A Circularly Polarized Miniaturized Patch Array Using Combination of Circle and Rectangular Lines in the Sequential Phase Feed Structure

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Abstract **─** A sequential phase (SP) feed array antenna circularly polarized (CP) with 2×2 patch array is presented. The feeding network consist of two piece of circle that are filled with rectangular lines and have four arms that make 90^0 phase difference for the corner truncated elements which are connected to the feeding network. The combination of circle and rectangular lines reduces the size of the feeding network and thus, the overall size of the antenna with good characteristics to prove the antenna performance, the prototype antennas built and the results come in the form of: the measured 10 dB impedance bandwidth is 0.5 GHz (3.45 - 3.95 GHz), and the measured 3-dB AR bandwidth is 0.3 GHz (3.45 - 3.75 GHz).

Index Terms **─** Circular polarization, feeding network, incomplete ground, microstrip array, radiating patch element, sequential rotation.

I. INTRODUCTION

One of the most important subjects in designing antenna is to achieve circular polarization (CP), which also includes 2×2 patch array design. Sequential rotation (SR) techniques contribute significantly to achieving the optimal CP bandwidth [1].

So far, different feeding networks have been introduced which are discussed in [2-11]. These feeding networks have more complex structures. Nowadays, SR feeding networks with united structure is more interesting in which, narrow CP bandwidth problem can be solved.

Radiating elements in the patch have a smaller bandwidth than the DRAs (dielectric resonator antenna) due to the nature of the patch elements. For example, use of the center-truncated patch element, reduces characteristic of the AR bandwidth. The samples of these antennas have been introduced in [12, 14], which almost have a narrow bandwidth. Therefore, the ability to design 2×2 patch array with a wider bandwidth is very attractive.

Another issue that must be considered is the antennas dimensions. A large feeding network leads to a large antenna. Also, it is preferable that eliminate network complexity as much as possible.

According to the explanations that were given, we conclude that a desire SP feed should be able to provide some conditions. One significant problem is that the feeding network with four arms should have the same amplitude signals and 90^0 phase shifting on the arms to have 0^0, 90^0, 180^0, 270^0 phases. Secondly, the issue of commuting the antenna impedance to the feed I/O port impedance for contractual values should be established. Finally, the dimensions of the antenna have been discussed as to design a small feeding network reduces the size of the antenna.

Of course, in the design of a small antenna we should be careful to maintain desired characteristics of the antenna such as gain and AR bandwidth. In the following, an antenna has been introduced which provides these requirements very good.

II. ANTENNA DESIGN

Figure 1 (a) shows the structure of the patch array. The central section is the feeding network which includes two 90^0 arcs of a circle that is filled with rectangular lines. The reason of using this combination is to minimize the size of the feeding network. This design, based on two essential points: the first point is that by shrinking the size of the antenna, the gain is reduced and to compensate the reduced gain, the rectangular lines are designed quite compressed. Another issue is the impact of the network feeding to CP bandwidth. With regard to these two issues, the feeding network is designed as shown in Fig. 1 (b).

At the radiation patch element, the corner-truncated square technique is used which is connected to the feeding network with four strips. The feeding port located at the center of the substrate and feeding network. The antenna that has been introduced has a single-layer patch that is printed on the FR4 substrate with ε_r=4.4, tan δ = 0.024 and thickness of h=1.6 mm. The patch dimensions have been optimized by the HFSS full wave simulator and details of the patch array are shown in Table 1, and Table 2 showing details of the

Submitted On: November 2, 2015
Accepted On: March 10, 2017

feeding network.

Table 1: Dimensions of the patch

Parameter	mm	Parameter	mm
l_s	80	s_3	15.6
l_1	19.9	s_4	18.625
w_1	20	z	5.3
s_1	15.6	a	90^0
s_2	17		

Table 2: Dimensions of the feeding network

Parameter	mm	Parameter	mm
w_2	0.8	l_7	2.86
w_3	1.25	l_8	3.225
l_2	5.2	l_9	6.36
l_3	1.625	l_{10}	5.735
l_4	2.28	l_{11}	3.125
l_5	3.125	l_{12}	2.86
l_6	1.625	l_{13}	2

The center frequency of the antenna is 3.6 GHz. The value of λ_g is calculated according to the Equation (1) ((w) is the width of the microstrip line in feeding network and (h) is the height of the substrate). Different paths are shown in Fig. 1 (c), that each path creates a 90^0 phase difference. The length of each arc is $\lambda_g/4$. With regard to this issue, the value of the radius is calculated as r=8.15 mm.

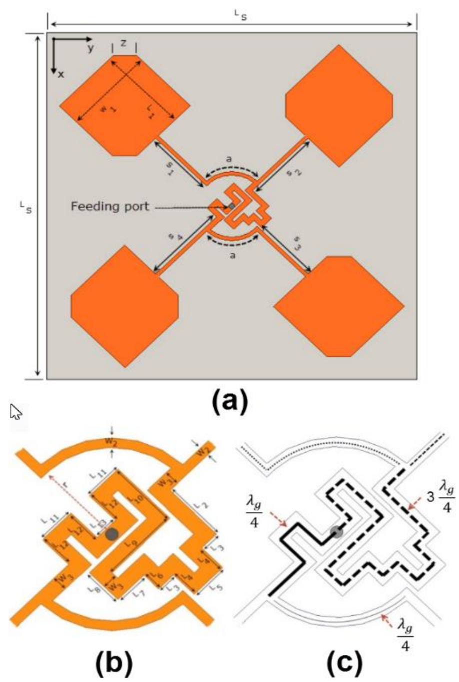

Fig. 1. Geometry of the proposed 2×2 antenna array: (a) dimensions of the antenna, (b) dimensions of the feeding network, and (c) length of paths.

By creating different paths, sequential phases of 0^0, 90^0, 180^0, 270^0 can be seen at the four arms (Fig. 2). The 90^0 phase differences at the center frequency of 3.6 GHz at the four arms of feeding network is visible in the Fig. 2 (c). When the value of the phase in output 2 is about -150^0, the values of the phases of port 3, port 4 and port 5 are -60^0, 30^0 and 120^0 respectively. Furthermore, the simulated results of the scattering parameters when port-1 is excited, is shown in Fig. 2 (b).

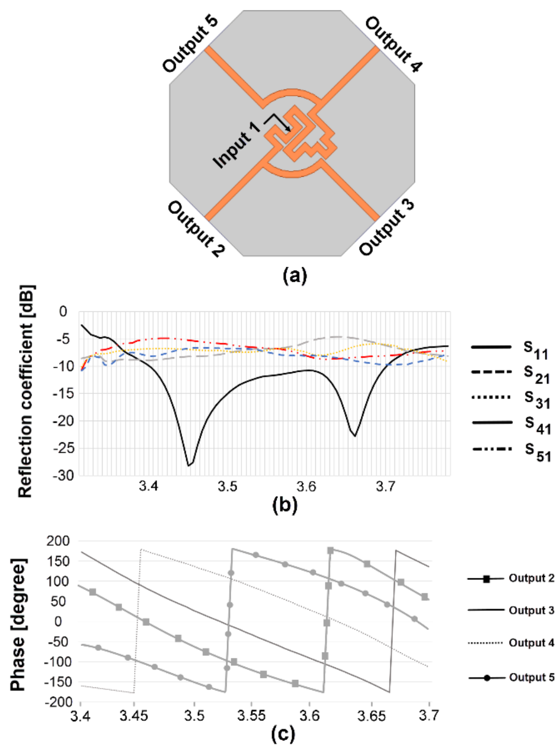

Fig. 2. (a) Structure of feeding network, (b) simulated results of the scattering parameters when port-1 is excited, and (c) simulated sequential phase differences at four arms of feeding network in desired frequency range.

The current distribution on the array at the frequency of 3.6 GHz is shown at Fig. 3. Direction of flow at the phases of 0^0, 90^0, 180^0, 270^0 is counter clockwise and this circular motion leads to the circular polarization:

$$\lambda_g = \frac{v_p}{f} = \frac{c}{f\sqrt{\varepsilon_{eff}}}. \quad (1)$$

If $(\frac{w}{h}) < 1 \rightarrow$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\frac{1}{\sqrt{1 + 12\frac{h}{w}}} + 0.04\left(1 - \frac{w}{h}\right)^2\right].$$

If $(\frac{w}{h}) \geq 1 \rightarrow$

$$\varepsilon_{eff} = \frac{1 + \varepsilon_r}{2} + \left[\frac{\varepsilon_r - 1}{2\sqrt{1 + 12\frac{h}{w}}}\right].$$

Figure 4 shows the schematic diagram of the SP feed. One of the impedances of z_1 is for the arm of the feeding network and arc of the circle (doted line in the Fig. 1 (c)) and the other one is for the arm of the feeding network alone (thin dashed line in the Fig. 1 (c)). According to the Fig. 3, the z_1 impedances are parallel with each other and the collection of the z_1 impedances are parallel too. The parallel impedances of z_1 are series with the impedances of z_2. Impedances of z_2 are for the paths of the $\lambda_g/4$ (thick line in the Fig. 1 (c)) and $3\lambda_g/4$ (thick dashed line in the Fig. 1 (c)) in the feeding network. Impedance of the feed line is 50 Ω, so we have a good impedance matching between the feed line and feeding network. According to the Equation (2), the impedance of feeding network has calculated as Z= 65 Ω ((w) is the width of the microstrip line in feeding network and (h) is the height of the substrate):

$$\text{If } \left(\frac{w}{h}\right) < 1 \rightarrow Z = \frac{60}{\sqrt{\varepsilon_{EFF}}} \ln\left(8\left(\frac{h}{w}\right) + 0.25\left(\frac{w}{h}\right)\right). \quad (2)$$

$$\text{If } \left(\frac{w}{h}\right) \geq 1 \rightarrow Z = \frac{120\pi}{\sqrt{\varepsilon_{eff}}} / \left(\frac{w}{h} + 1.393 + 0.667 \ln\left(\frac{w}{h} + 1.444\right)\right).$$

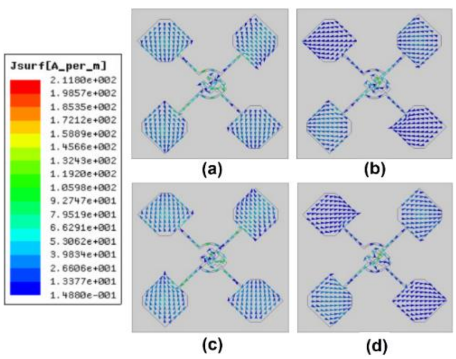

Fig. 3. Current distribution on the proposed array at 3.6 GHz with different phase: (a) 0^0, (b) 90^0, (c) 180^0, and (d) 270^0.

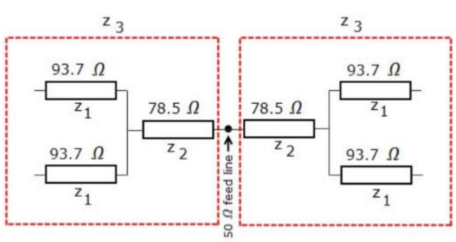

Fig. 4. Schematic diagram of the SP feed.

III. EXPERIMENTAL RESULT

Figure 5 shows the prototype of the antenna with 2×2 patch array. In Fig. 6, the measured value of reflection coefficient is shown. It can be seen that there is a good matching between simulated and measured results. The -10dB reflection coefficient bandwidth is from 3.45 GHz to 3.95 GHz. A little difference between simulated and measured results is related to dielectric loss, fabrication error and differences in the characteristics of the substrate.

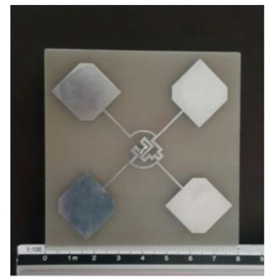

Fig. 5. Prototype of the proposed 2×2 patch array.

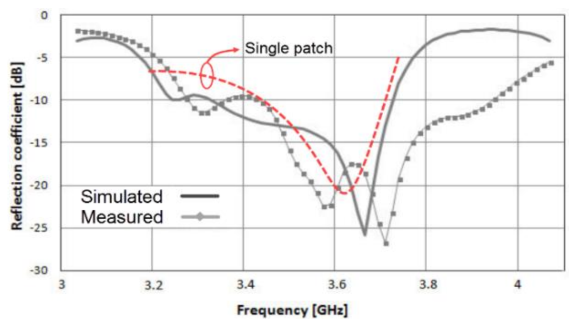

Fig. 6. Simulated and measured reflection coefficient of the 2×2 array.

Figure 7 shows the simulated and measured results of the AR parameter. The AR bandwidth is from 3.45 GHz to 3.75 GHz. In Fig. 8, the simulated and measured results of the gain is shown. According to the AR bandwidth, the gain in the desired range is more than 4 dB and the maximum gain is 7.8 dB, at the frequency of 3.7 GHz. The results of the radiation pattern at the frequencies of the 3.5 GHz and 3.6 GHz are shown at Fig. 9. According to the results, at the +Z direction, the gain of co-polarization (RHCP) is about 12dB higher than the cross-polarization (LHCP) and good agreement is observed between simulated and measured results.

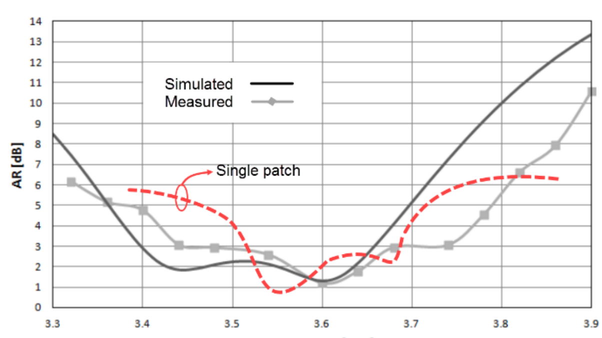

Fig. 7. Simulated and measured axial ratio of the 2×2 patch array.

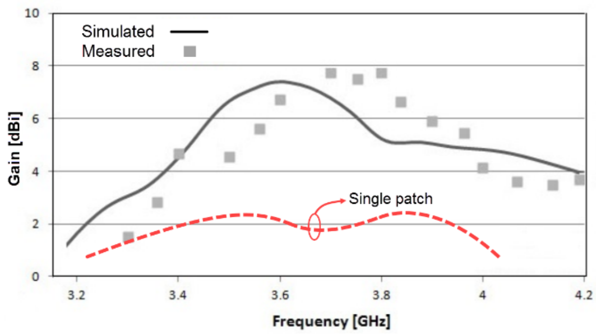

Fig. 8. Simulated and measured gain of the 2×2 patch array.

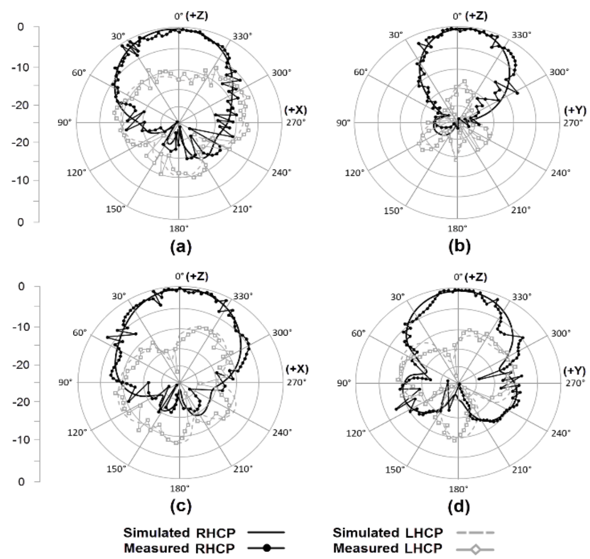

Fig. 9. Normalized radiation pattern at 3.5 and 3.6 GHz: (a) simulated and measured RHCP and LHCP in x-z plane at 3.5 GHz, (b) simulated and measured RHCP and LHCP in y-z plane at 3.5 GHz, (c) simulated and measured RHCP and LHCP in x-z plane at 3.6 GHz, and (d) simulated and measured RHCP and LHCP in y-z plane at 3.6 GHz.

Table 3 shows a comparison between the proposed patch array and the other single-layer patch arrays. One of the significant issues is the size of the feeding network that is small as much as possible. Another important issue is the material of the substrate which is reduced the cost of the antenna. It was also observed that the size of the proposed antenna is smaller than the other antennas.

According to the given explanations and with regard to the common bandwidth of s_{11}< -10 dB and AR< 3dB, we conclude that the operation of the antenna is quite acceptable. In addition, for high gain applications the proposed SP feed can be developed to the large CP planar array. By using compact and uniform properties, the larger scale $2^N \times 2^N$ arrays can be derived from the reported 2×2 SP feed and array element. For instance, the structure of 4×4 arrays by using the extended feeding network based on the module unite of the proposed 2×2 SP feed is shown in Fig. 10.

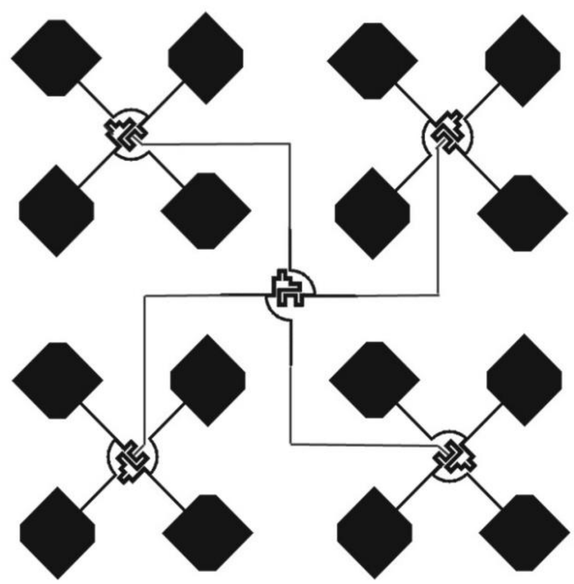

Fig. 10. Extended feeding network to achieve 4×4 SR arrays.

Table 3: A comparison between the proposed patch array and the other single-layer patch arrays

2×2 Patch Arrays	Ref [12]	Ref [13]	Ref [14]	Ref [15]	Proposed Antenna
10-db reflection coefficient bandwidth (%)	7.3	15.45	8	6	13.9
3-db AR bandwidth (%)	4.4	5.4	4.8	6.8	8.3
Material of substrate	Rogers	Rogers	FR4	Teflon	FR4
Substrate dimensions	Not given	3.43×3.43×0.039	3.15×3.15×0.022	2.83×2.83×0.085	2.59×2.59×0.052

IV. CONCLUSION

In this paper, a single layer SP feed array antenna with hybrid design of circle and rectangular lines in feeding network is introduced. The common 10dB impedance bandwidth and 3dB AR bandwidth is 300 MHz or 8.3% corresponding to the center frequency of 3.6 GHz. The maximum gain is 7.8 dB at the frequency of 3.7 GHz. The aim is to design an antenna with a small size and acceptable performance that is proved in comparison with the other single-layer 2×2 patch arrays. Design a SP feed with repeatability is an advantage. The presented design applies in the $2^N \times 2^N$ applications. With a comparison that is done, it can be seen that in the same material of the substrate, the area of the substrate has greatly decreased (about 67%), while the common bandwidth of 10dB reflection coefficient and 3dB AR is increased about 3.5%.

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