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Research Article

Modification of metasurface-based CP array antenna by using cascade feed network

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Abstract: In this work, a unique compact size high gain circularly polarised (CP) array antenna is proposed. The array is considered as a 2 × 2 metasurface-based CP patch antennas which fed by a cascade network. The single element consists of two different layers of substrate that metasurface layer excited by aperture slot on metallic ground layer in middle layer between metasurface cells and microstrip line, meanwhile this layer isolates destructive effects of feed lines on radiation layer. For achieving high gain at a compact size several techniques such as (i) use of broadband feed network, (ii) utilising of adjacent cells with unique structure as mutual coupling reducer, and etc. have been simultaneously applied. In order to validation of simulated parameters the proposed array has been fabricated and measured. The measurement results for the proposed compact size array antenna are the impedance bandwidth ($|S_{11}| < -10$ dB) of 4.22–7 GHz (49.55%), a 3-dB axial ratio bandwidth of 4.71 to 6.28 GHz (28.5%), and a peak gain of 16.57 dBic at 5.5 GHz.

1 Introduction

Microstrip antenna to have their benefits of light weight, low profile, low cost, and ease of fabrication are a good choice in many applications in wireless systems. Circularly polarised (CP) antennas because of their advantages include improved immunity to multipath distortion, polarisation mismatch losses, and Faraday rotation effects caused by the ionosphere, have been widely employed in many wireless systems. The CP array antennas performance are generally depended on radiation element and feed network. Many feed networks to improve CP characteristics have been presented [1–9]. A sequentially rotation (SR) feed has been reported as a common way for producing CP radiation in [3]. Though based on SR technique, many works [4–8] have been designed for different applications, the SR suffers low-phase shifting BW, impedance mismatching and consequently lower 3-dB AR and impedance BW. Two main techniques to improve characteristics of CP array antennas have been reported. The first solution is employing of broadband feed networks to increase phase and magnitude bandwidth. To get practical results of aforementioned solution, the use of couplers and broadband phase shifters can be a good alternative impedance matching network [1]. Second solution is employing of broadband and high gain elements with compact sizes. This technique causes to reduce zero coefficients of array factor and consequently decrement of side lobe numbers and levels and increment gain of array. In this technique array antennas confront with an issue as mutual coupling, in order to reduction of space among array radiation elements.

Recently, incorporation metasurface structures (MTS(s)) as an innovation [9] have been helping to improve their performance features.

Table 1 Comparison proposed array antenna with recently reported MTS-based CP array

Ref	Size (λ_0)	IBW, %	AR, %	Gain, dBic
[11]	1.72 × 1.72 × 0.077	75.4	46.5	12.8
[12]	1.60 × 1.60 × 0.065	41.45	23.16	13.5
[13]	1.26 × 1.26 × 0.046	55.6	41.67	12.08
this work	1.46 × 1.83 × 0.051	49.55	28.5	16.57

The main concepts behind using of metasurface [10] can be abridged as the reduction of mutual coupling, improvement of impedance matching, gain increment, suppression of surface waves, size compactness, polarisation conversion, and improvement of AR features. Hitherto, several works using MTSs with a total bandwidth of >20% have been reported [11–13]. As displayed in Table 1, more of reported antennas suffer of a low gain <13.5 dBic.

To addressed aforementioned problems, a broadband MTS-based CP slot array antenna with a plain structure is presented. The proposed array antenna consists of four elements. Each of radiation element is designed on two substrate layers which isolated each other with a metallic ground plane. The top layer consists of 4 × 4 metasurface cells which in order to retrieve CP feature two opposite corner of each cell is chamfered. Meanwhile to amend feed network a cascade feed network, includes two 90-degree branch line couplers and a 180-degree rat-race coupler, has been presented.

One of the factors make distinct the proposed array from former works is the method of assembling (arranging) of MTS cells. In proposed technique, the structure of middle cells is different from another cell, to reduce size of antenna. Indeed, these cells by generating a reverse rotation lead to a mutual coupling reduction and gain enhancement of array. Consequently, the combination of proposed method with cascade feed network causes to a broadband high gain array antenna.

2 Single MTS antenna elements

The configuration of MTS-based antenna element is displayed in Fig. 1. The dimension of the MTS-based antenna element is 42 mm × 42 mm × 2.8 mm, which it is implemented on two FR4-epoxy substrates ($\varepsilon_r = 4.4$ and $\tan\delta = 0.02$) with thickness of $h_1 =$ 0.8 mm and $h_2 = 2$ mm. The top layer of substrates plays a role as antenna and consequently it has a thick height (h_2). The upper side of substrate consists of 4 × 4 metal truncated-corner patch with the size of $d_x \times d_y$, with a constant gap of g in x- and y-axis directions. To isolate destructive effects of feed on metasurface cells an aperture slot between cells and feed is considered. Bottom layer of substrates with thin height is designed as an independent microstrip feed line and 50 ohm input impedance. To reform CP feature, the truncated-corner cell is used because it is the simplest CP structure

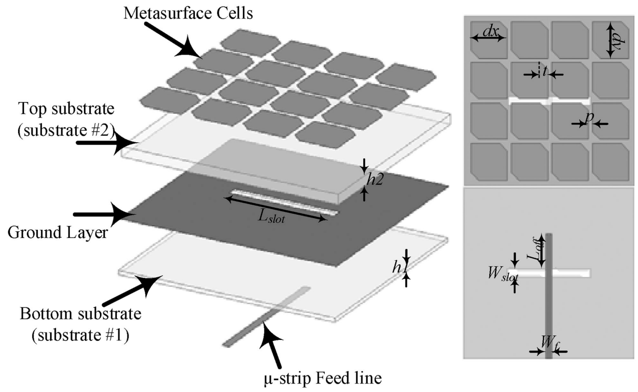

Fig. 1 *Configuration of proposed MTS-based single element antenna ($d_x = d_y = 9.5$, $t = 2$, $L_{off} = 9$, $W_{slot} = 2.2$, $L_{slot} = 21.25$ and $p = 1$ (all values in mm))*

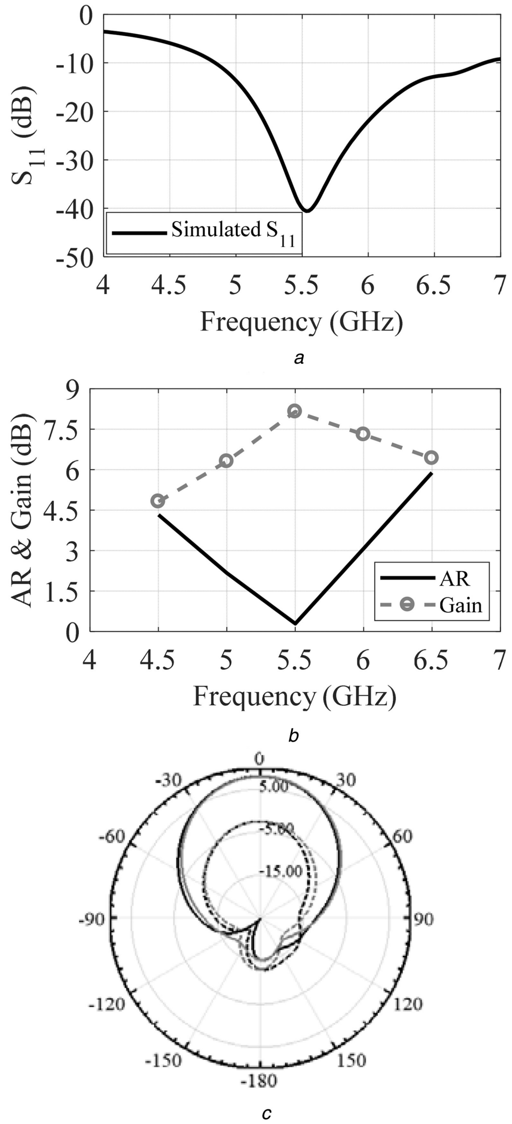

Fig. 2 *Simulated results of proposed single element*
(a) the simulated S_{11}, ***(b)*** the simulated AR and Gain, and ***(c)*** the radiation pattern of antenna at 5.5 GHz. (solid black line is LHCP at $\phi = 0°$, solid grey line is LHCP at $\phi = 90°$, dash black line is RHCP at $\phi = 0°$ and dash grey line is RHCP at $\phi = 90°$)

and has got its own advantages [14–18]. Indeed, each of cell portrays a CP patch antenna which a pair orthogonal (90-degree phase shifting) resonant modes of ($TM_{10} \perp TM_{01}$) are excited based on the periodicity and CP patch cells. To appraise the performances of the structure, a 4 × 4 patch array of the metasurface is considered, which can be equivalent to a two-orthogonal-resonant-

Table 2 Comparison single MTS antenna element with some recently reported MTS antenna

Ref	Size (λ_0)	IBW, %	AR, %	Gain, dBic
[14]	0.77 × 0.77 × 0.06	11.4	14.9	5.7
[15]	0.78 × 0.80 × 0.096	48.6	20.4	6.5
[16]	1 × 1 × 0.068	25.7	8	8
[17]	0.58 × 0.58 × 0.056	45.6	23.4	7.6
[18]	0.63 × 0.51 × 0.073	33.7	16.5	5.8
this work	0.77 × 0.77 × 0.051	36.7	22.01	8.1

mode patch. With the periodic arrangement, uniform electric field distribution is rotated on the aperture, and consequently, it provides better CP radiation characteristics. The proposed element has been simulated by commercial ANSYS HFSS software. The simulated results of S_{11}, AR, gain, and pattern of antenna are displayed in Fig. 2. As seen, the impedance and 3-dB AR bandwidth are (4.81–6.92 GHz) and (4.81–6 GHz), respectively. The peak gain of antenna is 8.1 dBic and half power beamwidth (HPBW) is 57.2° at 5.5 GHz.

Table 2 shows the comparison single MTS antenna element with some recently reported works. The proposed antenna in comparison all mentioned references except [17, 18] has lower size. The impedance BW is larger than all works except [15, 17] and 3-dB AR BW is better than all except [17]. In a fair judgment, though proposed antenna designed on a low cost substrate with high loss tangent ($\tan\delta = 0.02$) (FR4), it has a good result at compared references [17] (Rogers 4003 ($\tan\delta = 0.0027$)) and [15] (Rogers 5880 ($\tan\delta = 0.0009$)) with expensive substrates and low loss tangents. The gain of proposed antenna is more than other items. Generally, the proposed single antenna has worthy results and can be a good alternative for array elements.

3 Array configuration and results

In order to increase 3-dB ARBW and to have a balanced pattern, the feed network must be designed as provide 90-degree phase shifting between adjacent elements and 180-degree between opposite ones. Additionally, elements have to rotate regarding to provided phase shifting by feed network. To have a broadband, 3-dB ARBW is used a cascade feed network which can provide broadband phase-shifting distribution system among array elements. It consists of two 90-degree branch line couplers and a 180-degree rat-race coupler.

As seen in Fig. 3, the proposed MTS-based elements are used as CP radiator in array. The elements are rotated by changing produced phase shifting of feed network. The middle rows and colons of MTS cells between adjacent elements are considered as cells that four corners of they are truncated. Use of this technique causes to reduce size of array and provide a balanced pattern by creation isolation between elements. The surface currents vector distribution of proposed array is displayed in Fig. 4. The role of isolator middle cells is significantly indicated in this figure. Indeed, those cells by generating a reverse current rotation cause to eliminate mutual coupling effects among elements. The proposed antenna to validate simulation results has been fabricated and then tested. The S_{11} of MTS array antenna has been measured by Agilent^{TM} 8722ES vector network analyser. While S_{11} of array antenna has been tested, it put on a layer of polystyrene absorber to prevent destructive field. The comparison between simulated and measured S_{11} of MTS array antenna is displayed in Fig. 5. There is a good agreement between them. The measured results show the antenna can cover a frequency range (VSWR < 2) from 4.22 to 7 GHz. Although, the proposed array has an impedance bandwidth at frequencies >7 GHz, but loss tangent of FR4 has got an incredible increment at that frequencies, therefore, results at frequencies >7 GHz are very trivial.

The comparison simulated and measured AR and gain of antenna are demonstrated in Fig. 6. To measure 3-dB, ARBW use of dual CP receiving antennas and then maximum and minimum cross-polarisation isolation values for each antenna measured. The

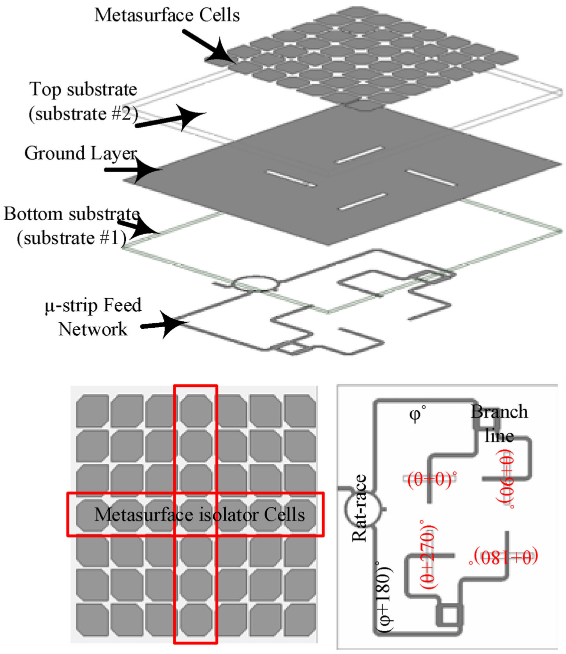

Fig. 3 *Configuration of proposed MTS-based array antenna fed by cascade feed network*

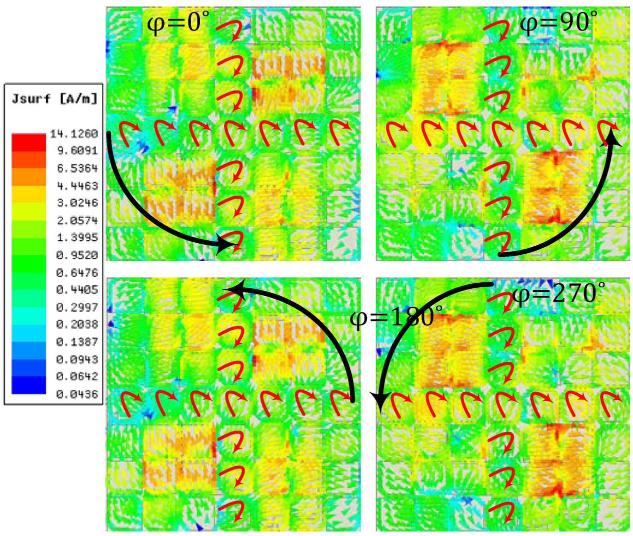

Fig. 4 *Surface currents distribution of proposed MTS-based array antenna*

attained data are sufficient to permit for the calculation of the 3-dB axial ratios and distinction between that for each antenna as well as for that of the incoming wave. The measured minimum value of AR (matching with simulation) is occurred at 5.5 GHz and the array treats as a CP antenna in frequency range from 4.71 to 6.28 GHz. The average measured gain of antenna is about 15.6 dBic and peak gain of it is 16.57 dBic at 5.5 GHz. As a conclusion, the most important factors in increasing gain of array up to 8.4 dBic in comparing with single element are: (i) the element is used into a 2 × 2 array, (ii) at array distance between elements is reduced by resorting on how to sort cells and it causes to reduce zero coefficients of array factor, and decrement of side lobe numbers and levels, and finally increment gain of array, (iii) a broadband low loss feed network is designed to prevent gain variation, and (iv) reduction of mutual coupling basis on aforementioned method.

However, those are a good agreement between simulated and measured results of an antenna, but many factor cause to creation a difference. The handy fabrication error is a main reason of difference.

The measured normalised radiation patterns of the array at 4.75, 5.5 and 6.5 GHz are presented in Fig. 7. The cross-polarisation (RHCP) is about 18 dBic less than co-polarisation (LHCP) at three

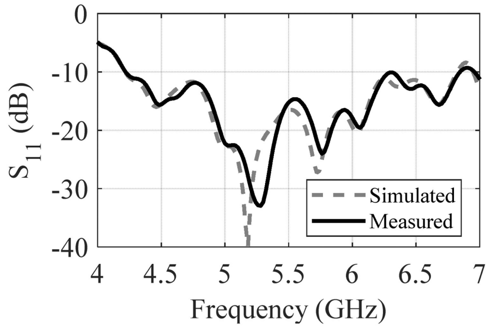

Fig. 5 *Comparison between simulated and measured S_{11}*

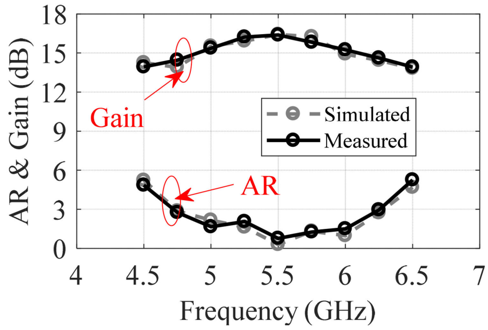

Fig. 6 *Comparison between simulated and measured 3-dB AR and gain of proposed array*

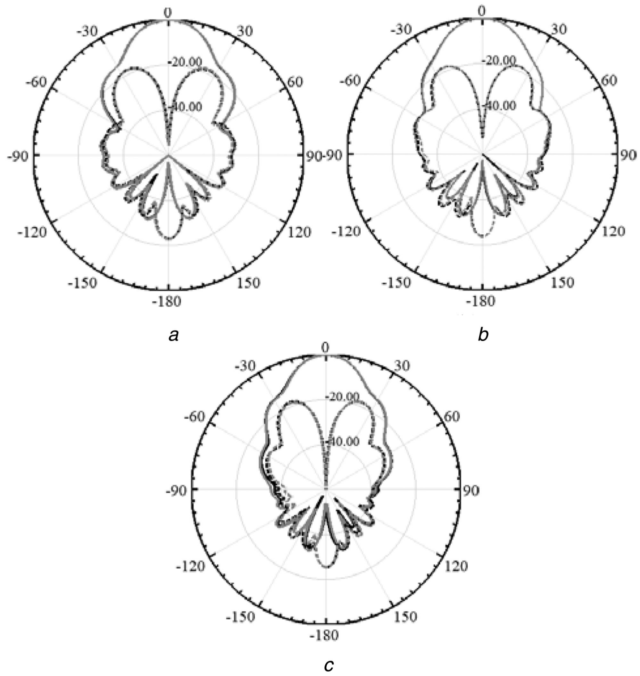

Fig. 7 *Measured results of the normalised radiation patterns of the array at*
(a) 4.75 GHz, ***(b)*** 5.5 GHz and ***(c)*** 6.5 GHz (solid black line is LHCP at $\phi = 0°$, solid grey line is LHCP at $\phi = 90°$, dash black line is RHCP at $\phi = 0°$ and dash grey line is RHCP at $\phi = 90°$)

frequency of the measured radiation patterns. The half power beamwidth of radiation pattern at 4.75, 5.5, and 6.5 GHz are 12.5°, 10.6°, and 13.1°, respectively. The comparison proposed array antenna with recently reported MTS-based CP array is displayed in Table 1. As proved array antenna with a relative small size generally have broadband impedance and AR with compared works while the gain of proposed array is minimum 3 dBic more than other reported works. Fig. 8 show layered structure of proposed MTS-based CP array antenna.

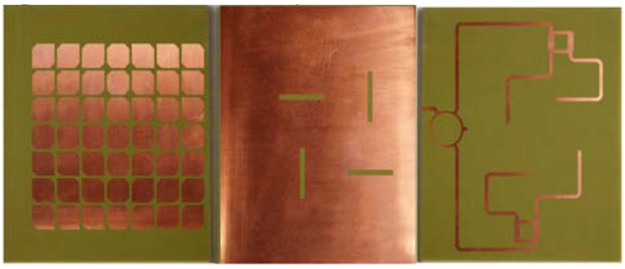

Fig. 8 *Photograph of prototype proposed CP MTS-based array antenna*

4 Conclusion

In this letter, the CP array antenna design for gain enhancement and size reduction is discussed. In the antenna design metasurface structures as the newness method has been used. Size of single element antenna is $(0.77\lambda_0 \times 0.77\lambda_0 \times 0.051\lambda_0)$ and the results shows that frequency range (VSWR < 2) is from 4.81 to 6.92 GHz (36.7%), 3-dB AR bandwidth is from 4.81 to 6 GHz (22.01%), the HPBW is 57.2° at 5.5 GH and the average gain of antenna is 8.1 dBic. In the array part cascade network for broadband operation has been utilised. The overall size for the fabricated array antenna is $(1.46\lambda_0 \times 1.83\lambda_0 \times 0.051\lambda_0)$ that improve the results as; results as; impedance bandwidth from 4.22 to 7 GHz (49.55%), a 3-dB axial ratio bandwidth of 4.71 to 6.28 GHz (28.5%) and a peak gain of 16.57 dBic at 5.5 GHz.

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