

READING RANGE IMPROVEMENT FOR UHF RFID READER WITH METAMATERIAL-BASED SRR ARRAY STRUCTURE

Pornpat Pramerudeechaisak and Rangsan Wongsan^{*}

Received: March 14, 2019; Revised: May 14, 2019; Accepted: May 17, 2019

Abstract

Nowadays, the use of high performance UHF RFID readers is growing rapidly, while their cost is still high. This research presents a method for improving the performance of low cost UHF RFID readers by focusing on the reading range extension at the center frequency of 910 MHz of such readers. The proposed method is to raise the gain of a reader's antenna by using an array structure of split ring resonators using a metamaterial technique; this is properly located at the front side, and a metallic sheet is added at the backside of the RFID reader without modifying its antenna or adding any RF amplifier circuit into the original reader. From the simulation results using CST software, we found that our proposed structure of metamaterial could improve the gain of the original UHF RFID reader by around 10.375 dB (from 0.825 dB to 11.20 dB) and cover the desired bandwidth of the UHF RFID (860-960 MHz). Finally, the prototype of the proposed structure was fabricated and tested in the laboratory and then compared to the simulation results. We found that they were in good agreement.

Keywords: RFID reader, split ring resonator, metamaterial, antennas

School of Telecommunication Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand. E-mail: rangsan@sut.ac.th; M5840786@g.sut.ac.th

^{} Corresponding author*

Introduction

In recent years, automatic identification procedures have become popular for applications in many industrial services, logistics, and manufacturing. They are used to identify and track items, verify, record, communicate, and store information. The automated information is processed more quickly and accurately than by humans. The most common technologies used to identify data are barcode labels that created a revolution in identification systems but which are being found to be increasingly inadequate; although barcode labels are cheap, they have a limited storage capacity and cannot be reprogramed (Ugarte-Muñoz *et al.*, 2008). The technology currently replacing barcode labels for tracking is called radio frequency identification (RFID) by which the storage of data in a chip can be read without mechanical contact, i.e. it is contactless. The RFID system uses electromagnetic fields to track automatically the tags which are attached to objects. Even though this technology was developed in 1980 by Leon Theremin, there is continuous interest in its development, especially for the topics of a high transmission rate, the reading of multiple tags, long distance tag reading, etc., because they are used in a variety of ways in business and daily life. An RFID system is formed with 2 devices: (1) the transponder or tag that is attached to the objects to be identified and (2) the reader or interrogator, which sends a signal to the tag and reads its response. At present, the RFID frequency bands are divided into 4 bands, namely, LF: 30-300 kHz, HF: 13.57 MHz, UHF: 900 MHz, and 2.45 GHz.

In this paper, we focus on the UHF RFID system because of its small size and the ability for some of its performances, such as high read rate and reading range extension, to be developed. From a literature review, researchers found that some serious restrictions relating to mountable platform objects, such as metals or high dielectric materials, are the major drawback (Park and Kim, 2014). To overcome such disadvantages, researchers have tried to explore methods and techniques to design a tag's antenna for mountable metallic objects

(Chen and Mittra, 2010; Abdulhadi and Abhari, 2012). Moreover, some have designed miniaturized tags for applications for small objects (Chen and Lin, 2008; Chen, 2009) and improved the performances of the systems (Tabakh *et al.*, 2015). However, these methods still have some disadvantages and may not be good enough for the current demand because the UHF RFID systems are growing rapidly. Presently, therefore, many researchers are exploring methods for increasing the performance of such the systems by getting the most benefit from metamaterials.

Metamaterials are a new class of composite materials that exhibit unusual electromagnetic properties that are not found in conventional materials, such as a negative refractive index and negative magnetic permeability (Angkawisittpan, 2010); these have been investigated and developed by many researchers and it was found that there are many types of metamaterial techniques to overcome some electromagnetic properties for improving the antenna's performance (Hamzaoui *et al.*, 2015; Dadgarpour *et al.*, 2016). However, it was found that a metamaterial base on a split ring resonator (SRR) is a magnetic resonator providing a negative permeability (μ -negative or MNG) region around the resonance frequencies (Castro *et al.*, 2013). Furthermore, it has the easiest structure to design and the lowest cost. From the literature review, we found that a metamaterial-based SRR's structure has been used to improve the characteristics of antennas. For instance, the gain enhancement of a rectangular waveguide antenna with a broadside S-shaped structure of metamaterials placed above its aperture was reported in Aribi *et al.* (2010), while improving the gain of a microstrip patch antenna was done by using an arrangement of a complementary G-shaped split ring resonator loaded around the rectangular patch (Bakry and Hamed, 2014). Besides that, the characteristics of the rectangular microstrip patch antenna could be improved by superimposing the rectangular metamaterial-based SRR structure with negative μ and ϵ on the opposite surface of the patch

(Tomar, 2014). In this paper, therefore, the SRR array is used to improve the antenna gain of a UHF RFID reader for reading the range extension between the RFID reader and the tag, while the inside of the original reader is without any modification.

This paper is organized as follows: Section I is the introduction, Section II is the theory and configurations of the proposed SRR array for the antenna's gain improvement, while in section III the optimized simulation results will be presented. Finally, the discussion and conclusion will be covered in Section IV.

Theory and Configurations

Study of Original Antenna of UHF RFID Reader

Initially, the antenna inside the selected UHF RFID reader was studied, and we found that the antenna of such a reader is a basic wire antenna (folded monopole) placed over the printed circuit board with dimensions of 60×85 mm. This antenna is made from an aluminum wire with a radius of 0.5 mm and it operated on the 860-960 MHz frequency band with the reader's and antenna's, as shown in Figure 1(a) and 1(b), respectively.

After that, the structure of the antenna with its dimensions was simulated by CST Microwave Studio (CST) software to obtain the reference results before development. From the simulated results as shown in Figure 2, it was found that the resonant frequency of the original wire antenna is around 910 MHz with the minimum reflection coefficient (S_{11}) about -5.944 dB, while its radiation pattern is nearly omnidirectional with a half power beamwidth (HPBW) equal to 92.8°, its directivity equal to 2.28 dBi, and the realized gain around 0.825 dB.

Numerical Simulation and Equivalent Circuit Modeling of the Isolated SRR Unit Cell

In order to extend the reading range between the RFID tag and the reader, the metamaterial-based SRR array structure is

used to increase the directive gain obtained from the previous section. We started with the unit cell design of a square SRR combined with the H-shaped structure of an additional inductance, as illustrated in Figure 3(a), operated at 910 MHz of center frequency and numerically analyzed by using the CST software that is based on the finite integration technique (FIT). However, such a structure is also represented by a simple LC resonant circuit, as shown in Figure 3(b), in which the resonance frequency can be obtained from the well-known formula $f_0 = (2\pi\sqrt{L_T C_T})^{-1}$, where L_T is the total inductance and C_T is the total capacitance.

Firstly, we started from the equivalent circuit of the square SRR element; the sketch is shown in Figure 4(a), while its equivalent circuit is shown in Figure 4(b), where L_l is the self-inductance of a square loop forming the SRR element and C_l is the capacitance of the split.

An expression for the self-inductance of a square loop mode from a rectangular cross section wire is given by Johnson *et al.* (2006):

$$L_1 = L_2 = 0.2\mu_0 \left(-\frac{w}{2} \sinh^{-1} 1 + \frac{w}{2} \sqrt{2} + \left(l - \frac{w}{2} \right) \sinh^{-1} \left(\frac{l - \frac{w}{2}}{\frac{w}{2}} \right) - \sqrt{\left(l - \frac{w}{2} \right)^2 + \left(\frac{w}{2} \right)^2} \right) \quad (1)$$

$$\begin{aligned} L_1 = L_2 &= 0.2(1.256 \times 10^{-6}) \\ &\left(-\frac{3 \times 10^{-3}}{2} \sinh^{-1} 1 + \frac{3 \times 10^{-3}}{2} \sqrt{2} + \left(44 \times 10^{-3} - \frac{3 \times 10^{-3}}{2} \right) \sinh^{-1} \left(\frac{44 \times 10^{-3} - \frac{3 \times 10^{-3}}{2}}{\frac{3 \times 10^{-3}}{2}} \right) \right. \\ &\quad \left. - \sqrt{\left(44 \times 10^{-3} - \frac{3 \times 10^{-3}}{2} \right)^2 + \left(\frac{3 \times 10^{-3}}{2} \right)^2} \right) \\ &= 3.2624 \times 10^{-8} H. \end{aligned}$$

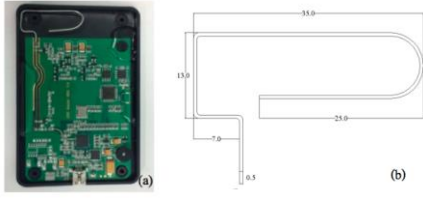


Figure 1. Structure of the UHF RFID reader: (a) antenna inside the reader and (b) structure of the antenna

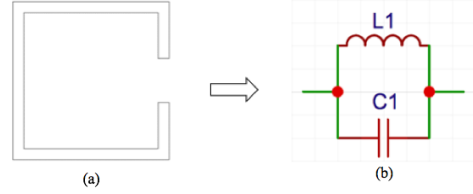


Figure 4. (a) Sketch and (b) equivalent circuit model of the square SRR element

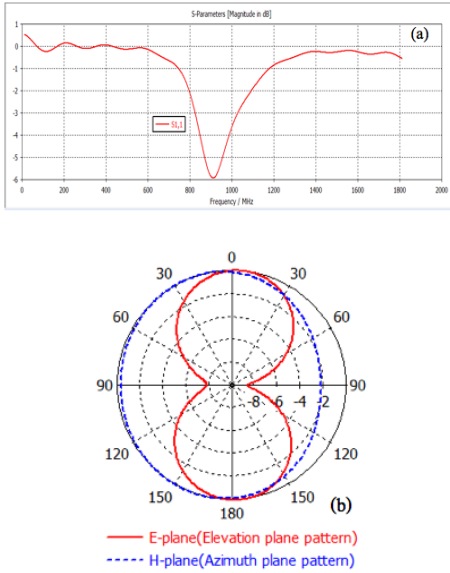


Figure 2. Simulated reflection coefficient (S_{11}) and radiation patterns of the original wire antenna of the RFID reader

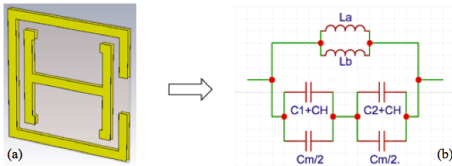


Figure 3. (a) Sketch and (b) equivalent circuit model of the proposed SRR

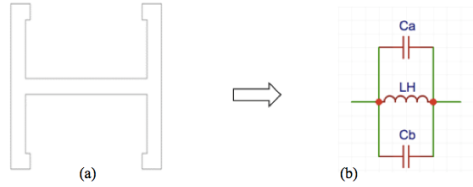


Figure 5. (a) Sketch and (b) equivalent circuit model of the H-shaped element

The capacitance can be approximated by

$$C_1 = C_2 = \frac{\epsilon_0 \epsilon_r w l}{g} \quad (2)$$

$$C_1 = C_2 = \frac{8.854 \times 10^{-12} \times 4.4 \times 3 \times 10^{-3} \times 44 \times 10^{-3}}{12 \times 10^{-3}},$$

$$= 4.2853 \times 10^{-3} \text{ F.}$$

where, referring to Figure 6, l is the length of the SRR element, w is the width of the wire forming the split ring, g is the opening of the rings or the gap, μ_0 is the permeability of vacuum equal to 1.256×10^{-6} [H/m], and ϵ_0 is the permittivity of vacuum equal to 8.854×10^{-12} [F/m].

In the second step, we focused on the H-shaped element and its equivalent circuit, as shown in Figure 5(a) and 5(b), respectively, where L_H is the self-inductance of the H-shaped element and C_a , C_b is the capacitance of the split.

An expression for the self-inductance of an H-shaped element can be calculated from Singh *et al.* (2015):

$$L_H = \mu_0 d \left[\log \left(\frac{2d}{w} \right) + 0.9 + 0.2 \left(\frac{w}{2d} \right)^2 \right] \quad (3)$$

$$L_H = (1.256 \times 10^{-6} \times 16.5 \times 10^{-3}) \left[\log \left(\frac{2 \times 16.5 \times 10^{-3}}{3 \times 10^{-3}} \right) + 0.9 + 0.2 \left(\frac{3 \times 10^{-3}}{2 \times 16.5 \times 10^{-3}} \right)^2 \right] = 9.01128 \times 10^{-3} H.$$

The total capacitance (C_H), can be calculated as, $C_H = C_a + C_b = C_H = 2 \times 1.7141 \times 10^{-13} = 3.4282 \times 10^{-13} F$. Since the split gaps have identical dimensions $S_1 = S_2$, hence the gap capacitance $C_a = C_b$, can be approximated by

$$C_a = C_b = \frac{\epsilon_0 \epsilon_r w l}{s} \quad (4)$$

$$C_a = C_b = \frac{8.854 \times 10^{-12} \times 4.4 \times 3 \times 10^{-3} \times 44 \times 10^{-3}}{30 \times 10^{-3}} = 1.7141 \times 10^{-13} F.$$

where s is the opening of the ring or the gap.

In the third step, a combination of the 2 previous steps was done by using the method from Can *et al.* (2017) for utilizing as the SRR unit cell, as shown in Figure 6.

From Figure 6, the total inductance (L_a), can be calculated as:

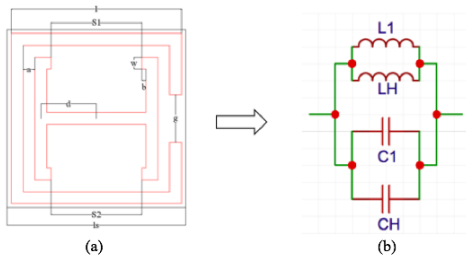


Figure 6. (a) Sketch and (b) equivalent circuit model of the proposed SRR unit cell

$$L_a = L_b = \frac{3.2624 \times 10^{-8} \times 9.01128 \times 10^{-9}}{(3.2624 \times 10^{-8}) + (9.01128 \times 10^{-9})} = 9.3905 \times 10^{-9} H.$$

Finally, our prototype is the new split ring resonator structure that was organized on 2 square surfaces of the structure. Each side of the substrate surface consists of an H-shaped SRR and a square-shaped SRR made from a copper strip on FR-4 PCB. Hence, the final SRR unit cell and its equivalent circuit model are shown in Figure 3 where C_m is the mutual capacitance between the 2 rings and h is the thickness of the substrate, and it can be approximated from Wang *et al.* (2009):

$$C_m / 2 = \frac{\epsilon_0 \epsilon_r (4l - g)}{2h} \quad (5)$$

$$C_m / 2 = \frac{(8.854 \times 10^{-12} \times 4.4 \times 3 \times 10^{-3}) ((4 \times 44 \times 10^{-3}) - (12 \times 10^{-3}))}{2 \times 1.6 \times 10^{-3}} = 5.9898 \times 10^{-12} F.$$

when they are assembled, the equivalent circuits of the SRR on 2 surfaces of FR-4 PCB as shown in Figure 3(b), the total of the capacitance, inductance, and the resonant frequency of the SRR unit cell will be calculated by these expressions:

$$C_c = C_d = 6.7612 \times 10^{-12} F.$$

$$L_T = L_A L_B / (L_A + L_B) = 4.6953 \times 10^{-9} H.$$

$$C_T = C_c C_d / (C_c + C_d) = 3.3806 \times 10^{-12} F.$$

$$f_0 = \left(2\pi \sqrt{L_T C_T} \right)^{-1} = 911.863 \text{ MHz}.$$

Obviously, the proposed equivalent circuit model achieved good agreement with only 0.204% of error.

The isolated unit cell of the SRR has 1 gap of the width (g) combined with the H-shaped structure, which is placed at the middle of each side of the square loop, as shown in Figure 6. This full structure of copper strips is printed on a low loss dielectric substrate (FR-4) with $\epsilon_r = 4.4$ and $\tan \alpha = 0.01$. In order to investigate

Table 1. Dimension of proposed SRR unit cell (mm)

ls	l	w	a	g	b	d	S ₁	S ₂
45	44	3	3	12	1	16.5	30	30

the most proper dimensions of this SRR structure, the parameters such as a , b , d , w , s , and g , as shown in Figure 6, will be adjusted and simulated by the CST software to obtain the appropriately desired results that are shown in Table 1. Here, l_s means the length of the substrate, l means the length of the SRR element, w means the wire forming the split ring, a means the dielectric width between the inner and the outer rings, g means the gap of the square ring, b means the length of the H-shape's arm, d means the distance between

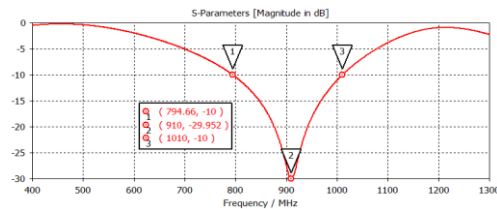


Figure 7. Simulated S_{11} of the proposed SRR unit cell

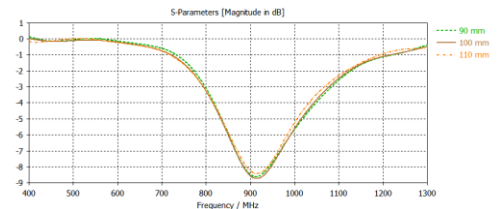


Figure 8. The simulated reflection coefficient versus frequency of each distance between the UHF RFID reader and the reflector

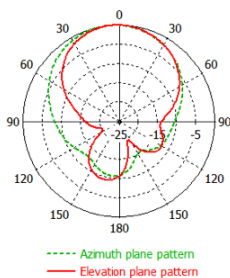


Figure 9. Simulated patterns of the RFID reader's antenna with a metallic reflector

the center of the H-shaped structure, and S_1 and S_2 mean the gap of the H-shaped structure.

In Figure 7, the simulated reflection coefficient (S_{11}) as a function of frequency is illustrated. It is seen that the simulated reflection coefficient (S_{11}) of the proposed SRR unit cell is around -29.972 dB at 908.8 MHz of the resonant frequency, while the obtained frequency bandwidth is around 200 MHz (800 MHz-1,000 MHz), which can cover the frequency band (860-960 MHz) such as that of the UHF RFID reader.

To modify the HPBW of the main beam of the reader's antenna matching with the size of the SRR's metamaterial structure and obtain a higher directive gain, the additional rectangular metallic reflector that is 200 mm in width and 250 mm in length was placed behind the UHF RFID reader. We found that the spacing between RFID antenna and reflector at 100 mm is the proper distance, even though S_{11} is still rather high; the simulated reflection coefficient of each varying distance between the UHF RFID reader and reflector is illustrated in Figure 8.

It was found that the resonant frequency of the reader's antenna is still in the desired band at 911.8 MHz with the simulated S_{11} being around -8.729 dB. Besides, its HPBWs in the E- and H-planes are around 76.1° and 91.2°, respectively, as shown in Figure 9, while the obtained gain is around 6.29 dB and the front-to-back (F/B) ratio is around 9.39 dB.

However, we found that the back lobe level (BLL) was also rather high. Therefore, to reduce its back lobe level (BLL) we added 4 small wings, which tilted from each edge of the old rectangular reflector at around 45°. Consequently, its new dimensions are 200 mm and 350 mm for the width and the length, respectively. After that, the spacing of the new reflector was adjusted again, as shown in Figure 10. It was found that the spacing of 90 mm can provide the lower BLL and a symmetric HPBW. However, the reflection coefficient at the resonant frequency at 911.8 MHz is not different (S_{11} is around -9.041 dB).

In Figure 11, the obtained HPBW in the E- and H-planes are around 66.8° and 74.6°, respectively. It was found that the simulated

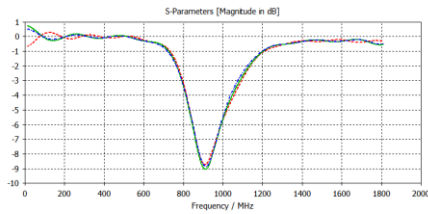


Figure 10. The simulated reflection coefficient of each distance between the UHF RFID reader and the new reflector

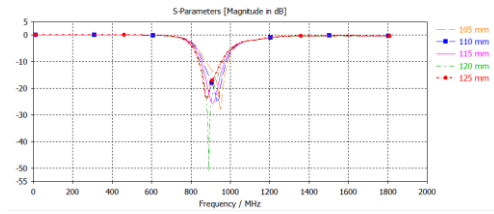


Figure 13. The simulated S_{11} of the proposed antenna structure when the spacing between the reader and metamaterial is varied

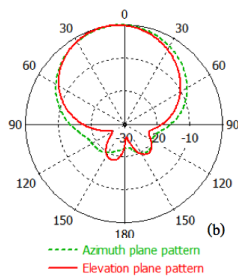


Figure 11. Simulated patterns of the RFID reader's antenna with a new reflector

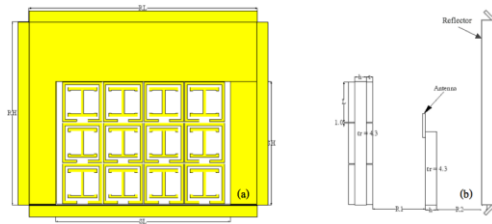


Figure 12. Geometrical structure of the SRR array-based metamaterials, reader's antenna, and reflector: (a) front view and (b) side view

patterns are rather symmetrical that accords with the shape and dimension of the SRR array structure, while the simulated gain is around 7.89 dB and the F/B ratio is around 18.542 dB.

In the last step, in order to increase the gain of the reader's antenna with the optimized reflector, the SRR's unit cells were organized to be an array structure of metamaterial with 3×4 elements placed at the front of the UHF RFID reader with the initial spacing around 115 mm, as displayed in Figure 12. The

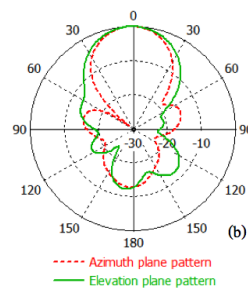
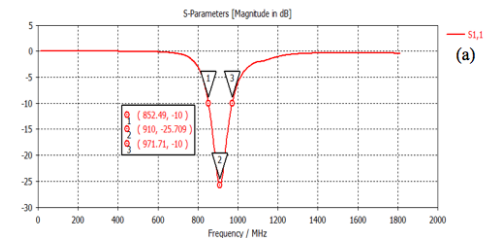


Figure 14. Simulated results of the proposed structure: (a) S_{11} and (b) 2D radiation patterns

geometry of the metamaterial structure, which was formed with the array of 3×4 elements for the proposed SRR unit cells, was installed at front of the UHF RFID reader with the proper spacing (R_3), while spacing between RFID reader and reflector is R_2 .

To optimize the spacing (R_3) between the SRR array structure and UHF RFID reader, such spacing was varied from 105-125 mm by simulation with the CST software. Then the simulated results of S_{11} were considered to

a good matching condition for all the antenna's structure, as illustrated in Figure 13.

We found that the spacing R_3 at 110 mm and 115 mm provided very good matching of the antenna's structure with the simulated results of S_{11} equal to -25.515 dB and -25.709 dB, respectively. However, we selected the spacing of 115 mm since the antenna still retained the resonant frequency at 910 MHz as

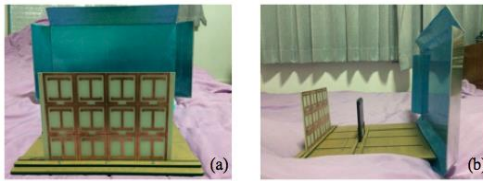


Figure 15. Structure of the antenna prototype comprising the UHF RFID reader, reflector sheet, and SRR's array

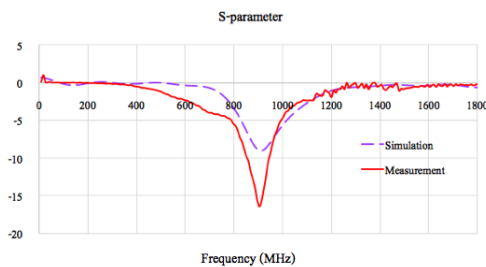


Figure 16. Comparison results of the simulated and measured S_{11} in the case of the UHF RFID reader and designed reflector

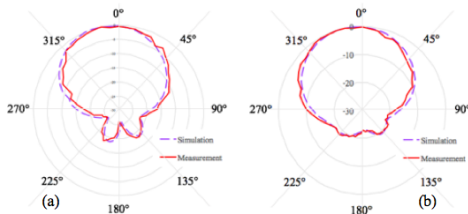


Figure 17. Comparison results of the normalized patterns in the elevation and azimuth plane of the UHF RFID reader with designed reflector

we required, while, with the spacing R_3 at 110 mm, the resonant frequency of the antenna shifted up to 935.2 MHz. Nevertheless, the obtained bandwidth started from 852.49 MHz to 971.71 MHz at S_{11} -10 dB, covering the specific bandwidth as illustrated in Figure 14(a). In addition, the simulated radiation patterns in the E- and H-planes provide the HPBW at around 49.6° and 41.7°, respectively, while the realized gain of the proposed structure is obtained around 11.2 dB and the F/B ratio is around 12.24 dB, as shown in Figure 14(b).

Fabrication and Test

A prototype of the proposed structure for testing and validating with the simulated results as aforementioned was fabricated, as shown in Figure 15. The original UHF RFID reader was sandwiched with the SRR array structure and the metallic reflector located at the front and behind the RFID reader with the optimized spacing R_2 and R_3 , respectively. In order to verify the simulated results, the antenna prototype was measured in an anechoic chamber room and compared to the simulation results, which will be discussed and concluded in this section.

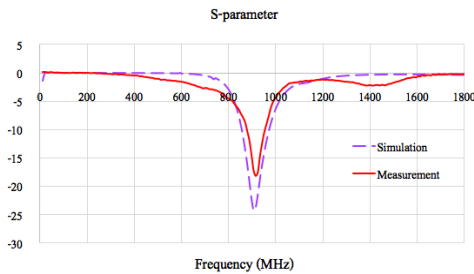
To verify the performance of the antenna before and after installing the SRR array structure, the UHF RFID reader with the reflector was measured for reference. It was found that the simulated and measured reflection coefficients in this case were in good agreement, as shown in Figure 16, in which S_{11} was around -9.041 dB and -16.43 dB at 911.8 MHz and 905 MHz, respectively.

Besides, the measured E- and H-plane patterns of the UHF RFID reader with the designed reflector were also compared to the simulated results, as illustrated in Figure 17. We found that its radiation patterns, especially the HPBWs were not very different. The E- and H-plane patterns are around 66° and 74.52°, respectively.

In this final step, the structure of the SRR array was placed at the front of the UHF RFID reader with the optimized spacing obtained from the simulation. Then all parts of the antenna's structure were measured to consider its performance. In Figure 18, the measured

Table 2. Comparison between the simulated and measurement gain of antennas

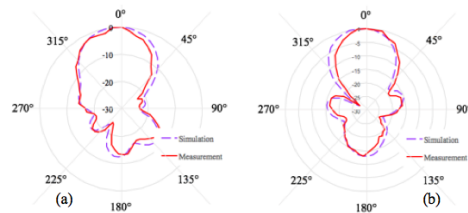
Gain of antenna	Simulation results	Measurement results
Original UHF RFID reader's antenna	0.825 dB	0.994 dB
UHF RFID reader with reflector	7.89 dB	6.61 dB
Proposed structure for UHF RFID reader	11.2 dB	10.68 dB

**Figure 18. Comparison results of S_{11} from the simulation and measurement of the proposed antenna structure**

result of S_{11} was compared to the result from the simulation. We found that the results from simulation and measurement were around -25.709 dB at 910 MHz and -18.26 dB at 913.95 MHz, respectively, showing that after the structure of the SRR array had been installed, the resonant frequency of the antenna was still retained and its matching condition was improved.

In Figure 19, the comparison of the E- and H-plane patterns of the proposed antenna's structure from the simulation and measurement are compared. It is noted that the simulated and measured patterns are in very good agreement, while the HPBW's in E- and H-planes are around 48° and 41.3° , respectively. Finally, we have summarized the obtained gains from the simulation and measurement from each step of our study into Table 2.

From Table 2, it is noted that when the original UHF RFID reader is sandwiched with the proper reflector and the proposed SRR array, the simulated gain of the RFID reader can be increased around 10.375 dB (from 0.825 dB to 11.20 dB) and the desired bandwidth of the UHF RFID still covers from 860 MHz to 960 MHz, while the measured gain is increased around 9.686 dB (from 0.994 dB to 10.68 dB). Furthermore, we tested the reading distance of

**Figure 19. Comparison results of the normalized patterns in the elevation and azimuth plane from the simulation and measurement of the proposed antenna structure**

the original UHF RFID reader compared to the obtained distance from our antenna's structure. We found that the original one could read the tag at 115 mm, while the proposed structure can read the tag at 540 mm, which shows that the structure can extend the reading range around 370%.

Conclusions

A technique for enhancement of the reading range of the UHF RFID reader using a metamaterial structure at a center frequency 910 MHz was proposed. The SRR array structure comprised 4×3 unit cells located in front and the designed metallic reflector is located behind the original antenna without modifying the structure of the original RFID reader or adding any RF amplification circuit into the system. The main object is to improve the reading distance of the general UHF RFID reader. The important parameters of the proposed structure, such as reflection coefficient (S_{11}), realized gain, and radiation patterns were calculated by using the CST software and were validated with the measured results of the antenna. To summarize, the proposed structure could improve the antenna

gain of the original UHF RFID reader by around 10.375 dB.

Acknowledgement

This work was supported by the Research Department, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima, Thailand.

References

- Abdulhadi, A.E. and Abhari, R. (2012). Passive UHF RFID printed monopole tag antenna for identification of metallic objects. *Proceedings of the IEEE International Symposium on Antennas and Propagation*; July 8- 14, 2012; Chicago, Illinois, USA, p. 1-2.
- Angkawisittpan, N. (2010). *Metamaterials*. CU Eng. J., 3(2):52-60. (in Thai)
- Aribi, T., Lou, K. M., and Ghobadi, C. (2010). Enhancement gain of rectangular waveguide antenna by electromagnetic metamaterial. *Proceedings of the 1st International Conference on Communications Engineering*; December 22- 24, 2010; Zahedan, Iran, p. 122-125.
- Bakry, M. M., Abel-Rahman, A. B., and Hamed, H. F. A. (2014). Gain and bandwidth improvement of microstrip patch antenna using complementary g-shape split ring resonator. *Proceedings of the 31st National Radio Science Conference*; April 28-30, 2014; Cairo, Egypt, p. 35-40.
- Can, S., Yilmaz, A. E., and Kapusuz, K. Y. (2017). An equivalent-circuit model of miniaturized split-ring resonator. *Proceedings of the 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*; July 9-15, 2017; San Diego, CA, USA, p. 263-264.
- Castro, P. J., Barroso, J. J., and Neto, J. L. (2013). Experimental study on split-ring resonators with different slit width. *J. Electromagn. Anal. Appl.*, 5(9):366-370.
- Chen, S.L. (2009). A miniature RFID tag antenna design for metallic objects application. *IEEE Antenn. Wirel. Pr.*, 8:1,043-1,045.
- Chen, S.L. and Lin, K.H. (2008). A slim RFID tag antenna design for metallic object applications. *IEEE Antenn. Wirel. Pr.*, 7:729-732.
- Chen, S.L. and Mittra, R. (2010). A long read range RFID tag design for metallic objects. *Proceedings of the 4th European Conference on Antennas and Propagation*; April 12- 16, 2010; Barcelona, Spain, p. 1-3.
- Dadgarpour, A., Kishk, A. A., and Denidni, T. A. (2016). Gain enhancement of planar antenna enabled by array of split-ring resonator. *IEEE T. Antenn Propag.*, 64(8):3,682-3,687.
- Hamzaoui, D., Vuong, T. P., Djahli, F., and Kiani, G. I. (2015). Metamaterial RFID tag designs for long read range. *Proceedings of the IEEE Antennas and Propagation & USNC/ URSI National Radio Science Meeting*; July 19- 24, 2015; Vancouver, BC, Canada, p. 1,764-1,765.
- Johnson, N. P., Khokhar, A. Z., Chong, H. M. H., De La Rue, R. M., and McMeekin, S. (2006). Characterization at infrared wavelengths of metamaterials formed by thin-film metallic split-ring resonator arrays on silicon. *Electron. Lett.*, 42:1,117-1,118.
- Park, I. Y. and Kim, D. (2014). Artificial magnetic conductor loaded long-range passive RFID tag antenna mountable on metallic objects. *Electron. Lett.*, 50:335-336.
- Singh, R., Kumar, N., and Gupta, S. C. (2015). Investigation of resonance characteristic and effective parameter of a metamaterial structure with split ring. *Sci. Res. Essays*, 10(4):156-163.
- Tabakh, I., Allabouche, K., Jorio, M., Idrissi, N. E., and Mazri, T. (2015). Design and simulation of a new dual-band microstrip patch antenna for UHF and Microwave RFID applications. *Proceedings of the 2015 3rd International Workshop on RFID and Adaptive Wireless Sensor Networks*; May 13-15, 2015; Agadir, Morocco, p. 33-37.
- Tomar, A. (2014). Design of square split ring resonator shaped metamaterial structure for enhancing the microstrip patch antenna parameters. *Int. J. Res. Elect. Comm. Tech.*, 1(3):21-24.
- Ugarte-Munoz, E., Herraiz-Martínez, F. J., Gonzalez-Posadas, V., and Segovia-Vargas, D. (2008). Patch antenna based on metamaterials for a RFID transponder. *Radioengineering*, 17(2):66-71.
- Wang, J., Qu, S., Zhang, J., Ma, H., Yang, Y., Gu, C., Wu, X., and Xu, Z. (2009). A tunable left-handed metamaterial based on modified broadside-coupled split ring resonators. *Prog. Electromagn. Res. Lett.*, 6:35-45.