This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LAWP.2018.2806993, IEEE Antennas and Wireless Propagation Letters

Broadband Circularly Polarized H-shaped Patch Antenna using Reactive Impedance Surface

Joysmita Chatterjee, Akhilesh Mohan, *Member IEEE*, and Vivek Dixit

***Abstract*— A compact, single-feed, broadband circularly polarized patch antenna is proposed in this letter. The antenna comprises of an H-shaped microstrip patch printed over a metamaterial inspired Reactive Impedance Surface (RIS). The RIS structure comprising of a lattice of 4 × 4 periodic metallic square patches help to increase the bandwidth of the antenna. The final optimized structure exhibits an impedance bandwidth of 44.5% (4.64 – 7.3 GHz) alongwith a 3-dB axial ratio bandwidth of 27.5% (4.55 – 6 GHz). Moreover, the proposed antenna yields a good broadside gain of 7.2 dBi at 5.5 GHz. The radiation efficiency of the present structure is better than 77% for the entire band of operation.**

***Index Terms*—Circular polarization, patch antenna, reactive impedance surface, broadband.**

I. INTRODUCTION

Microstrip patch antennas are extensively used in wireless communication systems because of their small size, light weight and low cost [1]. In the present scenario, for many wireless applications, circularly polarized (CP) antennas are gaining increasing importance compared to the linearly polarized (LP) antennas. This is due to the fact that a circularly polarized microstrip antenna (CPMA) allows signal reception irrespective of the orientation of the receive antenna with respect to the transmit antenna, and also has the ability to suppress the multipath interference. The generation of circularly polarized radiation takes place by exciting two orthogonal modes of equal amplitude but in phase quadrature. This is accomplished by two different feeding techniques such as single-feed and dual-feed. However, researchers over the last few decades have shown great interest in the design of single-feed CPMA as it involves a simpler network configuration compared to the dual-feed CPMA. Single-feed configuration involves some perturbations on the patch radiator in the form of slots or slits, truncating the corners of a square patch, or by feeding a nearly square patch diagonally [2], [3]. But the design of a broadband CPMA, in terms of axial ratio bandwidth (ARBW) and impedance bandwidth (IBW) using single-feed is a challenging problem.

In the recent years, electromagnetic metasurfaces are extensively used to improve the performance of a microstrip antenna in terms of size, gain and bandwidth. Among them the Reactive Impedance Surface (RIS) which comprises of periodic metallic patches on a grounded dielectric substrate have brought about remarkable improvements in CPMA performance [4]. This layer of metallic patches is not only used to miniaturize the size of the antenna [5], [6], but also improve its gain and bandwidth [7]. For certain wireless applications such as WLAN, Wi-Fi, WiMAX, etc, broader bandwidth is essential since it provides more flexibility as well as high data rates. Therefore, contributions from various researchers have been directed towards axial ratio bandwidth improvement of CPMAs. In [8], a 45° oriented dipole placed on an artificial ground plane made of rectangular patches gives Right Hand Circularly Polarized (RHCP) radiation. This structure yields an impedance bandwidth of 24% and 3 dB ARBW of 5.6%. This concept of angular rotation by 45° is later implemented on the RIS structures in [9]. Here a slot loaded square patch is printed over a metamaterial inspired 45° rotated RIS to obtain an ARBW of 15.3%. In [10], a circularly polarized patch antenna using an artificial ground structure with rectangular unit cells are used to provide a higher ARBW of 20.4% compared to the conventional square patches. Recently, a corner truncated square patch is inserted between a lattice of metallic square patches and ground to obtain an impedance bandwidth of 45.6% and an ARBW of 23.4% [11].

This letter aims at the improvement of Axial Ratio bandwidth of single feed CPMA using a simple conventional reactive impedance surface (RIS). Here we present a compact, H-shaped patch antenna printed over a RIS structure. The RIS constitutes of square shaped metallic patches whose size is optimized to achieve a wide bandwidth in terms of return loss and axial ratio. Impedance bandwidth of 44.5% and ARBW as high as 27.5% is achieved. To the best of authors' knowledge, the proposed structure has the widest bandwidth with a simple conventional RIS surface. The proposed antenna is suitable for WLAN and WiMAX applications.

II. ANTENNA CONFIGURATION

A. *Antenna Geometry*

Fig. 1 shows the proposed Circularly Polarized Microstrip Antenna (CPMA) with the RIS structure. The H-shaped patch is printed on top of a dual layer Rogers RO4003 substrate ($\varepsilon r = 3.38$ and tan $\delta = 0.0027$) of thickness $h_1 + h_2 = 5.588$mm. The ground plane lies at the bottom of the structure and the RIS is incorporated at the interface between the two dielectric layers at a height of $h_1 = 3.556$mm from the ground. The H-shaped patch radiator is developed by perturbing the sides of a simple square patch of dimensions $L_p \times L_p$ and a perturbation of d as shown in Fig. 1(b). The patch is probe fed at one of its arms diagonally The radiated beam turns out to be right-hand circularly polarized (RHCP) or left-hand circularly polarized (LHCP) depending on the orientation of the perturbation with respect to the feed point location. The outer part of 50 Ω SMA

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LAWP.2018.2806993, IEEE Antennas and Wireless Propagation Letters

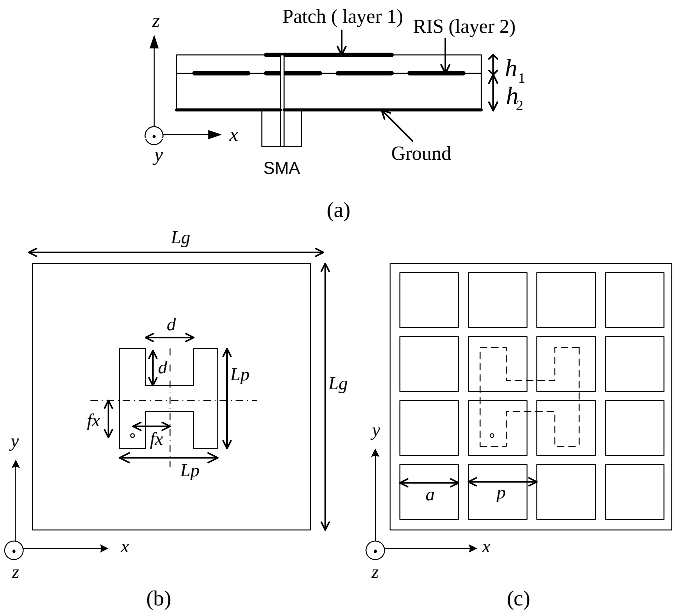


Fig. 1. Configuration of the proposed antenna. (a) Side view. (b) Top view of Patch (layer-1). (c) Top view of RIS Structure (layer-2).

connector is connected to the ground at the bottom whereas the inner conductor extends through the dual layer substrate and connects to the patch at the feeding location whose co-ordinates are (f_x, f_x). The lateral dimensions of the proposed antenna are $L_g \times L_g$, where L_g is an edge of the ground plane.

B. Bandwidth Enhancement

Here the effect of the RIS structure in increasing the antenna bandwidth is justified. Initially a simple square patch is considered which is diagonally fed and designed to resonate at 5.5 GHz. This structure is well known to be linearly polarized [1]. The square patch is then perturbed at two of its edges to obtain an H-shaped structure, which is fed diagonally at one of its arms. The patch as shown in Fig. 1(b) is optimized to generate CP radiations.

An RIS layer consisting of square patches of dimension *a* and periodicity *p*, is then introduced between the H-shaped patch radiator and the ground plane at a height of h_2 from the ground, as shown in Fig 1(c). Inserting this surface beneath the patch radiator causes a remarkable increase in its impedance bandwidth and ARBW. This RIS layer spatially distributes the image current so that there is reduced mutual interaction between the antenna current and its image. The inductive reactance of the surface cancels out the near-field capacitance of the H-shaped patch antenna resulting in broader bandwidth and compact size [7]. In order to obtain bandwidth enhancement, the reflection phase characteristics of the unit cell of the RIS structure as shown in Fig. 1(c) have to be optimized. This is accomplished by considering the interaction of the unit cell with a TEM wave and establishing PEC and PMC boundaries around the cell structure perpendicular to the incident electric and magnetic field, respectively, as shown in Fig. 2(a). The structure is optimized by keeping the periodicity *p* of the unit cell fixed, and altering the parameter *a* to maintain the operating frequency in the inductive RIS region, which in this case is below 6 GHz. This is necessary since an inductive RIS not only miniaturizes the antenna but also

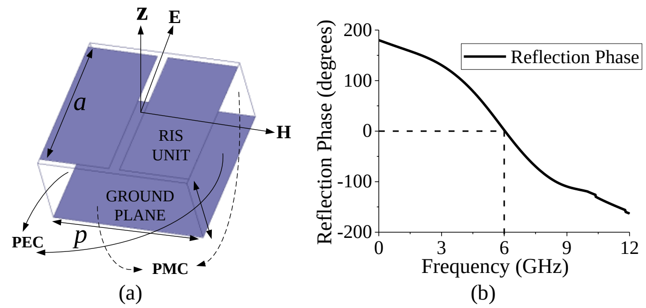


Fig. 2. (a) Unit cell of the RIS. (b) Reflection Phase of the RIS unit cell

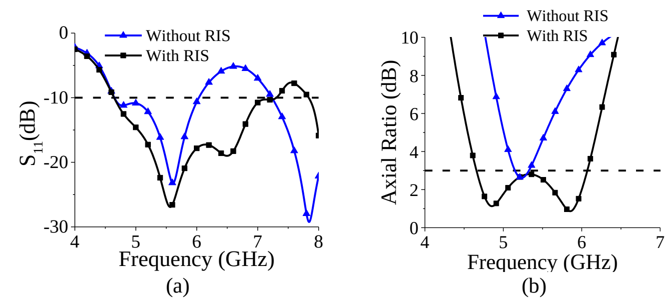


Fig. 3. (a) Simulated S_{11} and (b) AR values of the H-shaped patch antenna with and without the Reactive Impedance Surface

provides a wide impedance bandwidth. In view of this, the unit cell size *a* is chosen to be 5.5mm. It is found through simulations that this value gives optimized results both in terms of Impedance bandwidth and AR bandwidth.

This RIS structure also helps in enhancing the Axial Ratio bandwidth of the antenna. The surface waves propagating on the RIS structure generates additional resonance and AR minimum points. With the H-shaped patch, only one minimum AR point is obtained as seen in Fig. 3(b). Therefore, on introduction of RIS layer beneath the patch, the occurrence of additional AR points can be attributed to the fact that the surface waves propagating on the RIS structure generates additional CP radiations. It can also be justified by plotting S_{11} characteristics and AR performance of the proposed design with and without the RIS layer (Fig. 3). It is observed from the figure that the H-shaped patch without the RIS layer yields an impedance bandwidth of 25.6% (4.66 - 6.03 GHz) and 3-dB ARBW of 3.63% (5.14 –5.33 GHz) with a minimum value of 2.6 dB at 5.3 GHz. On the other hand, due to the presence of the RIS layer the impedance bandwidth and ARBW gets significantly improved. The proposed structure yields an impedance bandwidth of 44.5% (4.64 - 7.3 GHz) and an ARBW of 26.5% (4.6 - 6.07 GHz). Two AR minima are observed at 4.85 GHz and 5.85 GHz.

In order to find the optimum cell pattern, we have calculated AR performance for different number of unit cells. The plot which is depicted in Fig. 4 shows that as the number of unit cells increases, the AR minimum point generated by the driven patch does not alter significantly, but those caused by RIS structure shift to the low frequency region. For 4 × 4 cell configuration, the minimum AR points are located at frequencies of 4.85 GHz, and 5.85 GHz, with peak amplitude between the two dips given by 2.6 dB resulting in wide axial ratio bandwidth. This is not so in case of 3 × 3 or 5 × 5 cell

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LAWP.2018.2806993, IEEE Antennas and Wireless Propagation Letters

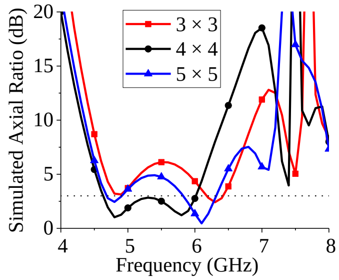
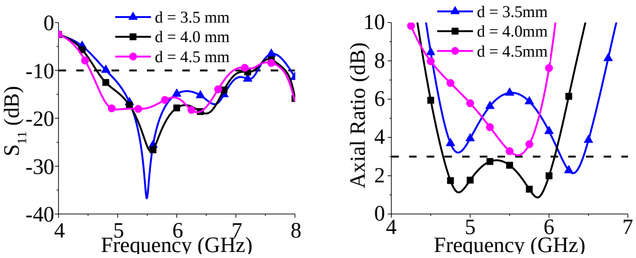
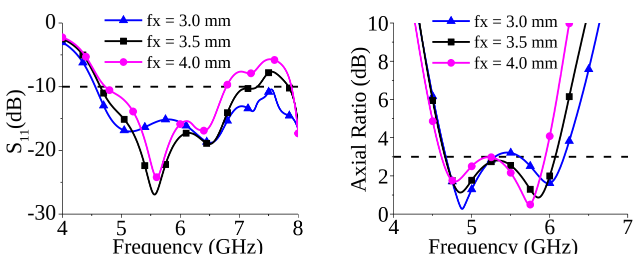


Fig. 4. Axial Ratio values of different cell configurations



(a) (b)

Fig. 5. Simulated (a) S_{11} (b) Axial ratio with different values of d



(a) (b)

Fig. 6. Simulated (a) S_{11} and (b) Axial ratio with different values of f_x

configurations where the peak amplitude between the two dips are well above 3 dB. Hence, by combining these resonances in the antenna system due to the patch and the RIS layer, the axial ratio bandwidth of the proposed antenna increases.

C. Parametric Analysis

Structural parametric analysis of the proposed CPMA with the RIS substrate is carried out in order to obtain the optimized design parameters. Note that when one parameter is optimized, the others are kept constant.

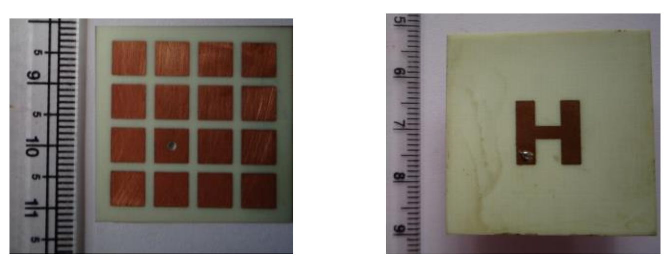
Firstly, the effects of the perturbation *d* on the CP performance of the antenna are studied. It is observed that the antenna performance is very sensitive to the perturbation. As it is evident from Fig. 5, with an increase in the value of *d* from 3.5 to 4.5 mm, the impedance bandwidth improves, specially at the lower frequencies. However, when the value of *d* is increased from 3.5 to 4 mm, the two resonances in AR performance can be brought closer resulting in wide ARBW. On further increasing the value of *d* to 4.5 mm, the minimum axial ratio value rises above 3dB and ARBW deteriorates. Hence *d* = 4 mm is chosen as an optimized design parameter value.

The feed point location (f_x, f_x) also plays an important role in the generation of CP radiations. Fig. 6. shows the S_{11} characteristics and the axial ratio performance of the designed antenna for different values of f_x. With an increase in the value of f_x from 3 to 3.5 mm, the impedance bandwidth degrades a little but ARBW improves to a reasonable extent. On further increasing the value of f_x to 4.5 mm both the impedance bandwidth and the ARBW reduces. An optimum feed point location which gives a good impedance bandwidth as well as a wide ARBW is found to be at (f_x, f_x) = (3.5mm, 3.5mm). Based on the above observations the final optimized dimensions of the proposed structure are: p = 7 mm, a = 5.5 mm, L_p = 10 mm, d = 4 mm, L_g = 32 mm, f_x = 3.5 mm.

III. Experimental Results

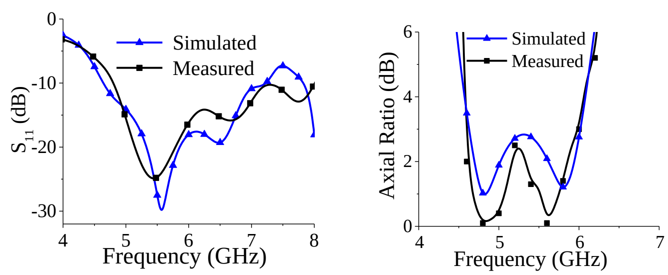
As per the designed dimensions, the proposed antenna is fabricated and measured to validate the numerical results. Fig. 7. shows the fabricated prototype whose overall dimensions are 32 × 32 × 5.588 mm^3 (~ 0.058 λ_o × 0.058 λ_o × 0.1λ_o at 5.5 GHz). The measurements are performed using Agilent E5071C Vector Network Analyzer (VNA). The simulated and measured S_{11} characteristics are shown in the Fig. 8(a). The measured impedance bandwidth of the proposed structure is 44% (4.7 – 7.35 GHz). The axial ratio is also measured and compared with the simulated results as shown in Fig. 8(b). The measured 3-dB AR bandwidth is approximately 27.5% (4.55 - 6 GHz), in the boresight direction. There is a good agreement between the simulated and measured results. However, a slight shift in the operating frequency is observed due to the fabrication tolerances and losses due to the SMA connectors, which are not considered during simulations.

The normalized radiation patterns of the proposed structure for 5 GHz and 5.5 GHz are plotted in Fig.9. As observed from the figure, the proposed antenna is Left Handed Circularly Polarized (LHCP) for z > 0. The measured half-power beamwidths (HPBWs) are 79° in the x-z plane and 90° in the y-z plane at 5.5GHz.



(a) (b)

Fig. 7. Fabricated prototype of the proposed structure. (a) Conventional Reactive Impedance Surface (RIS) structure. (b) Assembled structure



(a) (b)

Fig. 8. Simulated and measured results of (a) S_{11} (b) Axial Ratio

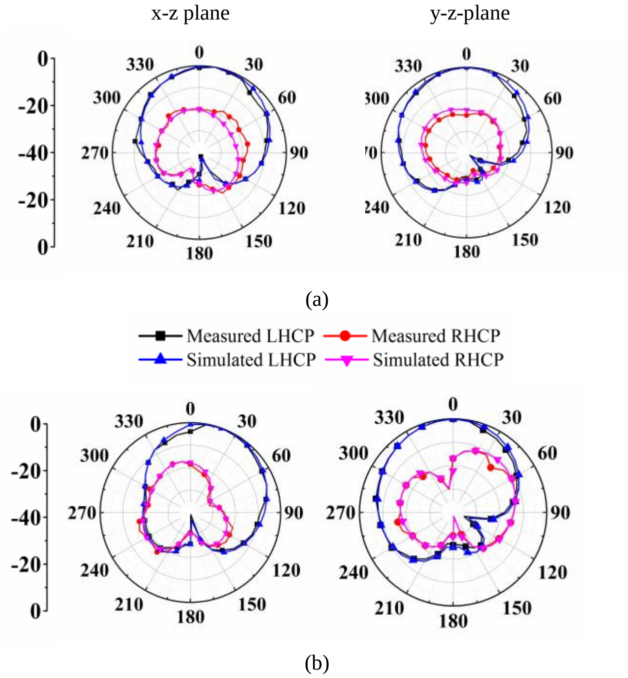


Fig. 9. Simulated and measured radiation patterns of the CP optimized antenna at (a) 5 GHz (b) 5.5 GHz

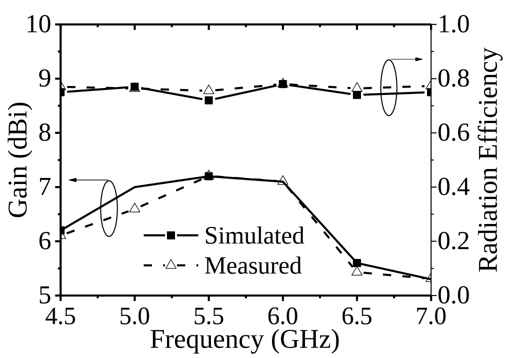


Fig. 10. Broadside gain and radiation efficiency of the proposed structure

Fig. 10. shows the peak gain and radiation efficiency of the proposed antenna. The measured gain and front-to-back ratio are found to be approximately 7.2 dBi, and 17 dB respectively at 5.5 GHz. At higher frequencies, the radiation pattern of the antenna degrades, since grating lobes appear. At frequencies above 6 GHz the pattern assumes an end-fire form. Due to this, the directivity in the broadside direction reduces, resulting in reduced gain and front-to-back ratio. The measured antenna efficiency is better than 77% for the entire 3-dB ARBW range.

A comparison of the proposed broadband H-shaped CPMA is made with other similar wideband structures existing in literature. The results are summarized in Table I. It is observed that the proposed simple H shaped patch antenna using conventional RIS structure yielded a broader 3-dB AR bandwidth and is also less complex compared to prior designs.

TABLE I
PERFORMANCE COMPARISON OF PROPOSED ANTENNA WITH OTHER SIMILAR ANTENNAS EXISTING IN LITERATURE

Ref.	Center freq. (GHz)	Antenna Size ($\lambda_o \times \lambda_o \times \lambda_o$)	Imp.BW (GHz, %)	3 dB ARBW (GHz, %)	Gain (dBi)
[9]	2.3	0.77 × 0.77 × 0.06	0.32, 14	0.35,15.3	5.7
[10]	6.0	0.78 × 0.80 × 0.096	2.78, 48.6	1.3, 20.4	6.5
[11]	5.5	0.58 × 0.58 × 0.056	2.9, 45.6	1.23,23.4	7.6
This Work	5.5	0.58 × 0.58 × 0.1	2.66, 44.5	1.45, 27.5	7.2

IV. CONCLUSION

A single-feed H-shaped circularly polarized patch antenna is presented in this letter. We have shown that by incorporating a conventional square RIS structure between the H-shaped patch radiator and the ground plane, both the impedance bandwidth and the ARBW can be improved remarkably. Impedance bandwidth of 44.5% and ARBW of 27.5% is achieved with this structure. The proposed antenna is compact with dimensions of $0.58\lambda_o \times 0.58\lambda_o \times 0.1\lambda_o$, where λ_o is the free space wavelength at 5.5 GHz. Besides being compact, low profile, and wideband, the structure also has a high gain of 7.2 dBi at the center frequency which makes it suitable for use in various wireless applications like WLAN and WiMAX.

REFERENCES

[1] C. A. Balanis, *Antenna Theory: Analysis and Design*, 2nd ed. New York: Wiley, 1997.
[2] P. C. Sharma and K. C. Gupta, "Analysis and optimized design of single feed circularly polarized microstrip antenna," *IEEE Trans. Antennas Propag.*, vol. 31, no. 6, pp. 949-955, Nov. 1983.
[3] M. Hanieshi and Y. Suzuki,"Circular Polarization and bandwidth," in *Handbook of Microstrip Antennas, ser.* IEE Electromagnetic Waves Series 28, J. R. James and P. S. Hall, Eds. London, U.K.: IET, ch. 4.
[4] K. Sarabandi and H. Mosallaei, "Compact Wideband UHF patch antenna on a reactive impedance substrate," *IEEE Antennas Wireless Propag. Lett.*, vol. 5., pp. 503-506, 2006.
[5] Y. Dong, H. Toyao, and T. Itoh, "Compact circularly-polarized patch antenna loaded with metamaterial structures," *IEEE Trans. Antennas Propag.*, vol. 59, no. 11, pp. 4329–4333, Nov. 2011.
[6] K. Agarwal, Nasimuddin, and A. Alphones, "RIS based compact circularly polarized microstrip antennas," *IEEE Trans. Antennas Propag.*, vol. 61, no. 2, pp. 547–554, Feb. 2013
[7] H. Mosallaei and K. Sarabandi, "Antenna miniaturization and bandwidth enhancement using a reactive impedance substrate," *IEEE Trans. Antennas Propag.*, vol. 52, no. 9, pp. 2403-2414, Sep. 2004.
[8] F. Yang and Y. Rahmat-Samii, "A low profile single dipole antenna radiating circularly polarized waves," *IEEE Trans. Antennas Propag.*, vol. 53, no. 9, pp. 3083–3086, Sep. 2005.
[9] L. Bernard, G. Chetier, and R. Sauleau, "Wideband circularly polarized patch antennas on reactive impedance substrates," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 1015–1018, Sep. 2011.
[10] R. Nakamura and T. Fukusako, "Broadband design of circularly polarized microstrip patch antenna using artificial ground structure with rectangular unit cells," *IEEE Trans. Antennas Propag.*, vol. 59, no. 6, pp. 2103–2110, Jun. 2011.
[11] S. X. Ta and I. Park, "Low profile broadband circularly polarized patch antenna using metasurface," *IEEE Trans. Antennas Propag.*, vol. 63, no. 12, pp. 5929–5934, Dec. 2015.