IUST Iran University of Science and Technology
Iranian Journal of Electrical and Electronic Engineering
Journal Homepage: ijeee.iust.ac.ir
Research Paper

Complementary Split Ring Resonator Effects on Radiation Pattern Reconfigurable Circular Microstrip Antennas

J. Fatemi-Nasab*, S. Jarchi*(C.A.), A. Keshtkar*

Abstract: In this study, a radiation pattern reconfigurable microstrip antenna is designed and fabricated. The antenna's radiation pattern is directed in 9 different angles by employing a radiating patch and embedding complementary split ring resonators (CSRR) on the ground plane. The radiating patch is of circular shape, while for CSRR elements both circular and rectangular shapes are investigated. The antenna is excited through coaxial feed. There are four CSRR cells on the ground plane. With applying slots on CSRR's arms and loading them by pin diodes, variable length CSRRs are obtained which result in radiation pattern reconfigurable property. Radiation characteristics of the antenna versus different switching modes of pin diodes are investigated and illustrated. The proposed antenna is also compact. The designed antenna was fabricated on FR4 substrate with thickness of 1.6 mm, and measurement results are provided. The results demonstrate that the presented antenna has impedance bandwidth of 2.39-2.47 GHz with a gain of more than 7 dBi.

Keywords: Microstrip Antenna, Reconfigurable Antenna, Radiation Pattern, Pin Diode.

1 Introduction

ANTENNA is part of a receiver or transmitter system that is designed to radiate or receive electromagnetic waves [1, 2]. A reconfigurable antenna is an antenna that reversible variations in antenna's impedance or radiation characteristics are provided by employing an internal mechanism, changing the current distribution and/or changing the electromagnetic fields of antenna's effective aperture. The advantages of using reconfigurable antennas include: ability to cover more than one wireless standard which will lead to cost reduction, decrease in occupied space, easier construction and better isolation between different wireless standards. In addition, these antennas could be used to create diversity in frequency, polarization and direction in systems that have high fading effects. Creating diversity in these systems will increase the system's security and quality. Additionally, the ability to control polarization could be used to increase the frequency band capacities.

Reconfigurable antenna of the radiation pattern can have various and numerous applications; the most common of which is the classic application of beam scan or beam steering. Steering the radiation pattern includes automatic rotation of the antenna's radiation pattern to the determined and desired direction. This mode of configurability is used in cellphone users in line of sight condition, because it provides high antenna gain [3]. In the same way as frequency configurability is used to eliminate extra-band interferences, radiation pattern configurability could remove interference, provided that the direction of the interfering signal is different from the main signal [4]. Another application of radiation pattern configurability is in multiple input multiple output (MIMO) systems. It replaces the numerous fixed antennas in MIMO systems with fewer antennas capable of configuring radiation pattern and we could achieve a significant channel capacity enhancement [5-7].

Radiation pattern of an antenna is dependent on its current distribution. Therefore, reconfigurable radiation

Iranian Journal of Electrical and Electronic Engineering, 2021.
Paper first received 25 January 2020, revised 03 July 2020, and accepted 06 July 2020.
* The authors are with the Department of Electrical Engineering, Faculty of Technical and Engineering, Imam Khomeini International University (IKIU), Qazvin, Iran.
E-mails: jafar.fateminasab@gmail.com, s.jarchi@eng.ikiu.ac.ir, and akeshtkar@gmail.com.
Corresponding Author: S. Jarchi.
https://doi.org/10.22068/IJEEE.17.1.1775

pattern can be achieved by changing the current distribution. In this type of antennas, frequency and polarization must be constant while, radiation pattern's shape, direction and gain is varied. One of the classic examples is designed in reference [8], which the arms of a dipole antenna rotate simultaneously with external stimuli, so that its radiation pattern could be directed. A different strategy for changing the radiation pattern's shape is using reconfigurable parasitic sections. Reconfigurable pattern antennas were implemented using parasitic switching for monopole antennas[9, 10], microstrip elements [11-13] and slot antennas [14]. There are two other structures that are used for pattern configurability which are leaky wave and multi-mode antennas. Using multiple switches in a multi-mode antenna, we can activate different modes separately [15].

SRRs are resonant elements with high quality factor which act like an LC circuit and can be activated by an external stimulus. Their most important feature is that when resonated in a relatively narrow range and higher than their resonant frequency, they show negative permeability [16]. Dual of this structure i.e. complementary split ring resonators also show interesting features. The electromagnetic behavior of CSRR is almost dual of SRR. Therefore, we can expect negative permittivity for a CSRR-based structure. CSRR can be implemented in microstrip configuration by removing the rings on the ground, exactly beneath the conductive strip [17]. CSRR structures are used in rectangular patch antenna for size reduction [18], in array patch antennas for side lobes reduction [19] and in patch antennas for pattern rotation with gap length changes of CSRR [20, 21]. It is shown that CSRR plays a crucial role in current flow which leads to a phase shift in antenna's electromagnetic fields [20]. A pattern reconfigurable antenna, with application of metasurface, is designed and proposed in [22]. Microstrip antennas, with pattern reconfigurable property using pin diodes are also studied in [23-27].

In this study, a compact circular patch antenna with low cost and ability of pattern guidance is presented. By loading the ground plane with CSRR cells, a high pattern guidance capability is provided and the system costs, to meet the requirements of wireless communications, are reduced. Measurement results indicate that antenna beam with two loaded CSRRs can scan 51 to 48 degree through changing parameters of the CSRR structure.

2 Antenna Structure

The antenna structure consists of a radiating patch, which is in circular shape, with four complementary split ring resonators (CSRR) on the ground plane. Each CSRR contains two slots loaded by pin diodes. The pin diodes, open or short circuit the CSRR arms and provide radiation pattern configurability, based on the switching settings. When two pin diodes on one CSRR are on, electric length of the current is shorter and the corresponding CSRR acts like director. While, when the pin diodes are off, electric length of the current is longer and the CSRR acts like reflector [25].

In the antenna of reference [21], parasitic patches loaded by pin diodes, which are in the same side of substrate as the radiating element, provide controlling of pattern direction. Also shorting pins are required in the design. However, when the CSRR cells are etched on the ground plane, as in [25], shorting pins are not required and fabrication of the structure is simpler and more cost effective.

In this work, CSRR cells are etched on the ground plane of a circular microstrip antenna. Combination of circular patch structure with CSRRs on the ground plane, has resulted in compact and radiation pattern reconfigurable antenna. The CSRRs are loaded by slots, which can be short circuited or left open circuit by on and off switching modes of pin diodes. In addition, shorting pins are removed and the bias lines are transferred to the ground plane which eliminate the side effects on the radiation pattern, and therefore radiation pattern is improved.

Three designs are proposed, which the first two are designed on Taconic (TLY-5) substrate. To compare performance of circular microstrip patches on the ground plane loaded by circular and rectangular CSRRs, the proposed antenna 1 and the proposed antenna 2 are designed and simulated. In the proposed antenna 1, circular CSRRs are applied while in the proposed antenna 2 rectangular CSRRs are applied. The third antenna is designed on FR4 substrate, which is easily available with low cost. This antenna is fabricated and measurement results are provided.

2.1 Proposed Antenna 1

Structure of the proposed antenna 1 is shown in Fig. 1. The antenna is a circular patch antenna designed on Taconic (TLY-5) substrate with 2.2 dielectric constant and 1.6 mm height. The antenna radius, to operate at frequency f_r, is calculated using [28]:

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi \varepsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{1/2}} \tag{1}$$

$$F = \frac{8.791 \times 10^9}{f_r \sqrt{\varepsilon_r}} \tag{2}$$

where, h is the substrate thickness in cm, f_r is the resonant frequency in Hz, and a is the radius of the antenna in cm. The antenna is fed by coaxial cable. The parameter "Xsma", as shown in the Fig. 1(a), indicates the distance of the feeding point from the center of the circular patch. Four CSRRs are embedded on the ground plane. Two slots are applied on each CSRR, and the pin diodes are included on these slots. Details of the

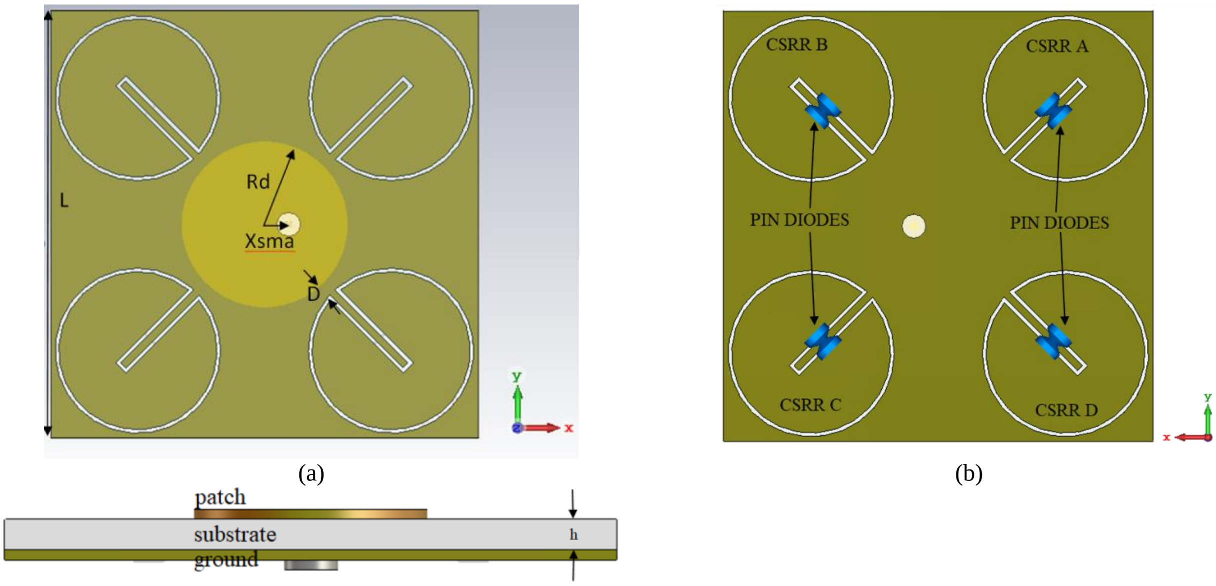


Fig. 1 Structure of the proposed antenna 1 with circular CSRRs: a) top view, b) bottom view, and c) side view.

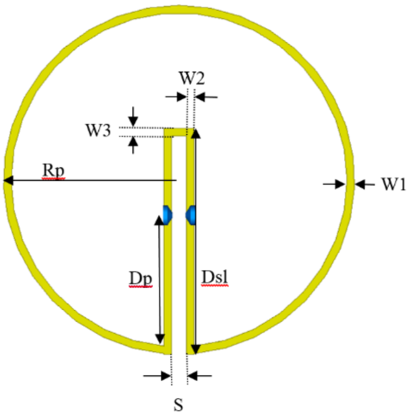


Fig. 2 Structure of a circular CSRR.

Table 1 Parameters of the proposed antenna 1 with circular CSRR (in millimeters).

Xsma	D	Rd	h	L
6.8	3.7	23.3	1.6	120

Table 2 Parameters of the CSRRs of the proposed antenna 1 (in millimeters).

W3	W2	W1	S	Dp	Dsl	Rp
1	1	1	2	17.4	30	23.2

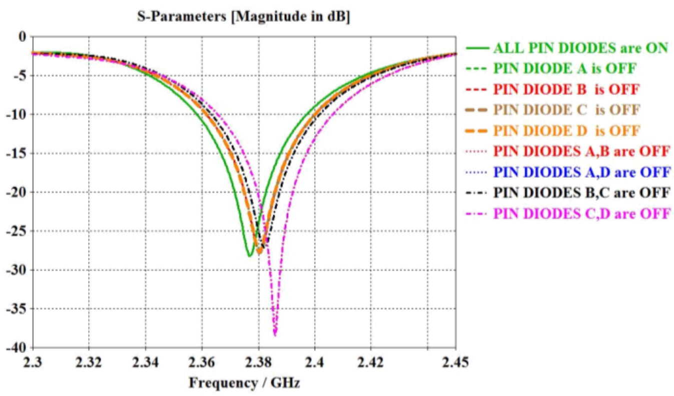


Fig. 3 Reflection coefficient of the proposed antenna 1.

circular CSRR structure are shown in Fig. 2. Table 1 has listed the parameters of the antenna while Table 2 has listed dimensions of the CSRRs.

The proposed antenna 1 is simulated using full wave software, CST Microwave Studio. Lumped element pin diodes are replaced by their equivalent circuit model, which is obtained using ADS (Advanced Design System) software. In simulations, BAR64_02V pin diode with on and off switching modes is used.

Reflection coefficient of the antenna, for different switching modes of the diodes, is simulated and shown in Fig. 3. It is observed that resonant frequency of the antenna represents slight dependence on different switching modes, which is a positive feature. Radiation pattern characteristics of the proposed antenna 1 at central frequency of 2.38 GHz is shown in Fig. 4, for several phi angles. It is observed that radiation pattern is directed in 9 different angles of (φ, θ).

Table 3 Radiation pattern characteristics of the proposed antenna 1 at central frequency of 2.38 GHz.

Switch				Gain [dbi]	Efficiency [%]	Angle of maximum radiation pattern (φ , θ)
A	B	C	D			
ON	ON	ON	ON	7.90	89	(0 , 0)
OFF	ON	ON	ON	7.59	89	(135 , 11)
OFF	OFF	ON	ON	7.48	90	(90 , 19)
ON	OFF	OFF	ON	7.50	89	(0 , 15)
ON	OFF	ON	ON	7.54	89	(45 , 11)
ON	ON	OFF	ON	7.55	89	(315 , 11)
ON	ON	OFF	OFF	7.49	90	(270 , 19)
OFF	ON	ON	OFF	7.57	89	(180 , 14)
ON	ON	ON	OFF	7.60	89	(225 , 11)

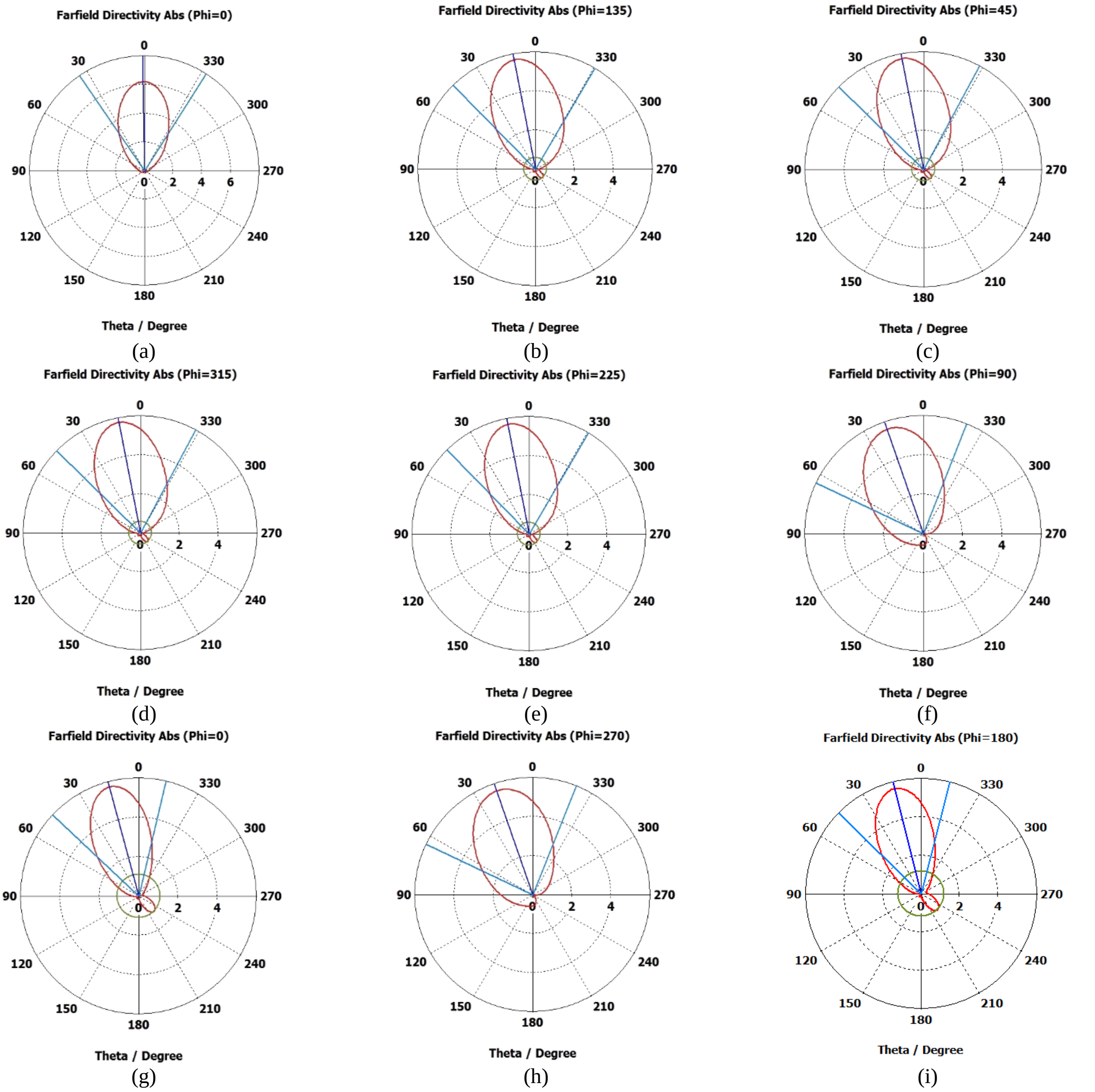
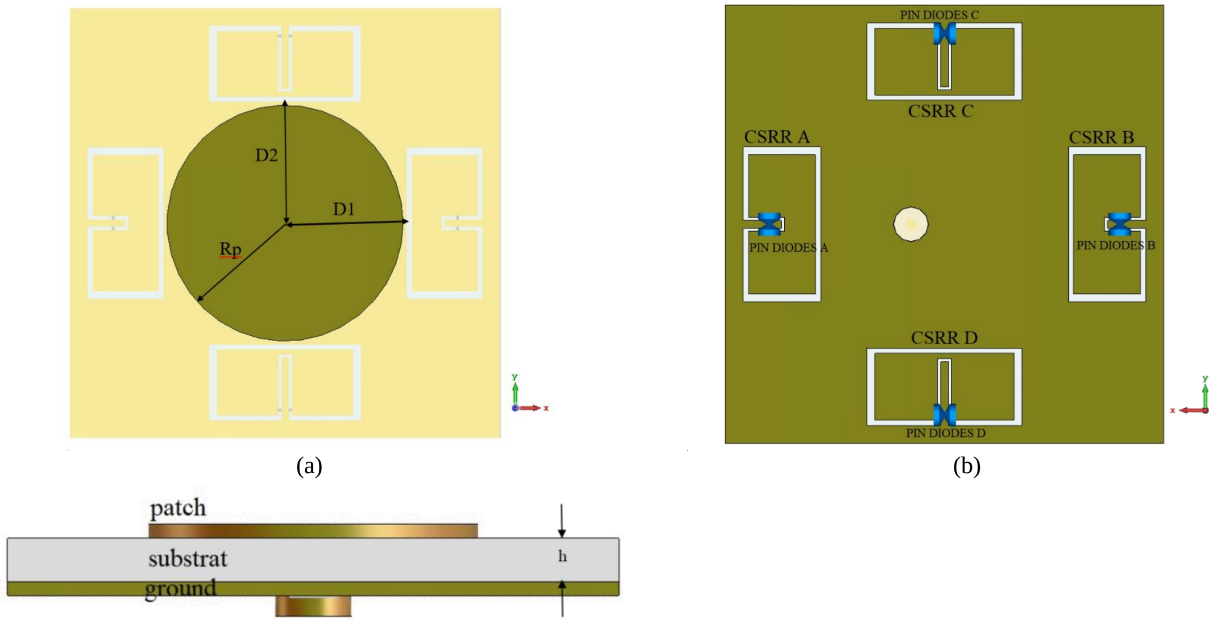


Fig. 4 Radiation pattern of the proposed antenna 1, with circular CSRR structure, for different switching modes at 2.38 GHz: a) all the pin diodes are on, b) pin diode A is off, c) pin diode B is off, d) pin diode C is off, e) pin diode D is off, f) pin diodes A and B are off, g) pin diodes B and C are off, h) pin diodes C and D are off, and i) pin diodes A and D are off.

2.2 Proposed Antenna 2

In this design, rectangular CSRRs are applied on the ground plane. The antenna structure is shown in Fig. 5, and the CSRRs configurations are shown in Fig. 6. The four CSRRs are not symmetrically placed with respect to the patch antenna center. The CSRRs are symmetric relative to the E-plane and H-plane, i.e., the CSRRs in the E-plane are the same, and the CSRRs in the H-plane are similar. As shown in Fig. 5, CSRRs A and B are similar, and CSRRs C and D are the same. This antenna is also designed on Taconic (TLY-5) substrate with 1.6 mm height. Table 4 has listed parameters of the proposed 2 antenna while table 5 has listed dimensions of the rectangular CSRRs. Using rectangular CSRRS, size reduction is achieved while gain and radiation pattern configurability is preserved as the previous design.

The structure is simulated for several switching modes of the pin diodes and return loss and radiation patterns are plotted in Figs. 7 and 8, respectively. There is not considerable difference of resonant frequencies for different switching modes, as shown in Fig. 7. However, compared to the proposed antenna 1, variation of resonant frequency is higher. Radiation pattern of the antenna, at the working frequency of 2.42 GHz, is directed in 9 different angles of (φ, θ) for various switching modes of the diodes, as shown in Fig. 8.



(a) (b)

(c)

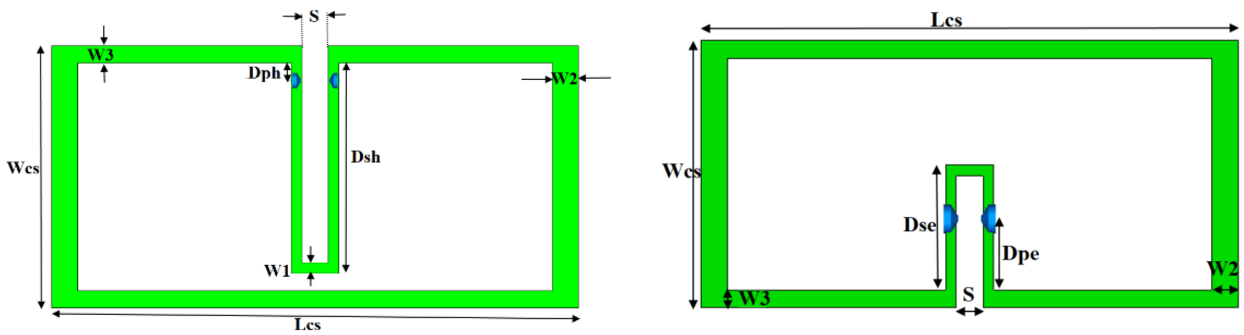
Fig. 5 Structure of the proposed antenna 2 with rectangular CSRRs: a) top view, b) bottom view, and c) side view.

Table 4 Parameters of the proposed antenna 2 with rectangular CSRRs (in millimeters).

D2	D1	Xsma	h	L	Rd
24	24	6.5	1.6	85	23.3

Table 5 Dimensions of the rectangular CSRRs (in millimeters).

S	W3	W2	W1	Dph	Dsh	Dpe	Dse	Lcs	Wcs
1.5	1	1.5	0.6	2	13	5	8	30	15



(a) (b)

Fig. 6 Rectangular CSRRs of the proposed antenna 2: a) CSRR C and D, and b) CSRRs A and B.

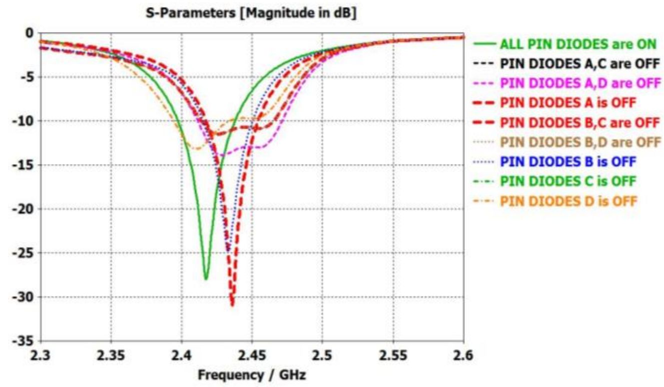


Fig. 7 Reflection coefficient of the proposed antenna 2.

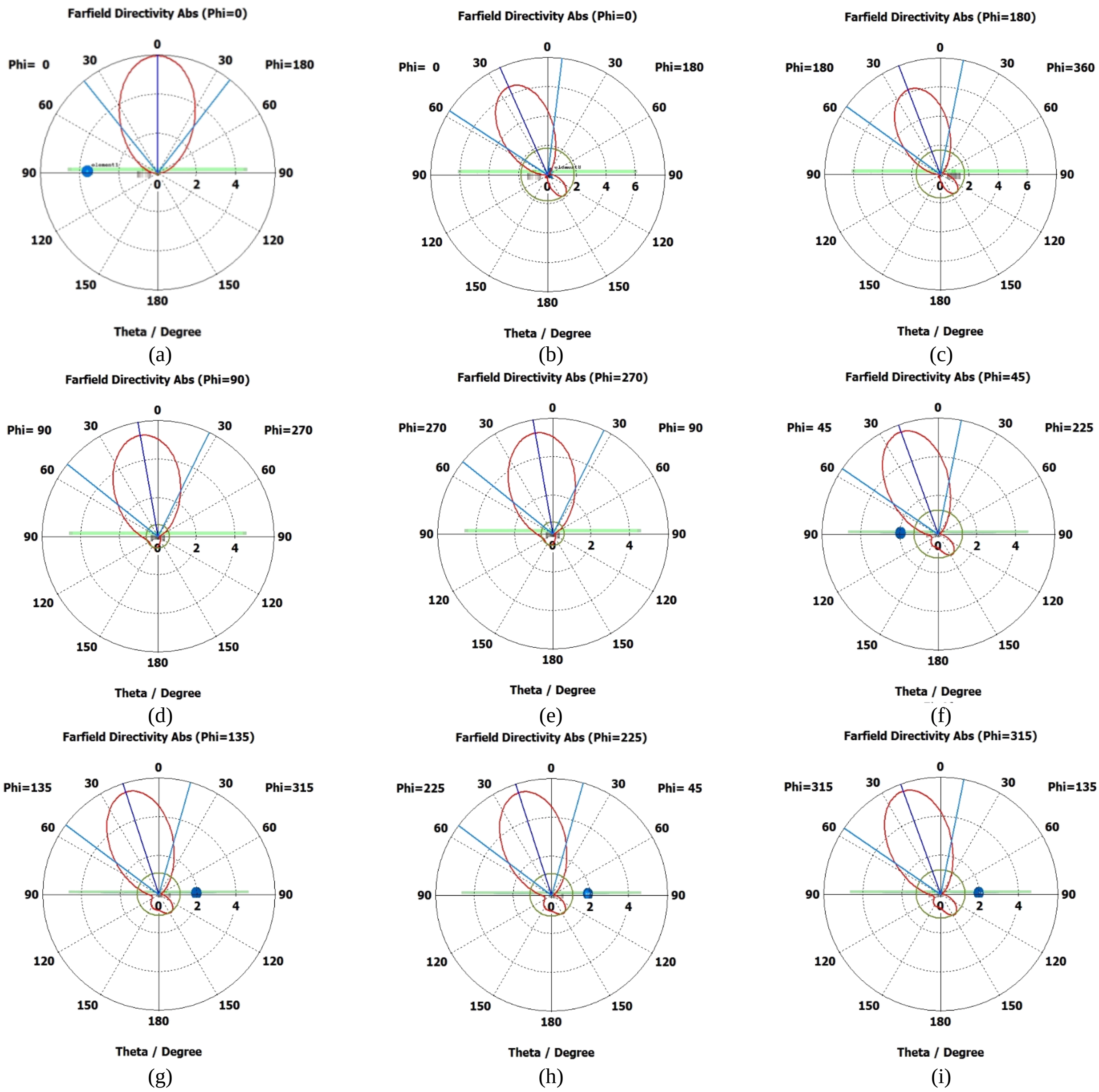
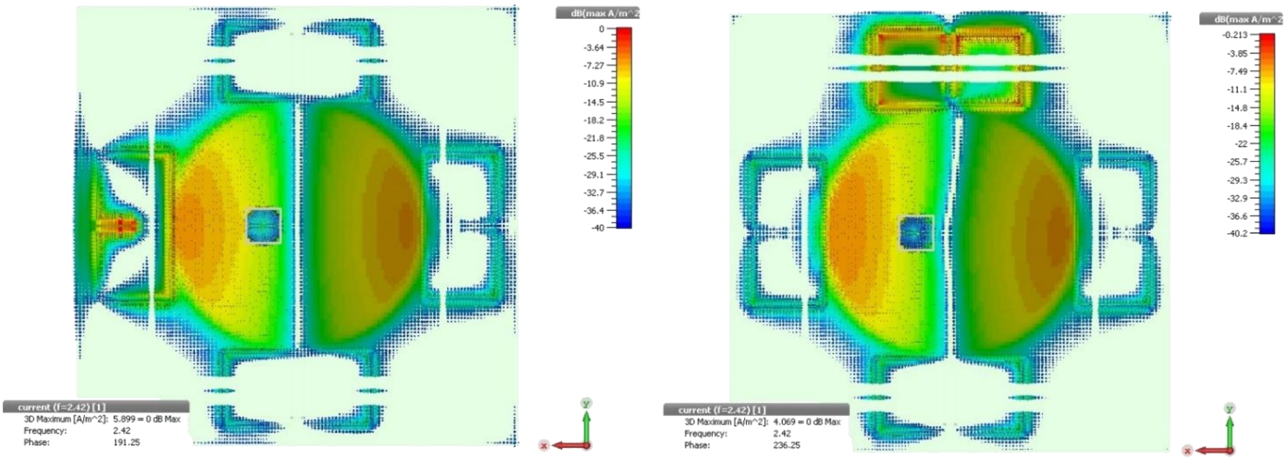


Fig. 8 Radiation pattern of the proposed antenna 2 with rectangular CSRRs for different switch modes at 2.42 GHz; a) all the pin diodes are on, b) pin diode A is off, c) pin diode B is off, d) pin diode C is off, e) pin diode D is off, f) pin diodes A and C are off, g) pin diodes B and C are off, h) pin diodes B and D are off, and i) pin diodes A and D are off.

Table 6 Radiation pattern characteristics of the proposed antenna 2 at central frequency of 2.42 GHz.

Switch				Gain [dbi]	Efficiency [%]	Angle of maximum radiation pattern (φ, θ)
A	B	C	D			
ON	ON	ON	ON	7.74	93	(0 , 0)
OFF	ON	ON	ON	8.16	76	(0 , 24)
ON	OFF	ON	ON	7.94	77	(180 , 21)
ON	ON	OFF	ON	7.24	82	(90 , 10)
ON	ON	ON	OFF	7.24	82	(270 , 10)
OFF	ON	ON	OFF	7.50	71	(315 , 20)
OFF	ON	OFF	ON	7.50	71	(45 , 20)
ON	OFF	OFF	ON	7.42	74	(135 , 18)
ON	OFF	ON	OFF	7.42	74	(225 , 18)



(a) (b)

Fig. 9 Current distribution on CSRR-loaded ground plane in 2.42 GHz: a) pin diodes A are off, and b) pin diodes C are off.

Table 6 has listed gain, efficiency and angle of maximum radiation of the proposed antenna 2 for different switching modes. As it can be seen, compared to reference [27], size of the proposed antenna 2 is decreased while efficiency is improved, and bandwidth and gain are approximately similar.

3 General Principle of Performance of the Proposed Antennas

The general principle of the performance of the proposed antenna with CSRR structure is analyzed by investigating the effective parameters of the CSRRs. With increasing the slot length, through varying the position of the diodes, resonance frequency of the CSRR moves toward lower frequencies and the effective refractive index of the CSRR increases, and therefore the phase change of electromagnetic waves increase according to the following formula [20]:

$$\theta = kd = 2\pi / \lambda_{eff} D \tag{3}$$

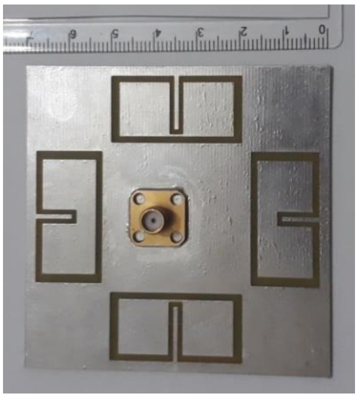
where, $\lambda_{eff} = \lambda_0/n$, n is the effective refractive index, λ_0 is the free space wavelength, k is the wave number, D is the unit cell dimension in propagation direction. In other words, with changing the position of the diodes, resonance frequency of the CSRRs changes, and as a result the electromagnetic waves experience a different phase change. Thus inclusion of the CSRRs on the ground plane operates like phase shifter which results in pattern reconfigurable property.

Current distribution on the ground is shown in Fig. 9. As it can be seen, most of the current distribution is on the patch and the CSRR which is in off-mode. This performance indicates different patch phases in the two modes which will lead to direction rotation of the main beam from the z axis.

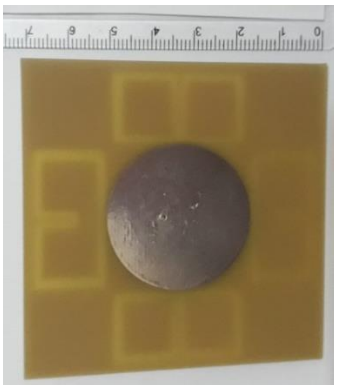
The proposed antennas have different parameters, due to the fact that a change in size of these parameters will change the refractive index and as a result the rotation size of the radiation pattern. The most influential parameters are: split length which affects the resonance frequency, and location of pin diodes which significantly influences the pattern rotation size.

4 Fabrication and Measurement

Another circular patch antenna with rectangular CSRRs is proposed, designed and fabricated on FR4 substrate with 1.6 mm thickness. Lateral dimensions of the final antenna, as shown in Fig. 10, is 70×70 mm^2. The antenna parameters are listed in tables 7 and 8. In the fabricated antenna the pin diodes in off-mode are applied through open circuits, while the pin diodes in on-mode are applied through short circuiting with thin



(a)



(b)

Fig. 10 The fabricated antenna: a) bottom view and b) top view.

Table 7 Parameters of the fabricated antenna with rectangular CSRR (in millimeters).

D2	D1	Xsma	h	L	Rd
17.5	17.5	8	1.6	70	16.7

Table 8 CSRR dimensions of the fabricated antenna (in millimeters).

S	W3	W2	W1	Dph	Dsh	Dpe	Dse	Lcs	Wcs
1.5	1	1.5	0.6	7	13	2	8	30	15

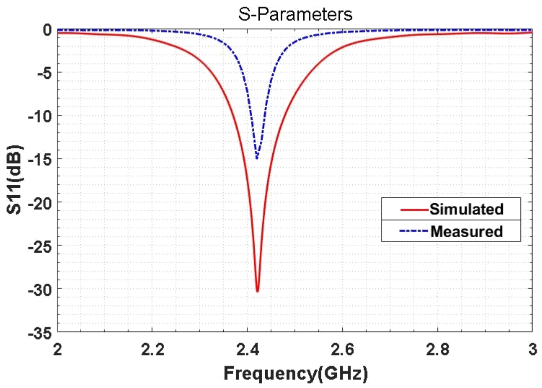
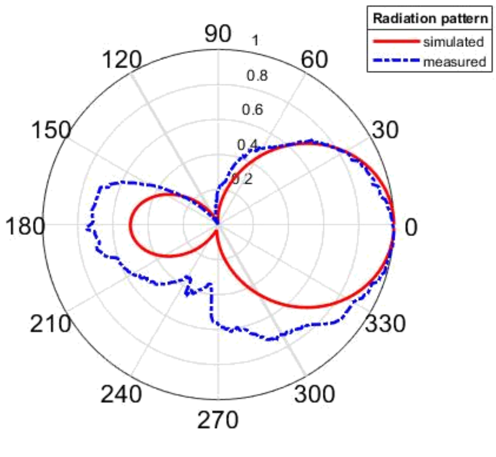
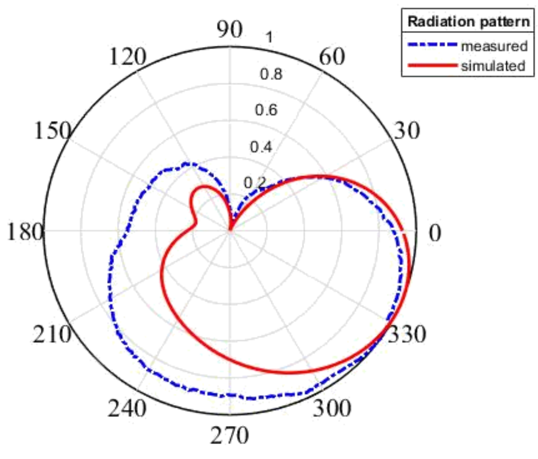


Fig. 11 S11 parameter of the fabricated antenna in mode Diode pins C are off.



(a)



(b)

Fig. 12 Radiation pattern at frequency of 2.42 GHz: a) all the pin diodes are on and b) pin diodes C are off.

metal contacts. In the fabricated antenna for measurement of return loss and radiation pattern, three CSRRs with pin diodes in on-mode and one CSRR with pin diodes in off mode are considered.

The antenna was tested and return loss and radiation pattern were measured. Return loss is shown in Fig. 11. There is a reasonable match between resonant frequencies of the simulated and measured antenna. However a discrepancy between magnitudes of return loss curves is observed which is due to fabrication tolerances of the feed point. Radiation pattern is shown in Fig. 12. Again a reasonable agreement between simulation and measurement is observed. Pattern configurability versus switching of pin diodes is clearly

Table 9 Comparing the Proposed antennas 1 & 2 with different references.

Design	Year published	Efficiency [%]	Patten rotation size	Gain [dBi]	Antenna's normalized volume	Dimensions based on wavelength	Central frequency	Bandwidth [%]
[21]	2014	70-77	0-25	7.25-8.32	1.95	0.95λ.×0.95 λ.×0.012 λ.	2.38	1.3
[22]	2015	-	32	>7.2	6	1.2λ.×0.028 λ.	5.5	3.6
[26]	2015	-	30	>8	4.21	0.817λ.×0.817 λ.×0.035 λ.	3.5	4.6
[24]	2016	-	0-30	>7	5.41	0.94λ.×0.94 λ.×0.034 λ.	2.84	1.76
[23]	2016	-	36	4.5	5.9	0.64λ.×0.0512 λ.	2.4	10.8
[27]	2016	86.1	25	7.27	45	0.98λ.×0.98 λ.×0.26 λ.	5.8	3.48
[25]	2016	-	0-32	6.33-7.92	2.76	0.82λ.×0.78 λ.×0.024 λ.	2.45	2.45
Proposed Antenna 1 (Taconic)		89-90	0-19	7.47-7.9	1.95	0.95λ.×0.95 λ.×0.012 λ.	2.38	1.7
Proposed Antenna 2 (Taconic)		71-93	0-24	7.24-8.16	**1**	0.68λ.×0.68 λ.×0.012 λ.	2.42	3.3
Fabricated Antenna (FR4)		-	30	6	0.68	0.56λ.×0.56 λ.×0.012 λ.	2.42	4.2

obvious from Fig. 12. The discrepancy between simulated and measured reflection coefficient is due to the fabrication tolerances and the effects of the coaxial cable on the measurement results. Another source of difference between the simulated and measured results is due to the fact that in simulations we have modeled the "off" and "on" modes of the diodes by their lumped element models, while in the fabricated antenna we used open circuit and short circuiting with a very thin strip, for the "off" and "on" modes of the diodes.

In the end, we compare the proposed antenna structures with the results of some of the references that were designed in recent years as pattern reconfigurable antenna, in Table 9. As it can be seen, the proposed antenna 1 has a better efficiency, while the proposed antenna 2 has significantly smaller dimensions compared to other antennas. Simpler structure and possibility of designing bias lines of pin diodes on the ground plate are of the proposed designs' features.

The designed antenna with a central frequency of 2.42 GHz can be employed in applications with IEEE 802.11 b\g WiMAX, WLAN standards. Also, because of its compact size, the antenna could be used for array design. It can also be used in any system that needs a pattern reconfigurable antenna including MIMO systems to increase the channel's capacity.

5 Conclusion

In this paper a compact radiation pattern reconfigurable circular microstrip antenna was designed and fabricated. The reconfigurable property of the radiation pattern was provided by loading the ground plane with four rectangular CSRRs. Through placing pin diodes on the CSRRs and with switching the state of the diodes, on or off cases, radiation pattern of the antenna was steered in 9 different angles. The proposed antenna was fabricated and experimental results were provided.

References

[1] J. Bernhard, "Reconfigurable antennas, ser," *Synthesis Lectures on Antennas. Morgan & Claypool Publishers*, 2007.

[2] D. R. Jackson, A. A. Oliner, and C. Balanis, *Modern antenna handbook*. Leaky-Wave Antennas: Wiley, 2008.

[3] A. Alexiou and M. Haardt, "Smart antenna technologies for future wireless systems: trends and challenges," *IEEE Communications Magazine*, Vol. 42, No. 9, pp. 90–97, 2004.

[4] R. Mehmood and J. W. Wallace, "Interference suppression using parasitic reconfigurable aperture (recap) antennas," in *International Workshop on Antenna Technology (iWAT)*, pp. 82–85, 2011.

[5] B. A. Cetiner, H. Jafarkhani, J. Y. Qian, H. J. Yoo, A. Grau, and F. De Flaviis, "Multifunctional reconfigurable MEMS integrated antennas for adaptive MIMO systems," *IEEE Communications Magazine*, Vol. 42, No. 12, pp. 62–70, 2004.

[6] F. Fazel, A. Grau, H. Jafarkhani, and F. De Flaviis, "Space-time-state block coded MIMO communication systems using reconfigurable antennas," *IEEE Transactions on Wireless Communications*, Vol. 8, No. 12, pp. 6019–6029, 2009.

[7] D. Piazza, N. J. Kirsch, A. Forenza, R. W. Heath, and K. R. Dandekar, "Design and evaluation of a reconfigurable antenna array for MIMO systems," *IEEE Transactions on Antennas and Propagation*, Vol. 56, No. 3, pp. 869–881, 2008.

[8] J. C. Chiao, Y. Fu, I. M. Chio, M. DeLisio, and L. Y. Lin, "MEMS reconfigurable Vee antenna," in *IEEE MTT-S International Microwave Symposium Digest (Cat. No. 99CH36282)*, Vol. 4, pp. 1515–1518, 1999.

[9] R. Vaughan, "Switched parasitic elements for antenna diversity," *IEEE Transactions on Antennas and Propagation*, Vol. 47, No. 2, pp. 399–405, 1999.

[10] M. D. Migliore, D. Pinchera, and F. Schettino, "A simple and robust adaptive parasitic antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 10, pp. 3262–3272, 2005.

[11] M. Donelli, R. Azaro, L. Fimognari, and A. Massa, "A planar electronically reconfigurable Wi-Fi band antenna based on a parasitic microstrip structure," *IEEE Antennas and Wireless Propagation Letters*, Vol. 6, pp. 623–626, 2007.

[12] X. S. Yang, B. Z. Wang, and W. Wu, "Pattern reconfigurable patch antenna with two orthogonal quasi-Yagi arrays," in *IEEE Antennas and Propagation Society International Symposium*, Vol. 2, pp. 617–620, 2005.

[13] S. Zhang, G. Huff, J. Feng, and J. T. Bernhard, "A pattern reconfigurable microstrip parasitic array," *IEEE Transactions on Antennas and Propagation*, Vol. 52, No. 10, pp. 2773–2776, 2004.

[14] L. Petit, L. Dussopt, and J. M. Laheurte, "MEMS-switched parasitic-antenna array for radiation pattern diversity," I*EEE Transactions on Antennas and Propagation,* Vol. 54, No. 9, pp. 2624–2631, 2006.

[15] C. Won Jung, M. J. Lee, G. Li, and F. De Flaviis, "Reconfigurable scan-beam single-arm spiral antenna integrated with RF-MEMS switches," *IEEE Transactions on Antennas and Propagation*, Vol. 54, No. 2, pp. 455–463, 2006.

[16] F. Martin, F. Falcone, J. Bonache, R. Marques, and M. Sorolla, "Miniaturized coplanar waveguide stop band filters based on multiple tuned split ring resonators," *IEEE Microwave and Wireless Components Letters,* Vol. 13, No. 12, pp. 511–513, 2003.

[17] F. Falcone, T. Lopetegi, J. D. Baena, R. Marqués, F. Martín, and M. Sorolla, "Effective negative-/spl epsiv/stopband microstrip lines based on complementary split ring resonators," *IEEE Microwave and Wireless Components Letters*, Vol. 14, No. 6, pp. 280–282, 2004.

[18] M. S. Sharawi, M. U. Khan, A. B. Numan, and D. N. Aloi, "A CSRR loaded MIMO antenna system for ISM band operation," *IEEE Transactions on antennas and propagation*, Vol. 61, No. 8, pp. 4265–4274, 2013.

[19] A. Wahid, M. Sreenivasan, and P. Rao, "CSRR loaded microstrip array antenna with low sidelobe level," *IEEE Antennas and Wireless Propagation Letters,* Vol. 14, pp. 1169–1171, 2015.

[20] W. Cao, Y. Xiang, B. Zhang, A. Liu, T. Yu, and D. Guo, "A low-cost compact patch antenna with beam steering based on CSRR-loaded ground," *IEEE Antennas and Wireless Propagation Letters*, Vol. 10, pp. 1520–1523, 2011.

[21] M. Jusoh, T. Aboufoul, T. Sabapathy, A. Alomainy, and M. R. Kamarudin, "Pattern-reconfigurable microstrip patch antenna with multidirectional beam for WiMAX application," *IEEE Antennas and Wireless Propagation Letters,* Vol. 13, pp. 860–863, 2014.

[22] H. L. Zhu, S. W. Cheung, and T. I. Yuk, "Mechanically pattern reconfigurable antenna using metasurface," *IET Microwaves, Antennas & Propagation*, Vol. 9, No. 12, pp. 1331–1336, 2015.

[23] M. S. Alam and A. Abbosh, "Planar pattern reconfigurable antenna with eight switchable beams for WiMax and WLAN applications," *IET Microwaves, Antennas & Propagation*, Vol. 10, No. 10, pp. 1030–1035, 2016.

[24] W. Li and Y. Zhao, "A pattern reconfigurable patch antenna for wide-angle scanning phased array," in *IEEE/ACES International Conference on Wireless Information Technology and Systems (ICWITS)* and *Applied Computational Electromagnetics (ACES)*, pp. 1–2, 2016.

[25] Z. L. Lu, X. X. Yang, and G. N. Tan, "A multidirectional pattern-reconfigurable patch antenna with CSRR on the ground," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, pp. 416–419, 2016.

[26] S. J. Shi and W. P. Ding, "Radiation pattern reconfigurable microstrip antenna for WiMAX application," *Electronics Letters*, Vol. 51, No. 9, pp. 662–664, 2015.

[27] L. Zhong, J. S. Hong, and H. C. Zhou, "A novel pattern-reconfigurable cylindrical dielectric resonator antenna with enhanced gain," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, pp. 1253–1256, 2015.

[28] C. A. Balanis, *Antenna theory: analysis and design*. John Wiley & Sons, 2016.

J. Fatemi-Nasab was born in Qazvin, Iran, 1984. He received the B.Sc. degree in Electronic engineering from Qazvin Islamic Azad University, Qazvin,Iran,in 2010, the M.Sc. degree in Telecommunications Engineering from Imam Khomeini International University,Qazvin (IKIU), Iran, in 2017. He is currently a Technical Engineer in IRIB, Qazvin, Iran. His research interests include antennas, planar antennas, and reconfigurable antennas.

S. Jarchi received her B.S. degree in Electrical Engineering from Amirkabir University of Technology and M.Sc. from University of Tehran. She received Ph.D. degree in Field and Wave Communications from University of Tehran in 2012. In 2012, she joined Faculty of Technical and Engineering, Imam Khomeini International University (IKIU) as an Assistant Professor. Her work background and research interests include metamaterials and plasmonics; applications of metamaterials and periodic structures in antenna enhancement providing compact, planar, wideband and high gain antennas, as well as design of planar, low profile and dynamically tunable antennas and metamaterial absorbers in microwave, millimeter-wave, and terahertz frequency bands.

A. Keshtkar received the B.Sc. degree in Electrical Engineering from Tehran University,Tehran,Iran,in 1989, the M.Sc. degree in Electrical Engineering from the University of Khaje Nasir,Tehran,in 1992, and the Ph.D. degree in Electrical Engineering from the Iran University of Science and Technology (IUST), Tehran, in 1999. He is currently a Professor with the Faculty of Engineering and Technology, Imam Khomeini International University (IKIU), Qazvin, Iran. His current research interests include electromagnetism, electromagnetic launchers, and antennas.