A MINIATURIZED LOOPED-SLOT PATCH ANTENNA FOR PASSIVE UHF RFID APPLICATIONS USING A SLIM SINGLE-LAYER SUBSTRATE

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Abstract:

Passive ultra-high frequency radio frequency identification systems (UHF RFID) have become essential components of contemporary logistics in various industries. They play a crucial role in facilitating critical operations such as asset tracking, inventory management and supply chain optimization. However, the effectiveness of these systems depends heavily on the design and efficiency of the antennas used. Therefore, this paper aims to improve the efficiency of a passive UHF RFID antenna by adopting a microstrip patch design. The proposed antenna comprises a rectangular patch with a looped slot printed on a slim single-layer dielectric substrate. To optimize performance, a comprehensive parametric study is carried out using the CST simulator with the objective of increasing the gain while reducing the overall antenna. As a result is a miniaturised slot antenna design with a total size of 87×85×0.9 mm3 and a gain of 4.14 dBi at 894.4 MHz frequency. This result will contribute to the advancement of passive UHF RFID antennas and create opportunities for enhanced detection reliability in relevant applications while simultaneously reducing system costs.

1 Introduction

Microstrip patch antennas have already become very popular in the wireless communications world. They are typically useful for applications that require limited size due to the low profile, low cost, and easy fabrication using photolithography. Famously, the microstrip patch antenna consists of two highly conductive metal planes, which are a radiating patch and a ground plane. These two surfaces are separated by a substrate that is made of a dielectric material. The antenna patch is most commonly fed by a microstrip line or coaxial cable. The microstrip line has an advantage that it can be etched on the same substrate to provide a planar structure [1].

Due to the tiny nature of the microstrip antennas, they are used in various applications including cellular phones, RFID systems, satellites, missiles, and radar [2]–[5]. However, the microstrip antennas still experience some limitations in bandwidth and gain because the electromagnetic fringing, and hence radiation, occurs from only two sides of the patch [6]. To enhance the radiation characteristics of such antennas, several options can be involved, such as decreasing the substrate permittivity, increasing the substrate thickness (height), adding more dielectric layers to the substrate, changing the patch design, or inserting slot(s) into the patch [7]. In practice, introducing a slot into a simple patch design can improve the radiation significantly while simultaneously maintaining a small antenna size [8]–[27]. It is also very easy to model and fabricate compared to other options.

Based on that, this research is dedicated to enhance the gain of a microstrip antenna in the UHF RFID band using a slotted patch and targeting a reading distance of approximately 15 m. This particular band is considered because it has lately gained much attention for various industrial services, such as inventory management,

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logistics, tracking, supply chain, purchasing, library management, and sensing [8], [28]–[31]. In effect, the performance of a passive RFID system largely depends on the efficiency of the tag antenna that is responsible for transmitting and receiving signals between the tag and the reader. Therefore, the objective is to improve the design of the tag antenna by introducing a slot in the patch such that the performance and reliability of the entire RFID system is considerably improved.

In literature, several works have already been presented using different slot designs to improve the microstrip antenna performance in the considered frequency band. For instance, an antenna with a quasi H-shaped slot has been presented [32] in which the slot was created by connecting many rectangular slots of different dimensions. The antenna was fed by a 50-Ω coaxial cable, and the overall antenna size was 68×66×1.6 mm^3. This design yielded a good resonance bandwidth that is 40 MHz, ranging from 889 MHz to 939 MHz. However, the entire design is relatively complicated to fabricate while the maximum gain was only 1.73 at 915 MHz. Another work has proposed a simpler design in a compact size using a truncated corner with a rectangular slot for the RFID UHF reader [33]. The maximum gain achieved by this antenna was 2.5 dBi with a bandwidth of 40 MHz. In another research, a rectangular patch with two truncated corners has been designed for UHF band [34]. The original goal was to solve the polarization mismatch problem between the tag antenna and the reader antenna. The antenna overall size was 115×115×1.6 mm^3, and the maximum gain was 5.3 dBi in the range 919-932 MHz. However, the antenna size was relatively big, and the maximum reading distance was only 2 m. In another paper, a rectangular patch antenna with U-slot for the entire RFID UHF band (860-960 MHz) has been proposed [35]. This design is interesting as it is relatively simple, broadband, and it yields 7-dBi gain. However, the maximum reading distance was only 2.2 m. In another work, a miniature microstrip antenna for RFID UHF tag applications has been proposed with an overall patch area of 49.3×55.57 mm^2 [36]. The antenna showed good impedance matching along with stable radiation patterns using nested slots in the patch. However, the maximum gain did not exceed 1.21 dBi.

In an attractive work, a looped-slot microstrip patch antenna for RFID UHF tags has been presented with a 2.5-dBi gain and a reading distance of about 12.5 to 16 m [37]–[38]. However, the design was composed of three substrate layers: single layer of flame retardant FR4 with a thickness of 1.5 mm, and two layers of RT duroid with thicknesses of 0.787 and 1.575 mm, respectively. Thus, the overall size became 85×85×3.862 mm^3. Although the antenna surface is reasonably small in the context of UHF RFID antennas, the substrate structure is comparatively complex, and its thickness of 3.862 mm is considered too big. Nevertheless, such a looped-slot patch is still interesting due to the relative simplicity in modelling and fabrication. Moreover, the existence of the looped slot enables further size reduction while enhancing antenna performance due to increased electrical length within a compact area, introduced additional coupling, and excited resonances. This in turn urges us to conduct further examinations on the substrate structure and dimensions to simplify the above antenna design significantly.

Therefore, this paper involves a thorough investigation over the entire looped-slot antenna in order to enhance the gain while minimizing the number of substrate layers and total height. As a result, the paper concludes by presenting a new miniature design with a slim single-layer substrate of 0.9-mm thickness and a 4.14-dBi gain at 894.4 MHz.

2 Parametric study

To achieve an optimal design for the considered antenna, a detailed parametric study is essential. Initially, the antenna is designed such that it has the same shape and dimensions of the previous work [38] but with one substrate layer of arbitrary thickness. The patch and ground metal is changed to aluminium rather than copper due to less price, while the substrate is chosen to be FR4 with dielectric constant 4.3. The initial antenna parameters are summarized in Table 1, noting that the original slot design has not been modified.

Table 1. Initial antenna parameters.

Parameter	Value (mm)
Substrate thickness	2
Substrate & ground length	85
Substrate & ground width	85
Patch length	81.29

Figure 1 shows the preliminary S11 results obtained from the initial values, where no reflection coefficient ≤ −10 dB is observed yet. Therefore, the parameters are empirically changed where the substrate thickness is decreased from 2 to 1.5 mm, and its length and width (hence ground's) are increased from 85 to 95 mm. Figure 2 shows the reflection coefficient results. It is obvious that the reflection drops below −10 dB at around 912 MHz, but the curve still needs more improvement, as much lower reflection coefficient is demanded for safe fabrication.

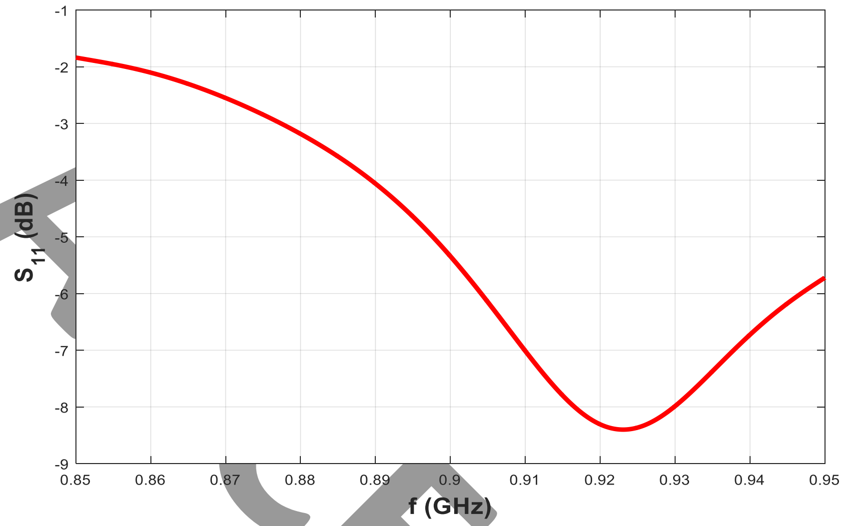

Figure 1. Initial reflection coefficient results.

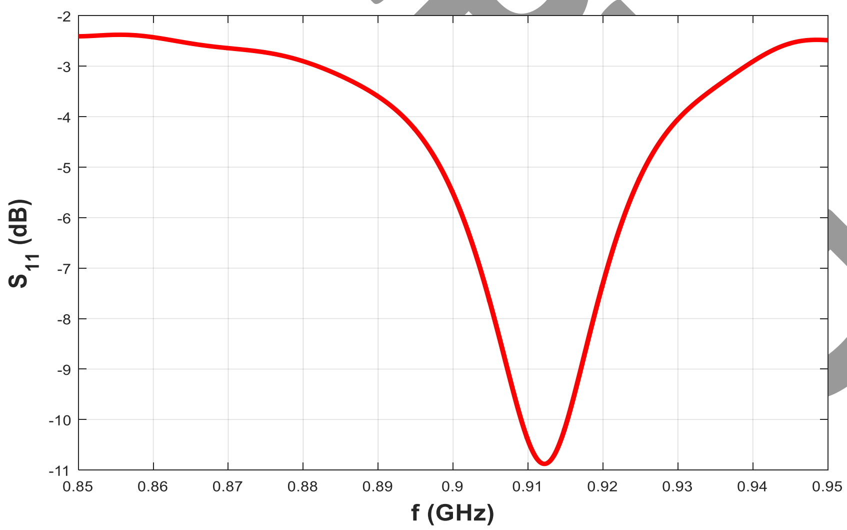

Figure 2. Reflection coefficient results for 1.5-mm substrate thickness and 95-mm substrate length and width.

In the next step, the substrate length and width are extremely increased to reach 120 mm, but the reflection results improve very slowly and they eventually show small overall enhancement. This leads us to move on to another key parameter that is the patch width, where it is empirically varied between 90 and 115 mm using 5-mm variation steps. The results are shown in Figure 3, noting that the substrate width and length (hence ground's) are both fixed at 120 mm for the time being.

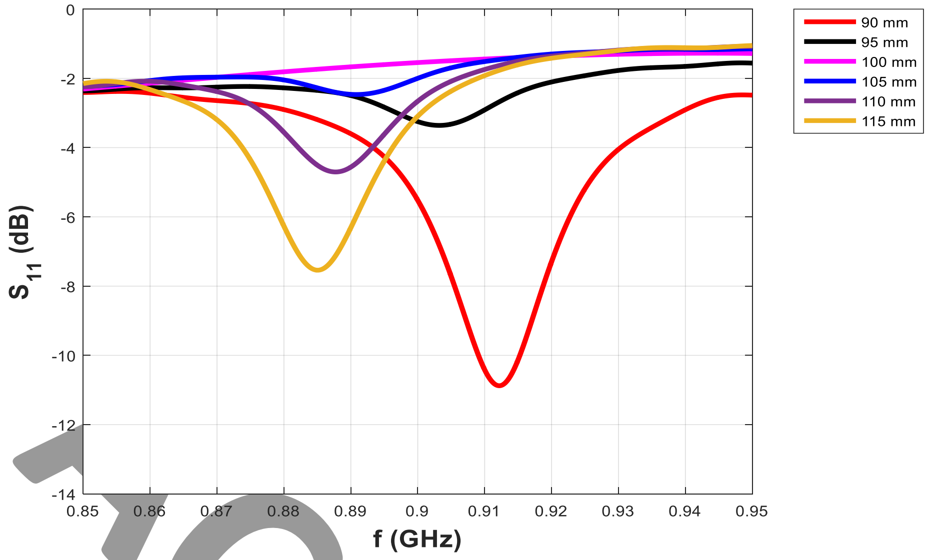

Figure 3. Reflection coefficient results for different patch width values between 90 and 115 mm.

It is clear that the best curve to be considered is the red one that belongs to 90-mm patch width. Now, the patch length is increased from its original value towards 91 mm with 2-mm variation steps, and the reflection results are shown in Figure 4. As seen, a considerable improvement is achieved, where the best curve is related to 87-mm patch length.

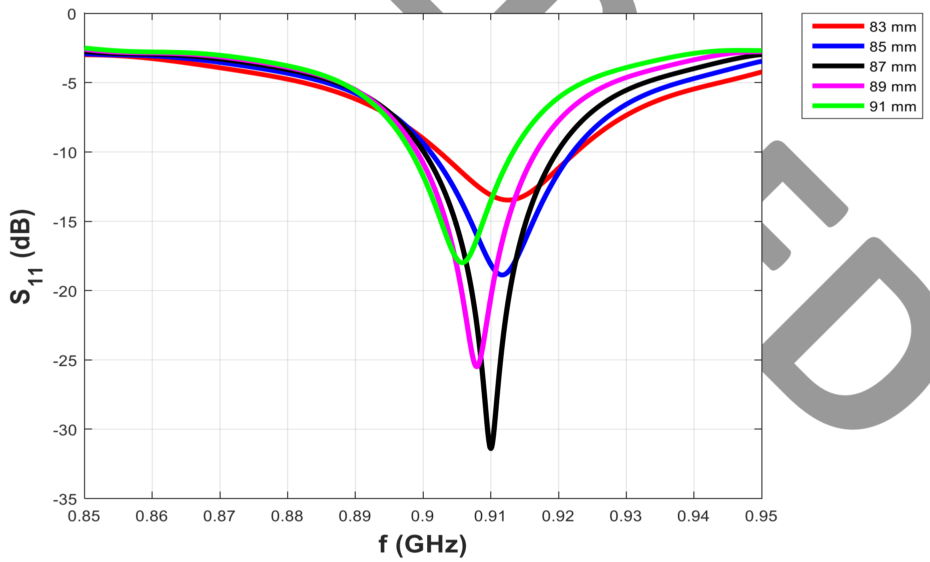

Figure 4. Reflection coefficient results for different patch length values.

By fixing the patch length at 87 mm and going back to further optimize the patch width using 1-mm variation steps, the reflection results show that 86 mm is the best antenna width as seen in Figure 5 (the red curve).

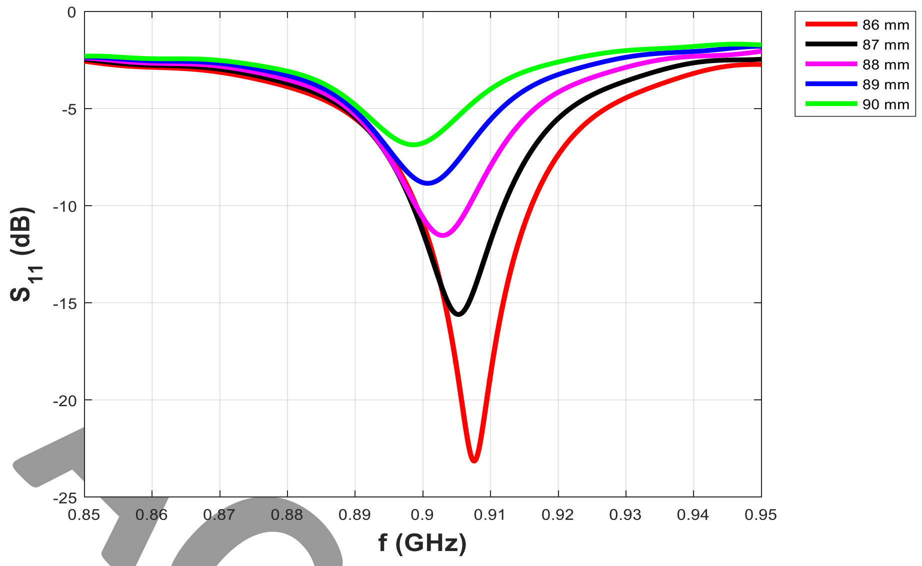

Figure 5. Reflection coefficient results for different patch width values using 87-mm patch length.

For more accuracy, a fine parametric test is conducted between the 86-mm patch width and the original 85-mm value using 0.2-mm steps, and the results show that 85.2 mm is the best value for our design so far. Figure 6 shows the entire comparison.

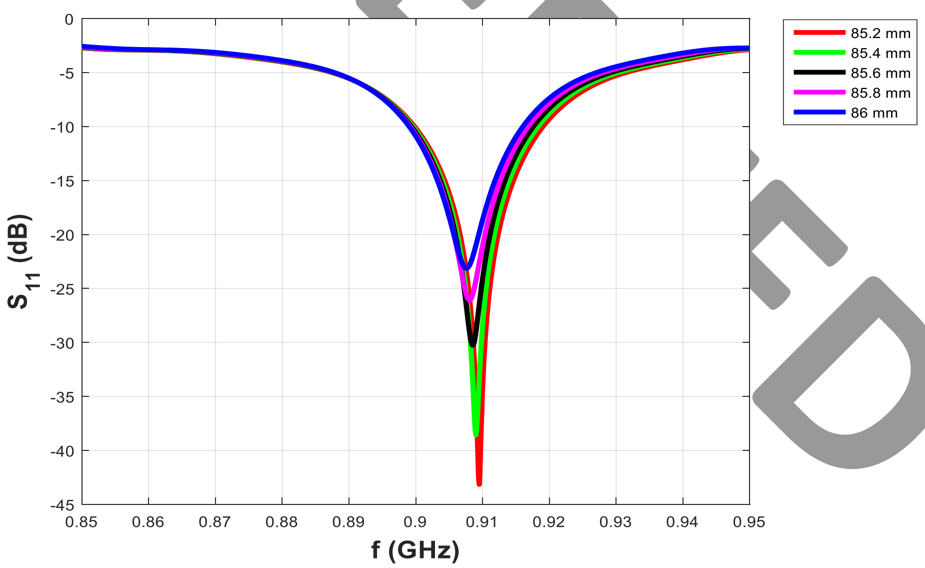

Figure 6. Reflection coefficient results for fine variations in the patch width.

Based on the above results, it is worth returning to the dimensions of the substrate and carrying out further investigations to minimise its overall size. Figure 7 and Figure 8 show the results of the reflection coefficient for reduced values of substrate width and length respectively.

The results show that the best substrate width is 96.2 mm while the best length is 97 mm.

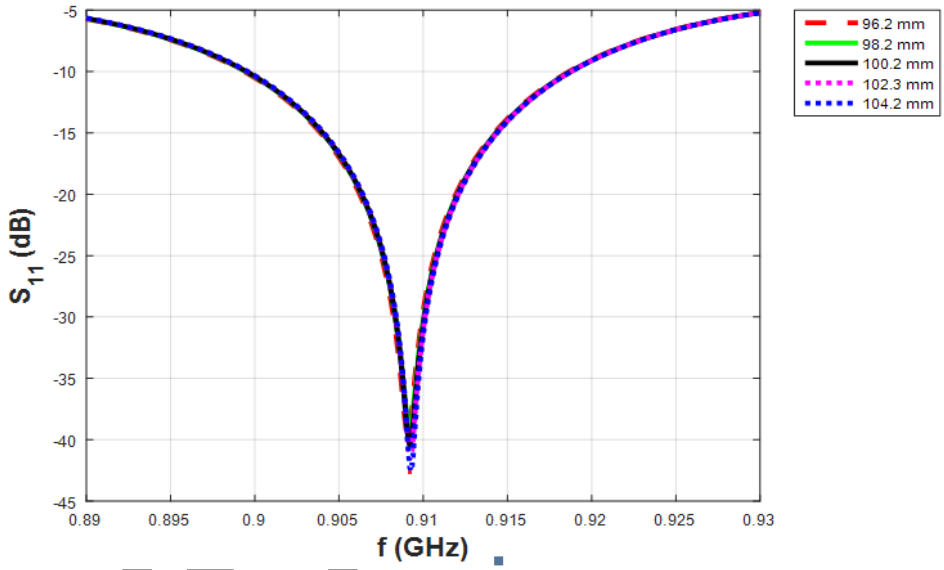

Figure 7. Reflection coefficient results for reduced substrate width values.

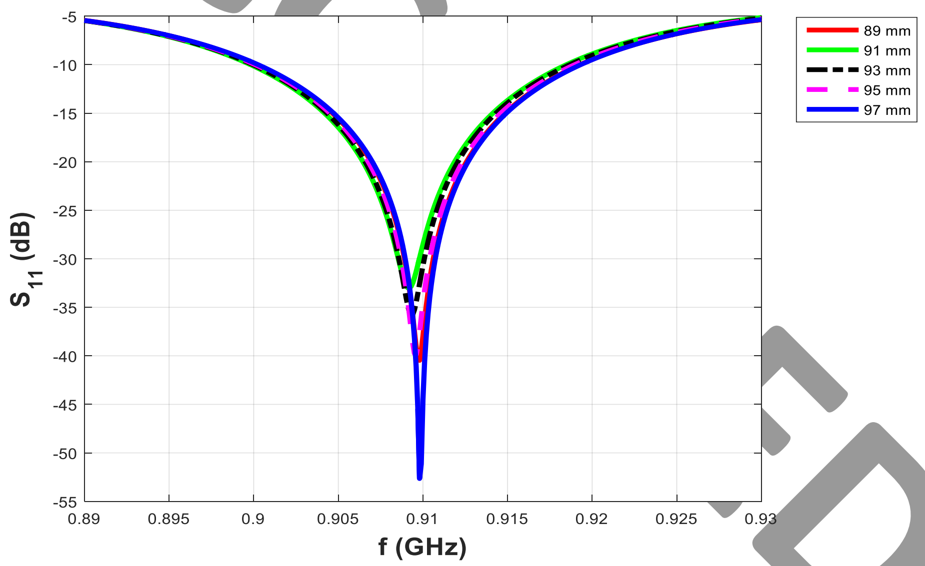

Figure 8. Reflection coefficient results for reduced substrate length values.

Now, an empirical study on the substrate thickness (height) can be conducted, where the results are shown in Figure 9. It is obvious that the best reflection results are obtained at 1.9 mm (the blue curve).

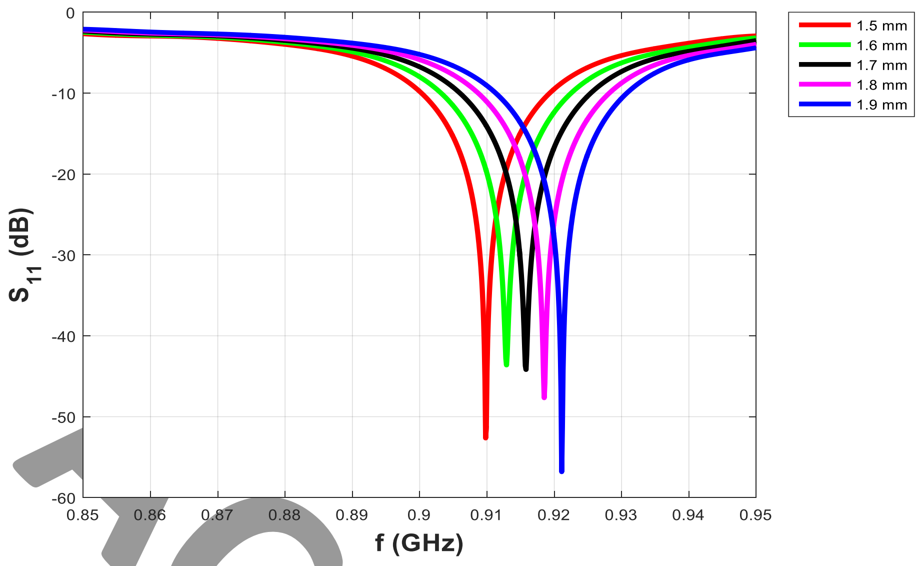

Figure 9. Reflection coefficient results for different substrate thickness values.

Since the aim is to minimize the entire antenna size, further reduction on the substrate area (hence ground's) is applied, where its width is reduced from 96.2 to 90 mm and its length is reduced from 97 to 90.5 mm. The results are shown in Figure 10 using 1.9-mm thickness.

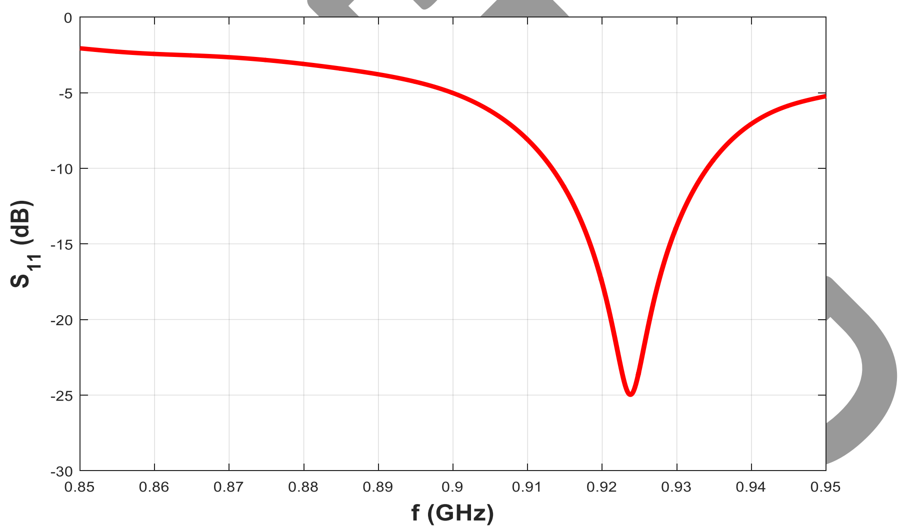

Figure 10. Reflection coefficient results using 90-mm substrate width, 90.5-mm length and 1.9-mm thickness.

Although the reflection is increased dramatically, it is still way below −10 dB, and thus it is worth going back again to the substrate thickness and reducing it further. Figure 11 shows the results when the thickness is decreased from 1.9 to 1.4 mm.

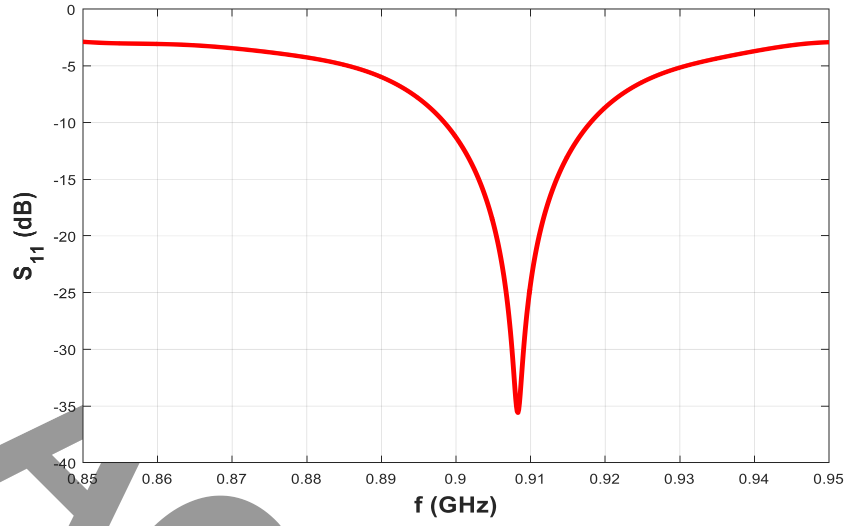

Figure 11. Reflection coefficient results using 90-mm substrate width, 90.5-mm length and 1.4-mm thickness.

Again, since the reflection coefficient is still well below −10 dB, further reductions on the substrate width (of 90 mm) can be applied, where the new results are shown in Figure 12 and Figure 13 that correspond to 87 mm and 85.2 mm, respectively. It is obvious that the reflection is increased at < 87 mm and gets closer to −10 dB. However, the width can still be fixed at 85.2 mm, which is considered optimal for now.

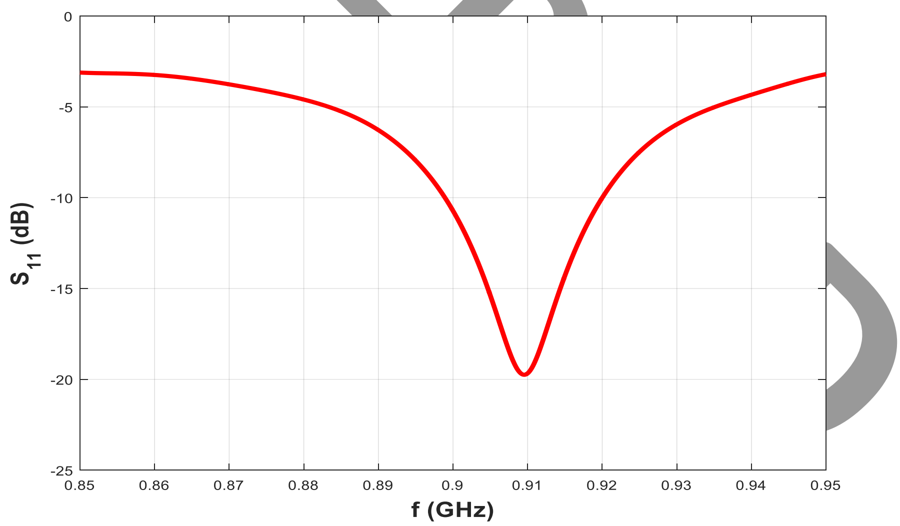

Figure 12. Reflection coefficient results using 87-mm substrate width.

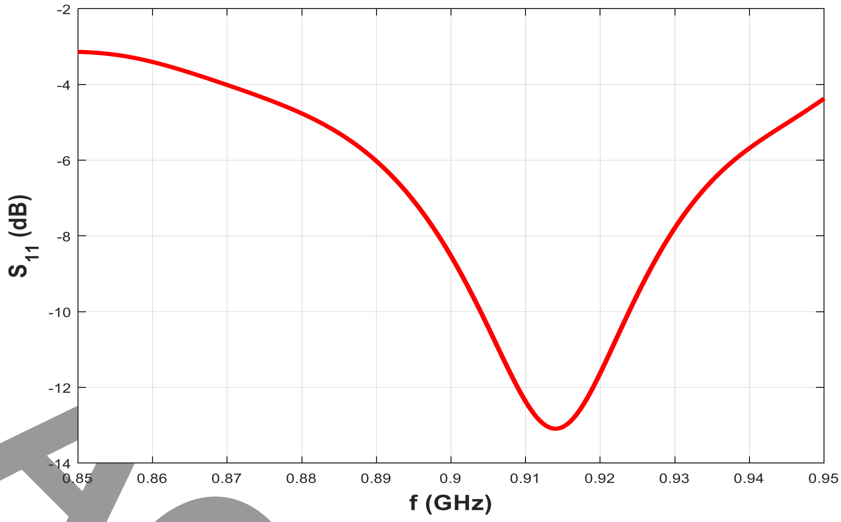

Figure 13. Reflection coefficient results using 85.2-mm substrate width.

Similarly, an empirical test is done over the substrate length at this stage, where the lowest acceptable value is found to be 87 mm whose reflection coefficient results are shown in Figure 14.

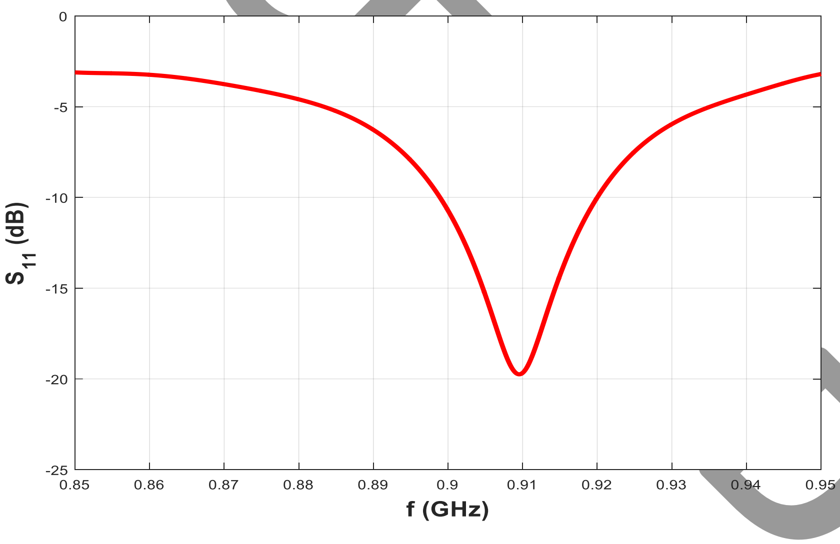

Figure 14. Reflection coefficient results using 87-mm substrate length.

Based on the above, the optimal empirical substrate width and length are temporarily 85.2 and 87 mm, respectively. Again, these values apply to the ground plane as well. However, there is still a huge potential to play around the substrate thickness to reduce it below 1.4 mm that is considered large so far. Therefore, the thickness is arbitrarily decreased to 1.3 mm in order to see the trend, and an improved reflection curve is yielded as shown in Figure 15.

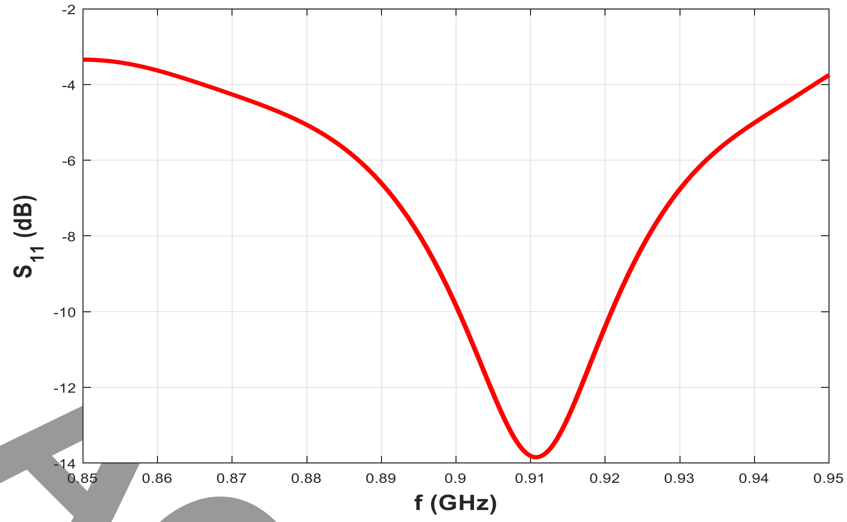

Figure 15. Reflection coefficient results using 1.3-mm substrate thickness.

In fact, the antenna dimensions and reflection results achieved so far are quite satisfactory for passive UHF RFID applications. However, at this stage, a final step still needs to be performed, which involves a careful empirical reduction of all achieved dimensions to ensure an ultimate miniature size.

As a result, the minimum successful values obtained are 0.9 mm for the substrate thickness, 85 mm for the substrate width, 85 mm for the patch width, and 85.6 mm for the patch length. The final reflection results are shown in Figure 16, noting that the optimal substrate length does not vary from 87 mm.

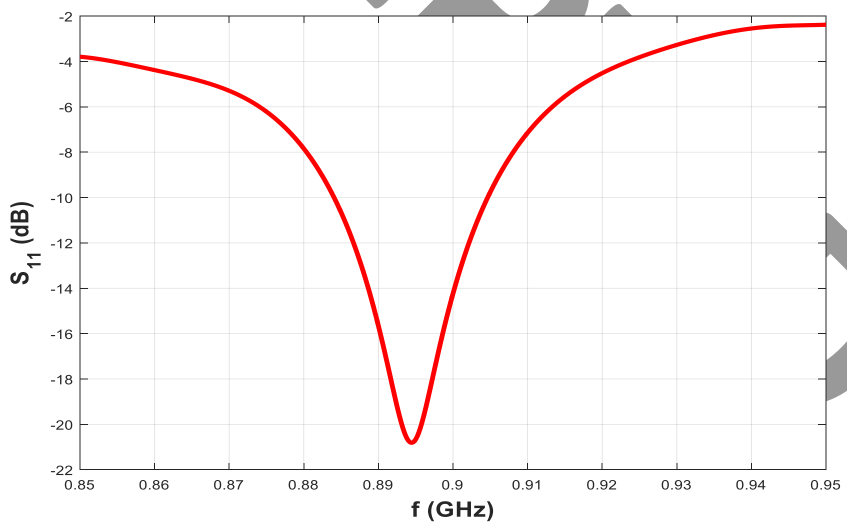

Figure 16. Reflection coefficient results using 0.9-mm substrate thickness, 87-mm substrate length, 85-mm substrate width, 85.6-mm patch length, and 85-mm patch width.

3 Antenna design

Based on the above comprehensive parametric study, the final antenna design can be concluded at this point, where it maintains the original looped-slot dimensions [38] but with updated specifications of the patch, substrate, and ground. Again, the patch and ground are made of aluminium rather than copper due to less price, while the substrate is made of FR4 dielectric. Figure 17 shows the top-view of the final CST design upon which the slot values are written (in mm). Table 2 shows the new antenna parameters and the comparison with the pervious values.

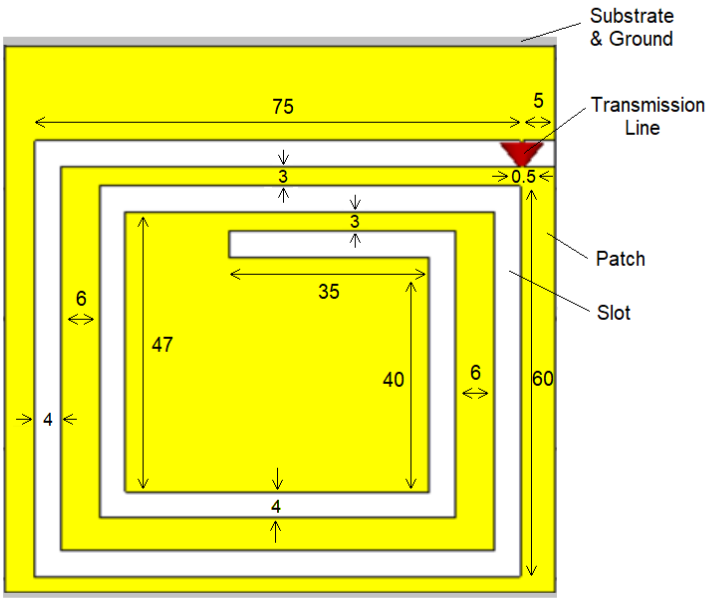

Figure 17. Final antenna design (dimensions are in mm).

Table 2. Final antenna parameters.

Parameter	Value (mm)	Previous value [38]
Substrate thickness	0.9 (1-layer)	3.862 (3-layers)
Substrate & ground length	87	85
Substrate & ground width	85	85
Patch length	85.6	81.29
Patch width	85	85

It is obvious that the significant reduction in substrate thickness required some expansion of the patch and substrate lengths, although it should be noted that the expansion was in a direction that, from our perspective, is above the slit. However, the new antenna surface remains comparable to the previous design, with the increment in the substrate (and ground) length being less than 3%, while the patch increment is approximately 5%. Nevertheless, the overall structure is much simpler and smaller since the entire thickness is reduced by more than 75% using a single-layered material instead of three layers of two different materials.

4 Results

The reflection characteristics of the new design were already shown at the end of the parametric study in Figure 16. However, the curve is repeated in Figure 18 to show the precise resonant value along with the bandwidth measurement. It is obvious that the curve is perfectly smooth and has a resonant frequency at 894.4 MHz with a bandwidth reading of 20.5 MHz in the range 884.1-904.6 MHz.

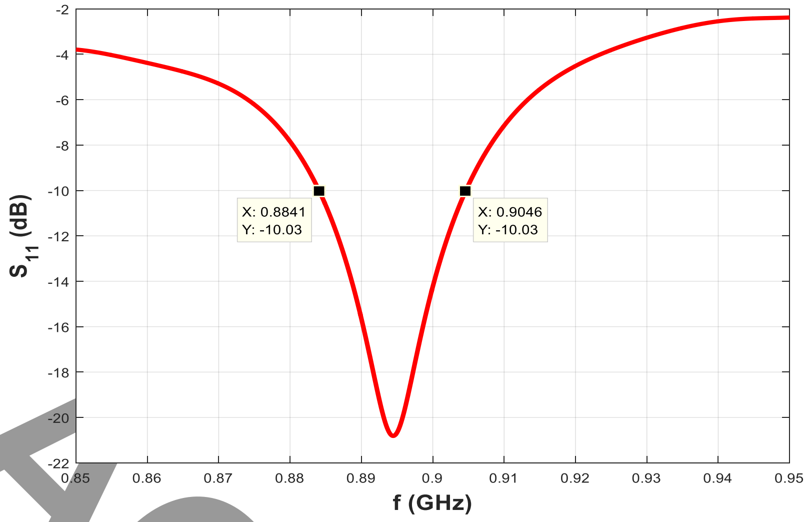

Figure 18. Final reflection coefficient results showing the resonant frequency and the bandwidth.

At this point, it is essential to present the radiation pattern of the new design in the E-plane and H-plane, as depicted in Figure 19. Obviously, the main lobe gain successfully reaches 4.14 dBi in the H-plane at the resonant frequency of 894.4 MHz. In addition, Figure 20 plots the directivity versus degree, clearly indicating a main lobe direction of 34°. Furthermore, the reading distance has been computed through simulation to be between 12 and 15 meters. This result implies that, in addition to the dramatic antenna size reduction, the maximum gain is improved by 1.64 dB (46%) with acceptable directivity and resonance bandwidth.

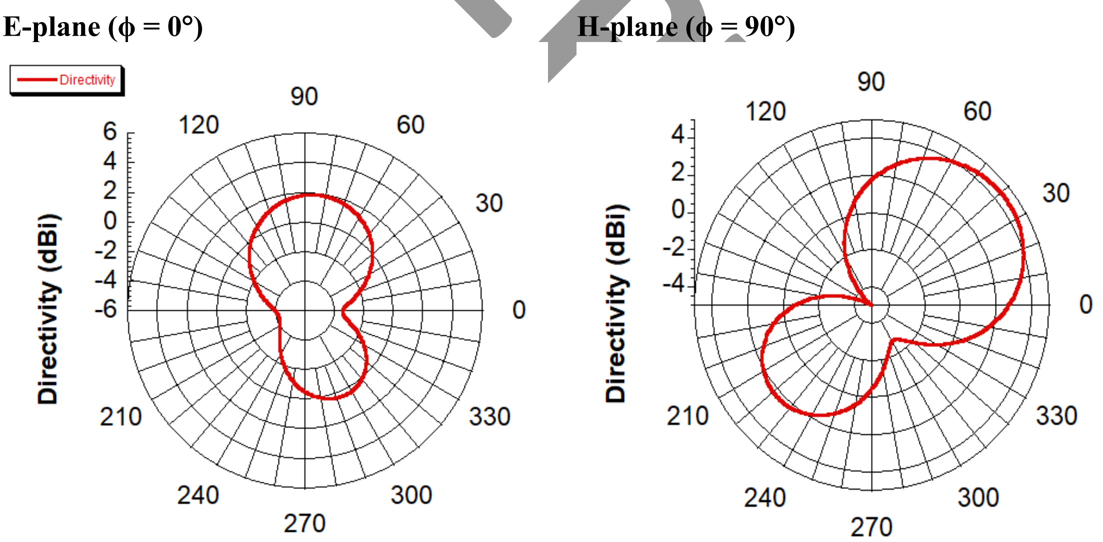

Figure 19. 2D directivity patterns of the new antenna.

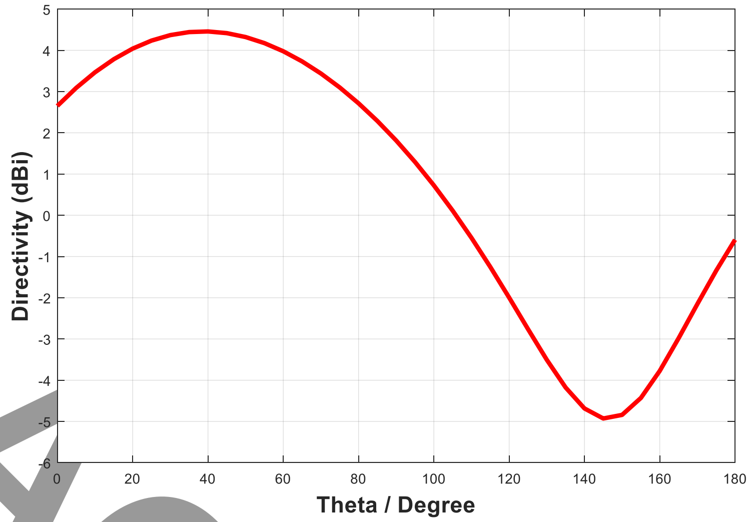

Figure 20. Gain with respect to theta.

In essence, the enhanced performance of the antenna can be attributed to two factors: 1) the existence of a looped slot, which acts as a resonating element and effectively increases the electrical size of the patch within compact physical dimensions, and 2) the careful selection of design parameters, including substrate size, ground dimensions, and patch area.

5 Conclusion

This paper presented a gain enhancement and a size reduction results of a looped-slot microstrip patch antenna for passive UHF RFID applications. The paper demonstrated a detailed parametric investigation using the CST simulator in order to optimize the overall antenna design. As a result, a miniaturized design has been achieved with a total surface area of 87×85 mm^2, utilizing an aluminium patch and ground plane separated by a single FR4 substrate with 0.9-mm thickness. The proposed antenna yielded a gain of 4.14 dBi at 894.4 MHz with a frequency bandwidth of 20.5 MHz, ranging from 884.1 to 904.6 MHz. The powerful point of the design is that the number of substrate layers was securely reduced from three layers of two dielectric materials to single dielectric layer. This allowed the overall thickness of the antenna to be reduced by more than 75%, while at the same time increasing the gain by 46%. In practice, this achievement would facilitate antenna fabrication processes and result in a significant reduction in the overall cost of RFID systems, while also improving directivity.

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