. [13] has designed the antenna using a broadband rectangular patch with U-slot intended for UHF RFID reader. The proposed antenna will be operated at frequency band of 860 to 960 MHz. It provides a unidirectional radiation pattern that result in higher gain. The results show that the simulated gain is recorded in three different frequencies which are 8.52 dBi, 8.32 dBi and 7.47 dBi at 860 MHz, 910 MHz, and 960 MHz respectively. However, the detection rate drops sharply and becomes zero above 2.2m.

The antenna requires a high gain performance to have a long-read range as stated in [2], [14], [15]. The gain obtained in [15] is 9 dBi for UHF RFID reader application. However, research from [14] suffers from low gain which is -2.21 dB for UHF RFID application due to miniaturize technique and the read range of the antenna is quite low as well. Various E-shaped microstrip patch antennas design was discussed in [16]–[20]. The maximum achievable gain from the proposed design was 7.3dB.

This research work is dedicated to design a compact RFID reader antenna that boasts high gain. As the gain of the reader antenna increases, its power amplifies, allowing it to effectively cover extended read ranges. This amplification of gain enhances the antenna's capability to capture signals from distant RFID tags, contributing to improved performance in identification and data collection tasks. Based on [21], the reader antenna must have high gain and every additional 3 dB of reader antenna gain would increase the range of the tag by 40%. The microstrip patch design will be used in this research since it is small and easy to manufacture. The proposed design will be conducted by using CST Suite Software. The target frequency range for this design is 860 MHz to 960 MHz, which falls within the standardized UHF spectrum used for RFID applications. Since the target frequency range for this design is 860 MHz to 960 MHz, this suggest that the center frequency should be around 910 MHz to 920 MHz.

2. Research Method

2.1 Antenna Design

The antenna design introduced in this work employs a microstrip patch antenna due to its advantageous characteristics, including compactness, affordability, conformity, and suitability for array fabrication. Specifically, the design features a rectangular microstrip patch antenna with an E-shaped configuration. This choice of antenna design facilitates the integration of these attributes into the proposed solution. The microstrip patch antenna consisted of high conductivity metal with a wide arbitrary shape called radiating element and dielectric substrate. The material that was used to design the antenna was Aluminum because it is much cheaper than Copper but had a good conductivity as copper. The gain of the antenna will increase exponentially with the increase of antenna or ground patch conductivity.

To address the antenna design objectives, a rectangular microstrip patch antenna is utilized, featuring an E-shaped configuration. The initial phase involves designing this rectangular microstrip patch antenna utilizing a standard procedure. This procedure is crucial for determining the optimal length and width parameters to achieve a frequency of 860 MHz to 960 MHz, which aligns with the UHF RFID frequency range. The design methodology leverages the utilization of a coaxial probe for accurate implementation. The antenna specification must have return loss below -10 dB for the S-parameter for better efficiency of the antenna.

2.2 Microstip Patch Antenna

This type of microstrip patch antenna was widely used due to its low cost and ease of fabrication. The antenna was designed with an air gap of 20.5 mm between the radiating plate and the ground plate with dielectric constant ε_r=1. The dimensions of the patch antenna are determined based on the calculation below. The antenna is designed using CST Studio Suite 2022.

The patch width can be calculated with the following equation,

$$W = \frac{c}{2f_o}\sqrt{\frac{\varepsilon_{r+1}}{2}} \tag{1}$$

Where f_o : operating frequency
ε_r : dielectric constant
c : speed of light $(3x10^8)\frac{m}{s}$

The effective dielectric constant can be calculated by using (2)

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\sqrt{1 + 12\frac{h}{W}} \tag{2}$$

The effective length can be calculated by using (3)

$$L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{reff}}} \tag{3}$$

The length extension can be calculated by using (4)

$$\Delta L = 0.412h\frac{\left(\varepsilon_{reff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{reff} + 0.258\right)\left(\frac{W}{h} + 0.8\right)} \tag{4}$$

Where h : substrate thickness

The actual patch length can be calculated by using (5)

$$L = L_{eff} - 2\Delta L \tag{5}$$

The ground plane extension can be calculated by using (6) and (7)

$$L_g = 6h + L \tag{6}$$

$$W_g = 6h + W \tag{7}$$

The feed length can be calculated by using (8)

$$L_f = \frac{L}{2\sqrt{\varepsilon_{reff}}} \tag{8}$$

The feed width can be calculated by using (9)

$$Z_o = \frac{60}{\sqrt{\varepsilon_{reff}}} ln\left[\frac{8h}{Wf} + \frac{Wf}{4h}\right] \tag{9}$$

Where Z_o : line impedance
h : substrate thickness

2.3 Feed Technique of Patch Antenna

The coaxial feedline method involves connecting the inner conductor of the coaxial cable to the radiation patch of the antenna, while the outer conductor is linked to the ground plane as shown in Fig. 1. This technique is commonly utilized to feed microstrip patch antennas, ensuring efficient signal transfer between the feedline and the antenna structure. This type of feed line is usually used in wireless communications because it is simple, low cost, efficient and can be used as a gain input match by adjusting feed position. This method is used in the design of an E-shaped planar antenna with an air gap.

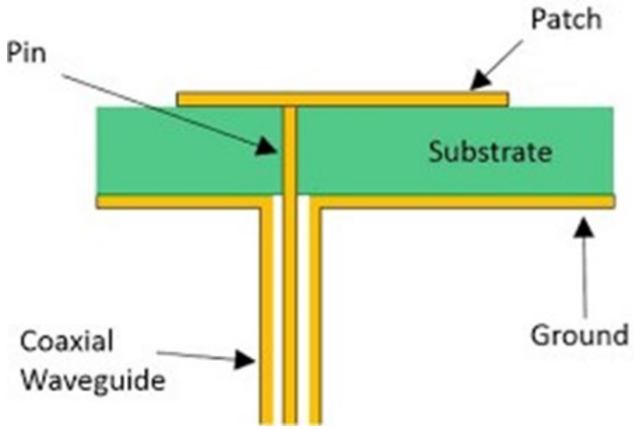
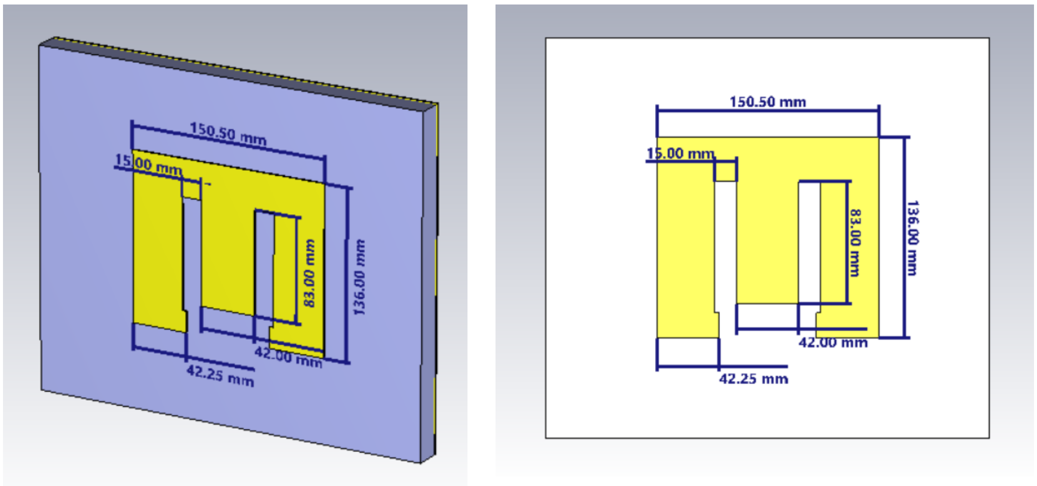


Fig. 1 *Coaxial line feed*

2.4 Antenna Design

Fig. 2(a) and (b) show the final design of an E-shaped microstrip patch antenna. Table 1 shows the parameters of the designed antenna with E-shaped design. The design also used an air gap as a substrate.



(a) **(b)**

Fig. 2 *Antenna design from (a) Side view; and (b) Front view*

Table 1 *Parameters of E-shaped microstrip patch antenna with air gap*

No.	Parameter Name	Designed Value
1	The material of the substrate	Air
2	The dielectric permittivity of the substrate, ε_r	1
3	The thickness of air gap, h (mm)	20.5
4	The resonant frequency (MHz)	921
5	Length of Patch, L (mm)	136
6	Width of Patch, W (mm)	150.50
7	Width of center arm dimension, Wt (mm)	42
8	Length of Inset Fed, Yo (mm)	106
9	Thickness of patch, tp (mm)	1.02
10	Length of air gap, Ls (mm)	272
11	Width of air gap, Ws (mm)	301
12	Height of air gap, h (mm)	20.5
13	Length of feedline, Lf (mm)	7.6
14	Radius of inner pin, R1 (mm)	1.3
15	Radius of outer pin, R2 (mm)	4.1
16	Thickness of Ground plane, tg (mm)	1.02
17	Width of the gap feedline, gpf (mm)	13

2.5 Antenna’s Parameter Analysis

In this section, some parameter of antenna design would be varied and observed. It is because the changes in parameters would affect the S11 performance of the antenna. Fig. 3 shows the antenna design with the length of the patch, Lp, the width of the center arms dimension, Wt, and the thickness of the air gap, h. (3) shows that the size of patch antenna is inversely proportional to the frequency and directly proportional to the wavelength.

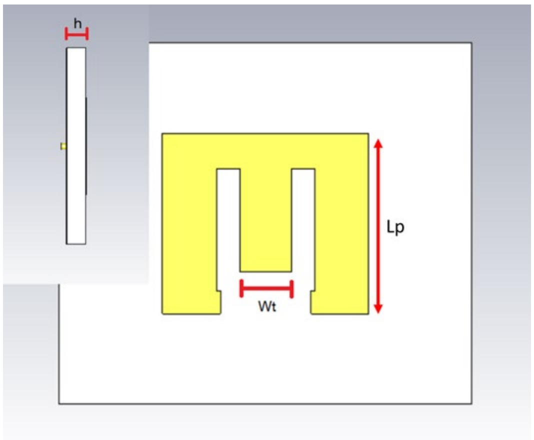


Fig. 3 *Parameters of the patch Length (Lp), Width (Wt) and Thickness of air gap (h)*

2.5.1 Variations of Lp

The length of the patch Lp, as illustrated in Fig. 3, is varied between 136 mm and 154 mm. Fig. 4 illustrates the reflection coefficient S11 correspond to different value of Lp. As Lp increases, the resonant frequency decreases, S11 also decrease, Lp increases, S11 increases. Ideally, a desirable antenna design aims for an S11 parameter that is less than -10 dB throughout its operational frequency range. This indicates minimal signal reflection at the antenna interface and efficient power transfer from the feed to the antenna structure. This criterion demonstrates good impedance matching and effective energy propagation, which are crucial for optimal antenna performance. For practical antennas, an S11 below -10 dB is generally considered sufficient for effective operation.

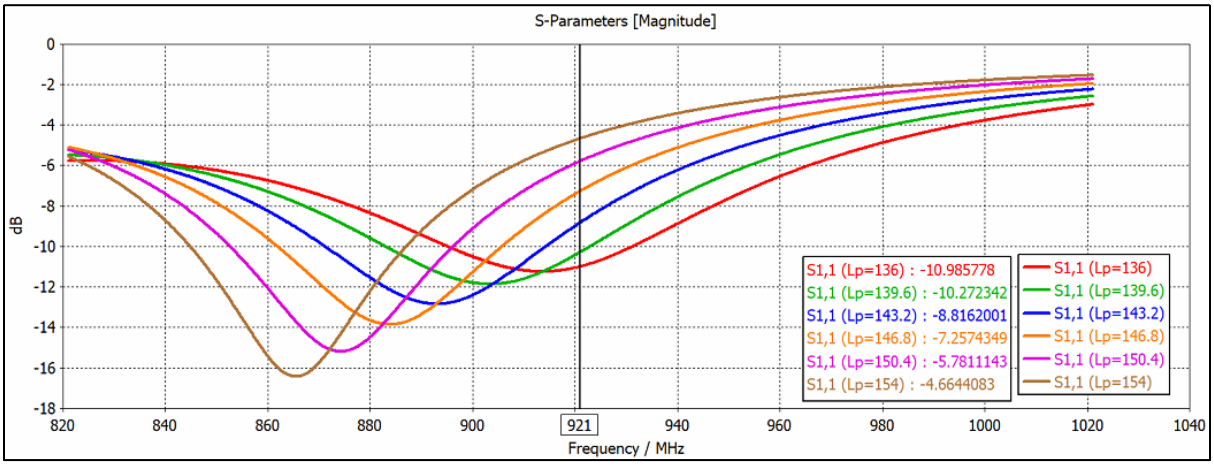


Fig. 4 *The S11 with different value of length of patch*

2.5.2 Variations of Wt

The width of center arms dimension, (Wt) is varied from 40 mm to 58 mm. Fig. 5 shows the simulation result of S11 for various Wt. It could be seen that the S11 increases as the Wt increases and vice versa. As Wt increases, the S11 curve deviates from the desired value of -10 dB. This behavior signifies impedance mismatch and poor energy transfer between the antenna and the transmission line. An S11 value below -10 dB ensures efficient power transmission and reduced signal reflection. Antenna efficiency heavily depends on impedance matching, and any deviation from the target S11 value indicates less effective energy utilization.

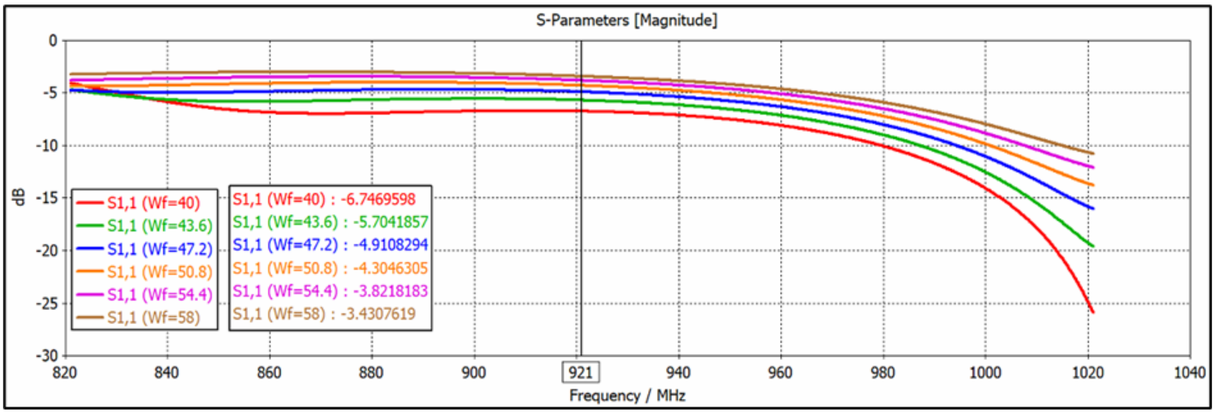


Fig.5 *The S11 for different width of center arms dimension*

2.5.3 Variations of h

Achieving optimal antenna performance involves selecting substrates with specific properties. Thick substrates with lower dielectric constants offer improved performance due to their ability to support efficient energy propagation. Such substrates minimize signal losses, leading to higher gain and better antenna performance. The substrate used in this simulation is an air substrate with a dielectric constant of ε_r = 1. The thickness of an air substrate h, is varied from 18 mm to 36 mm. The simulated S11 result is shown in Fig. 6. From Fig. 6, increasing the h leads to a decrease in resonant frequency. As the h, serving as an air gap, is increased, the S11 parameter is decreased as observed at 921 MHz. Additionally,better S11 is achieved at h=21.6mm. The result emphasizes the significance of substrate thickness in determining optimal impedance and efficient energy utilization in antenna systems.

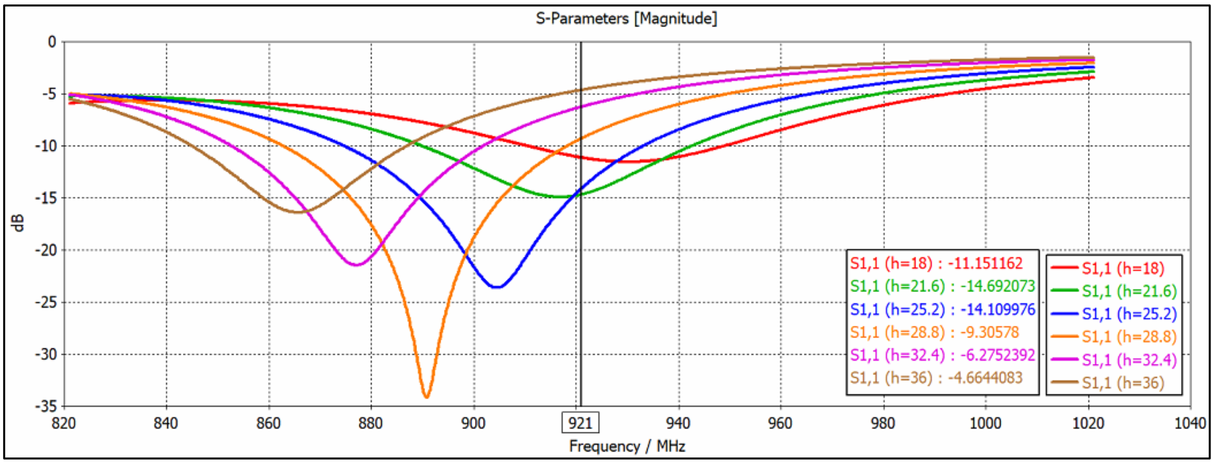


Fig. 6 *The S11 for different thickness of air gap and S11 value*

From the study, it can be concluded that the width of the patch and the thickness of the substrate have been identified as crucial factors affecting the S11 value, which, in turn, affects overall antenna performance such as gain, radiation pattern, and efficiency. Changes in these dimensions can lead to variations in the resonant frequency and impedance matching, influencing energy propagation and efficiency. As a result, antenna designers need to carefully consider these dimensions to achieve desired performance outcomes and optimize antenna designs for specific applications.

3. Simulation Result and Discussion

3.1 Optimized Antenna Design

3.1.1 Return Loss

In this section, the return loss is discussed. The return loss is described as a ratio of the power reflected from the antenna to the power reflected from the transmission line into the antenna. It is widely used to evaluate the performance of an antenna and represents the ratio of the incident power to the reflected power of an antenna. Thus, the return loss can be written as follows:

$$Return\ Loss\ (dB) = 10log_{10}\frac{P_{out}}{P_{in}} \tag{10}$$

Fig. 7 shows the curve of return loss S11, which is -13.51 dB at a resonant frequency of 934 MHz, and -12.39dB at 921 MHz frequency. This value is acceptable because the S11 value should be equal to or less than -10 dB for better efficiency of antenna. High return loss prevents reflections caused by impedance discontinuities [22]. It also shows that the impedance matching is good, and the feed is well-matched. The design covers a portion of the UHF RFID frequency band, spanning from 904.32 MHz to 958.61 MHz, which corresponds to a bandwidth of 54.3 MHz and center frequency of 931 MHz.

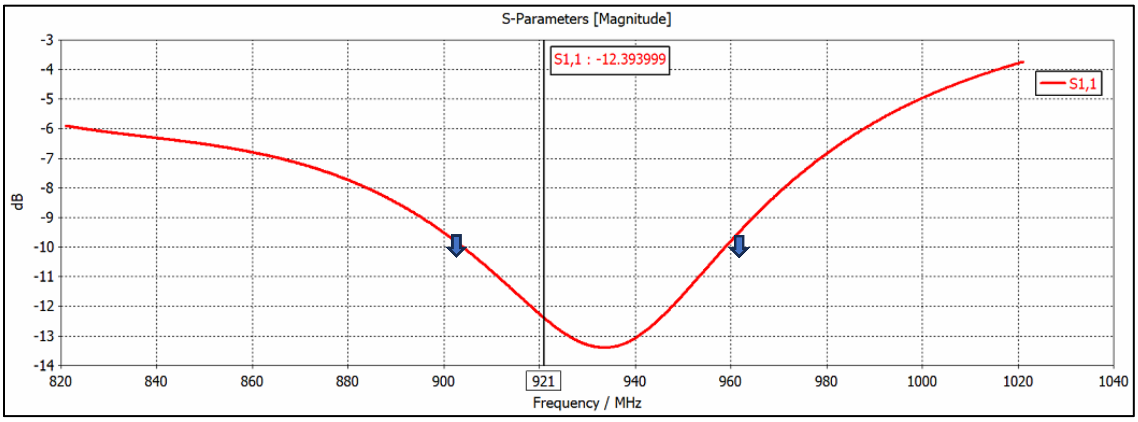


Fig. 7 *S11 parameter of E-shaped microstrip patch antenna*

3.1.2 VSWR

Voltage Standing Wave Ratio (VSWR) measures the efficiency of radio frequency power transmitted from a power source through a transmission line. The ideal VSWR is between 1 and 2 [23] because the smaller the value of VSWR, the easier for the antenna to match the transmission line. As shown in Fig. 8, the VSWR at 931 MHz is 1.5, while at 910 MHz is 1.75 and at 921 MHz is 1.63. The acceptable range of VSWR values is between 1 and 2. Therefore the VSWR value at each observed frequency is sufficient.

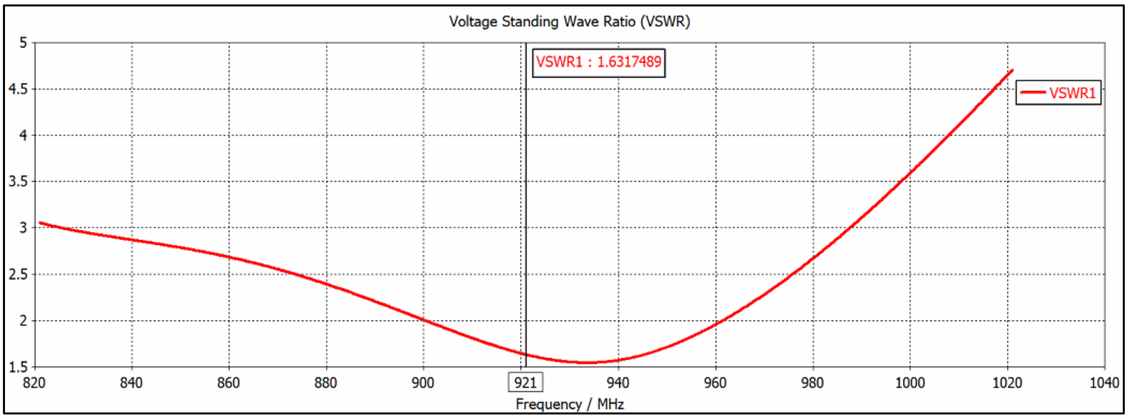


Fig. 8 *VSWR of E-shaped microstrip patch antenna*

3.1.3 Directive Gain

According to [24], gain is used to describe the performance of an antenna. It is defined as the ratio of the intensity to the radiation intensity that would result if the power absorbed by the antenna were radiated isotropically. Fig. 9 shows the maximum gain of the antenna designed. The figure indicates that the antenna achieves a maximum gain of around 9.33 dB at a frequency of 910.05 MHz. The gain then slightly decreases to 9.32 dB at 921.06 MHz. After this point, the gain decreases rapidly as the frequency increases. The gain of the microstrip antenna can be increased by increasing the dimensions of the patch antenna. Considering the S11 in Fig. 7 and maximum gain in Fig.9, the operating frequency of this antenna is best at 921 MHz.

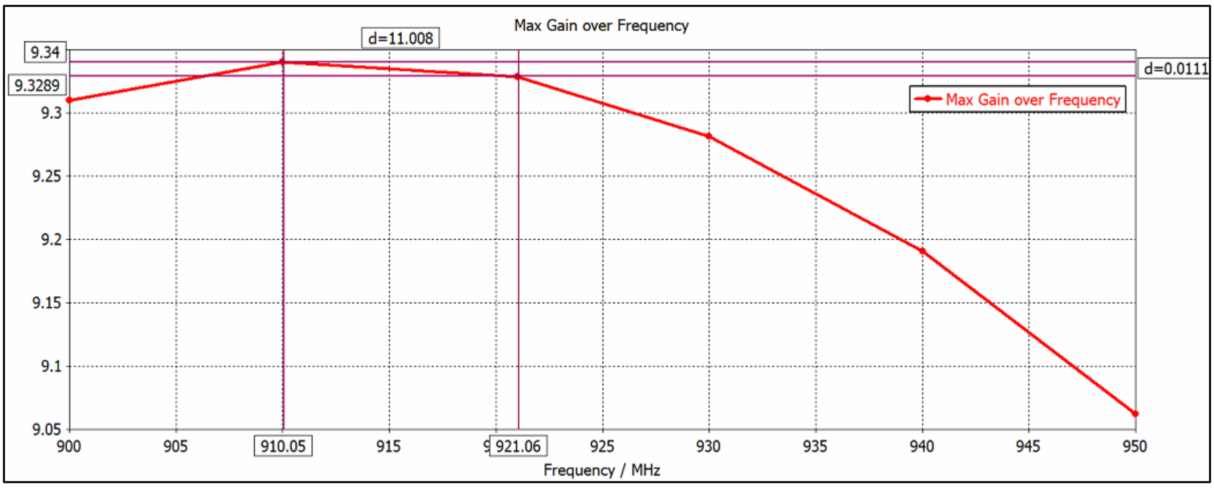
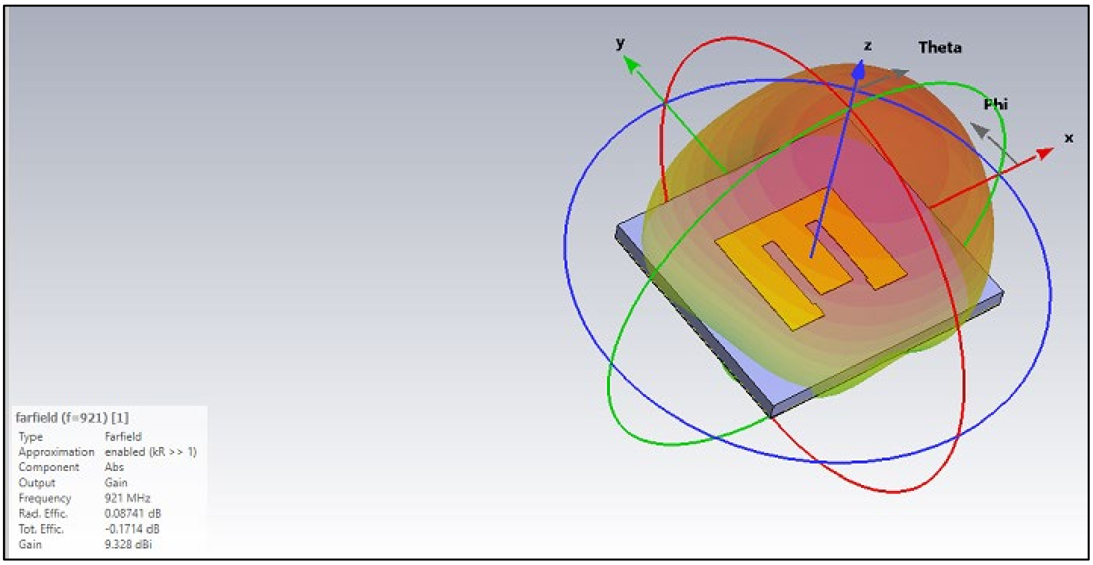


Fig. 9 Maximum *gain of E-shaped microstrip patch antenna at different frequency*

Fig. 10 shows the 3D polar diagram at 921 MHz. The gain obtained from the simulation is 9.328 dBi, which is sufficiently high, and indicates good antenna performance.



farfield (f=921) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Gain
Frequency	921 MHz
Rad. Effic.	0.08741 dB
Tot. Effic.	-0.1714 dB
Gain	9.328 dBi

Fig. 10 *Gain of E-shaped microstrip patch antenna*

3.1.4 Radiation Pattern

The radiation pattern of an antenna describes the directional properties of its electromagnetic radiation. It shows how the radiated power varies with respect to the direction in the space surrounding the antenna. It determines how the antenna transmits or receives signals in different directions. Fig. 11 shows the radiation pattern of an E-shaped microstrip patch antenna. The result shows that the coverage beamwidth is 68.7°. The coverage area is quite large, and shows that the radiation pattern is directional, that is the radiation is concentrated in a certain direction and has a narrow beam. In order for the signals to be transmitted or received in a certain direction, a high gain antenna is required.

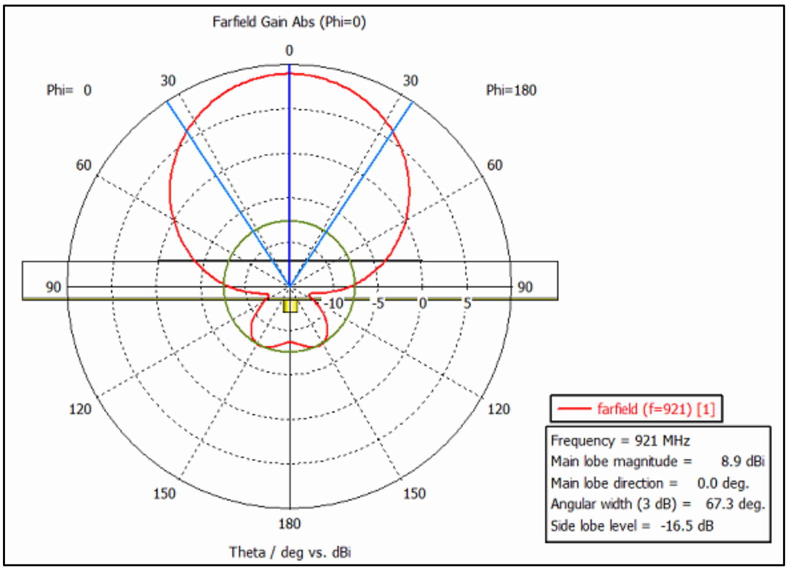


Fig. 11 *Radiation pattern of an E-shaped microstrip patch antenna*

3.2 Comparative Study of E-Shaped Patch Antenna and Other Reference Design

Table 2 shows the comparison between an E-shaped patch antenna and other reference designs. Based on Table 2, the antenna gain obtained from this work is 9.328 dB while [15], [16], [25] are 7.3 dB, 8.3 dB and 9.038 dB respectively. The variation in gain observed in the antenna design is attributed to the use of different substrates. Authors in [15], [25] utilize an air gap as the substrate, whereas [16] employs an FR-4 substrate. The contrasting dielectric properties of these substrates, especially the higher dielectric constant of FR-4, lead to increased dielectric losses. This difference in substrate properties directly influences antenna performance, including gain. Substrates with higher dielectric constants can introduce losses that impact overall antenna efficiency and performance. As a result, the choice of substrate becomes a crucial consideration in antenna design, as it significantly influences parameters like gain, impedance matching, and radiation pattern.

Table 2 *Performance comparison of 900 MHz range antenna design*

Parameters	This work	[16]	[25]	[15]
S_{11} (dB)	-12.39	-12.38	-15.00	-36.2
Gain (dBi)	9.328	7.3	8.300	9.038

The absolute gain discrepancy of this work compared to work in [15]. [16], [25] are 0.29, 2.028 and 1.028 respectively. The evaluation of the proposed antenna design indicates that it exhibits improved gain characteristics. This suggests that this design can enhance the antenna's performance by directing signal strength in a specific direction. The analysis emphasizes the significance of developing high-gain antennas to facilitate robust and reliable RFID communication, ultimately contributing to the efficiency and effectiveness of RFID systems.

In addition to the work listed in Table 2 regarding RFID antenna design, several works have contributed to the field of study. These papers [26-28] comprehensively study on the use of RFID technology for the underground and other applications. [26] and [27] achieves a wide bandwidth covering the entire GSM 900 band (824-960 MHz) and 4.5 dBi gain and (860-960 MHz) and 4.8 dBi gain respectively. While [28] demonstrate the gain of -8 dBi at (890 – 926 MHz) band.

4. Conclusion

An E-shaped microstrip patch antenna has been successfully designed for underground RFID reader application. Parametric analysis was performed to determine S11 value that affects the performance of the antenna. The return loss, VSWR, directive gain and radiation pattern of the antenna are observed. The gain obtained in this simulation is 9.328 dB which is considered as high gain for sufficient antenna, followed by return loss and VSWR which are -

12.39 dB and 1.63 respectively. The proposed E-shapanded antenna shows an improvement in gain performance which would increase the read range of the RFID and comparable to the existing antenna design.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Nurul Husna Mohamad Fadhil, Jamilah Karim, Nurul Huda Abd Rahman, Suhaila Subahir;* ***data collection:*** *Nurul Husna Mohamad Fadhil, Chan Kean Mun;* ***analysis and interpretation of results:*** *Nurul Husna Mohamad Fadhil, Jamilah Karim, Nurul Huda Abd Rahman,* ***draft manuscript preparation:*** *Nurul Husna Mohamad Fadhil, Jamilah Karim, Sohiful Anuar Zainol Murad. All authors reviewed the results and approved the final version of the manuscript.*

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