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Circularly Polarized Circular Slot Antenna Array Using Sequentially Rotated Feed Network

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Abstract—This paper presents the design, simulation, and measurement of two low-cost broadband circularly polarized (CP) printed antennas: a single element and an array at C band. The proposed single element antenna is excited by an L-shaped strip with a tapered end, located along the circular-slot diagonal line in the back plane. From the array experimental results, the 3 dB axial ratio bandwidth can reach as large as 1900 MHz which covers the 4.7 GHz to 6.6 GHz frequency band. In addition, the measured impedance bandwidth for reflection coefficient of less than -10 dB has the bandwidth with the frequency range from 4.2 GHz to 8 GHz (C Band application). The CP element achieves a bandwidth of 16.6% for an axial ratio less than 3 dB. The proposed antenna array can provide a peak gain of about 8.7 dBic at 5.9 GHz. Acceptable agreements between the simulation and measured results validates the proposed design.

Index Terms— Circularly polarized, Circular Slot antenna, Slot antenna array, sequentially rotated array.

I. INTRODUCTION

Circular polarization is particularly useful for applications on global position, satellite, and mobile communication systems. A number of circularly polarized (CP) microstrip antennas have been developed due to their very thin profile, light weight, low cost, better mobility and weather penetration than linearly polarized (LP) antennas in last decades [1]- [3]. As is well known, one main disadvantage of microstrip antenna is its narrow impedance bandwidth and its high loss. For a circularly polarized microstrip antenna, both axial ratio and impedance bandwidths need more considerations. For this reason much effort have been done about circularly polarized antenna design with different techniques [1]-[11]. Between these techniques sequentially rotated feed network is one of these famous methods. By a sequential rotation feed technique [4], we can design an array with good circular polarization and wide impedance bandwidth.

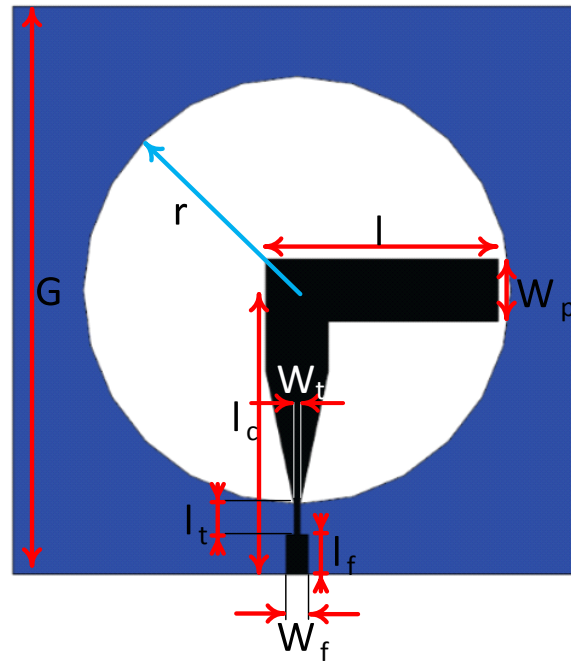


Figure 1. Configuration of the proposed single element circular slot antenna (CSA). $W_f=1.5$, $l_f=2.8$, $l_c=20$, $l=16.3$, $W_p=4.4$, $r=15$ and $G=40$. (All in mm)

Between different array antenna design techniques, sequential rotation feed technique is an interesting method for the design of CP array antennas, which was proposed to improve main beam, impedance bandwidth and polarization purity of the array [11]. The use of linearly polarized elements in sequential rotation feed technique leads to a gain reduction exceeding 4-dB and high cross-polarization level compared to circular polarization elements [5]-[11]. To enhance the CP bandwidth, the most commonly employed technique is the use of thicker substrate with lower dielectric constant. However, large inductance could be introduced by the feed mechanism. Hence, to resolve this issue, methods such as the use of an L-shaped probe [5] or an L-shaped ground-plane with air-layer acting as the antenna substrate [7] are recommended, utilizing two CP resonant elements in the ring-slot coupled microstrip antenna [8], or coupling the series probe inductance to a parallel capacitance introduced by adjusting the inner slot size of the square-ring patch [9], are used with previous researchers.

In this paper, we present a novel high-gain and low-cost microstrip antenna array with wide circular polarization is presented for first time. The operating frequency bandwidths of the proposed design is between 4.2GHz to 8GHz (C-Band application). The sequential rotation feed network [7], [11] is used to feed the circularly polarized circular slot antenna elements. As a result, impedance bandwidth, axial ratio of polarization, and symmetry of radiation are much improved in comparison with previous array structures. To achieved a better axial ratio bandwidth (ARBW) in proposed design, an L-shaped strip

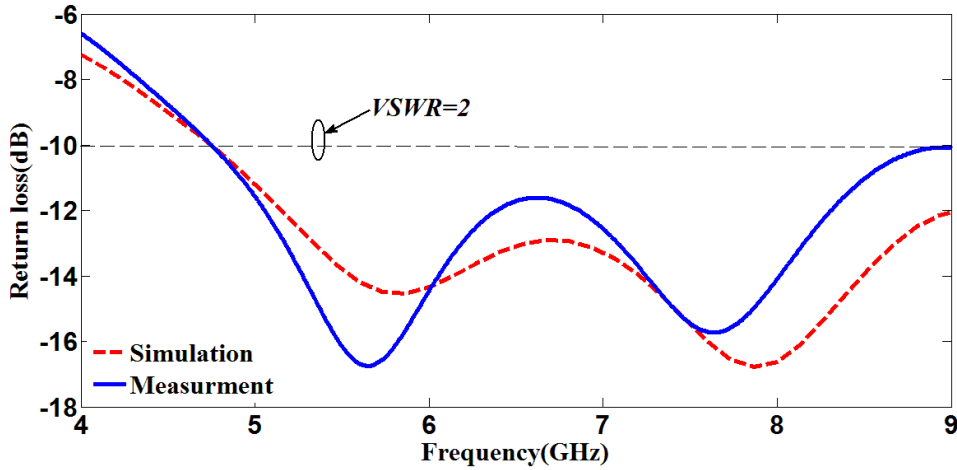


Figure 2. Comparison between measured and simulated S_{11} , results of proposed circular polarized circular slot element.

TABLE I
COMPARISON OF THE PROPOSED CPSA ANTENNA SIZE AND MEASURED CHARACTERISTICS WITH OTHER REFERENCES. THE SUBSTRATE IS FR4 WITH $\epsilon_r=4.4$, $TAN\delta=0.02$. THE IMPEDANCE BANDWIDTH IS FOR A FREQUENCY RANGE WHERE THE $VSWR \leq 2$; AND ARBW IS THE 3-dB AXIAL-RATIO BANDWIDTH.

Ref.	Size (mm ³)	BW (freq. range) (GHz)	ARBW (freq. range) (GHz)	Peak Gain (dBic)
[13]	70×70×1.60	0.85 (1.75-2.6)	0.4 (1.7-2.1)	3.7
[14]	70×70×1.60	0.20 (1.5-1.7)	0.3 (1.5-1.8)	3.5
[15]	70×70×1.60	0.80 (1.6-2.4)	0.2 (1.8-2.0)	3.5
[16]	60×60×0.76	0.80 (1.7-2.5)	0.7 (1.8-2.5)	3.5
[17]	60×60×0.74	1.40 (1.6-3.0)	0.7 (2.3-3.0)	4.0
This work	40×40×0.80	6.2 (4.8-11)	~1 (5.5-6.5)	3.6

with a taper end is used to excite two orthogonal radiation fields and in phase quadrature in single elements.

II. SINGLE ELEMENT AND CONFIGURATION

The geometry of the proposed dual layer circular slot antenna (CSA) with circular polarization is shown in Fig. 1. A circular slot with radius r is etched on the ground plane (GND) in back layer. The proposed circular slot antenna element is printed on a commercial cheap FR4 substrate with relative permittivity of 4.4. The right-hand L-shaped strip with a taper end is fabricated directly opposite the circular slot. Note that the 1 mm length of the strip along the y -axis measured from circular slot center etched in the ground plane, while W_s refers to width of the proposed strip along the x -axis. A thin microstrip line used as an impedance transformer between the 50 ohm microstrip line and the taper in the end of the L-shaped strip. As indicated in the Fig. 1, microstrip impedance transformer has a length of $l_t=2.1$ mm and width of $W_t=0.4$ mm. The comparison of simulated and measured impedance

bandwidth results for proposed circular slot element with optimized parameters are plotted in Fig. 2, as indicated in Fig. 2, the measured impedance bandwidth has an operating frequency range from 4.8 to 8 GHz.

The proposed CPSA has an area of 1600 mm^2 ($40 \text{ mm} \times 40 \text{ mm}$), which is considerably less than the previously published square slot antennas as summarized in Table I along with the other salient parameters. Compared to the other similar types of CPSAs fabricated on the same substrate the proposed antenna exhibits an impedance bandwidth which is significantly larger and with no reduction in the gain performance, as well as having a larger circular polarization bandwidth. The gain is comparable to the previous designs.

III. BROADBAND CIRCULAR POLARISED ARRAY ANTENNA

As shown in Fig. 3, in the proposed circular slot antenna array (CSAA) feed network to form a four port network, seven quarter-wave transformers that are linked together in a sequential rotation (0° , 90° , 180° and 270°) manner [12]. Fig. 3 shows the proposed circular slot antenna array feed network transmission-line equivalent circuit [12]. During design of the proposed CSA array feed network, some assumptions were made as follows: The input impedance of the individual circular slot antenna and characteristic impedance of the main input feed line were 50-ohm. As shown in Fig. 3, in this feed network, P_0 and $P_{m(m=1,2,3,4)}$ stands for the input power and the power flowing into m th ports (or CSA elements), respectively and the $P_{in}^{j(j=1,2,3)}$ stands for the total power flowing into the downstream. $Z_{m(m=1,2,3,4)}$, $Z_{inm(m=1,2,3,4)}$ and $Z_{in}^{j(j=1,2,3)}$ stands for respective characteristic impedances of the quarter-wavelength lines, the impedances looked into the four output ports and the impedance looked into the downstream ports at junctions, respectively. The configuration of the proposed CSAA array network was designed and simulated in Agilent™ Advanced Design System (ADS). As shown in Fig. 3, all $\lambda/4$ (λ is the wavelength in free space) transformers of feed were designed in a circular shape to reduce the discontinuity of feed network.

As shown in Fig. 4(a), the proposed circular slot antenna array is comprised of four sequentially rotated CSA elements and a sequentially rotated feed network. Length (L) and width (W) of each intersection transmission line lettered in Fig. 4(b) are as follows: $L_1=20 \text{ mm}$, $L_2=43 \text{ mm}$, $L_3=5.5 \text{ mm}$, $W_0=2.6 \text{ mm}$, $W_1=1.3 \text{ mm}$, $W_2=2.8 \text{ mm}$, $W_3=1.5 \text{ mm}$, $W_4=0.3 \text{ mm}$, $W_5=1.5 \text{ mm}$ and $W_6=0.3 \text{ mm}$. The low cost FR4 substrate was employed to construct the proposed circular slot antenna array. The proposed CPSA array is designed on a FR4 substrate with a thickness of 0.8 mm, a dielectric constant of 4.4, and a loss tangent of 0.02. The Ansoft™ electromagnetic simulation HFSS software was used to simulate and optimize the proposed configuration.

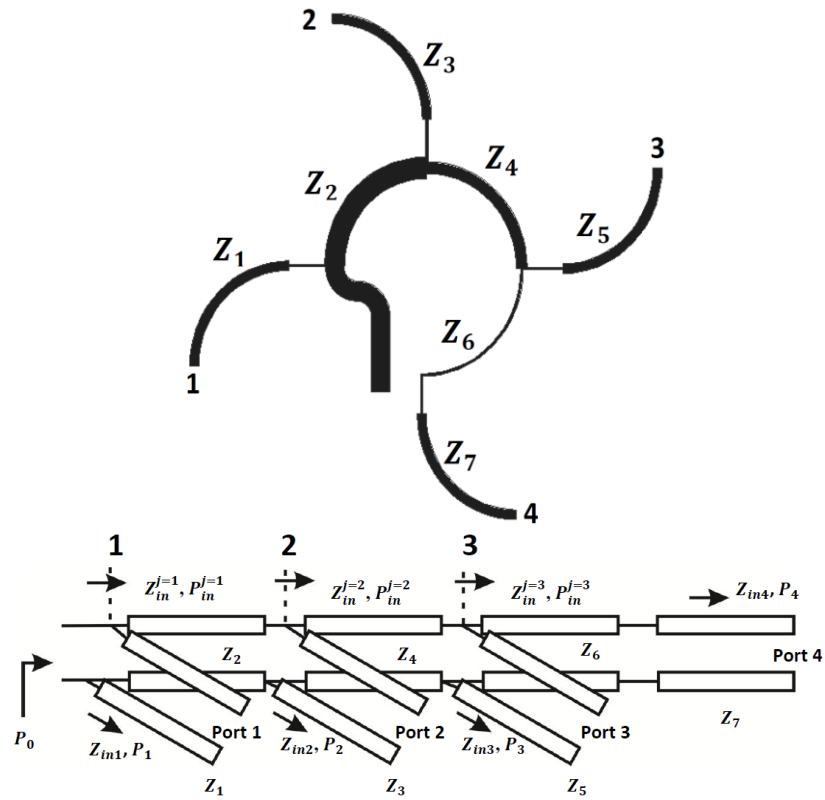


Figure 3. Equivalent circuit and diagram of the sequentially rotated CSA array.

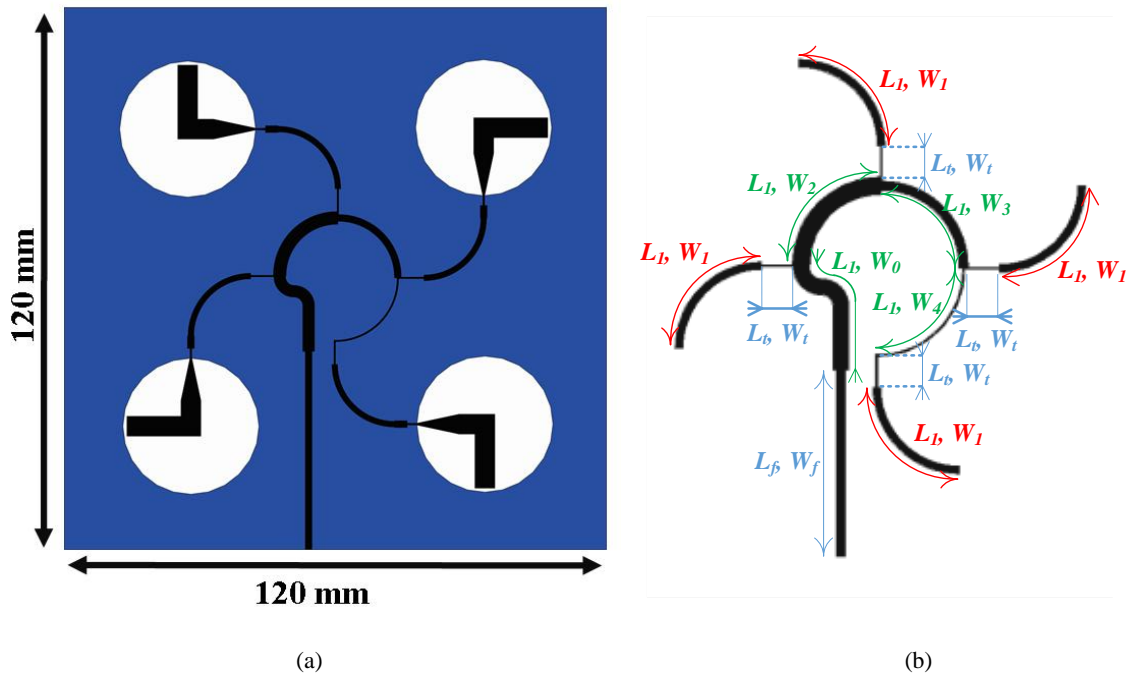


Figure 4. The Configuration of the proposed (a)circularly polarized circular slot antenna array and its (b)feed network.



Figure 5. Photograph of the fabricated CPS antenna array, (a) front (b) behind.

Fig. 5 shows the fabricated circular polarized circular slot (CPCS) antenna array with final size of $120 \times 120 \text{ mm}^2$, that is constructed using a 0.8mm-FR4 substrate. The proposed antenna array feeding network is fed with a 50 ohm SMA connector.

IV. RESULTS AND DISSCUSION

The proposed novel CPSA array is measured using the Agilent™ 8722ES network analyzer. The measured and simulated curves of array for final design are plotted in Fig. 6. The measured impedance bandwidth for Return Loss less than -10 dB has the bandwidth with the frequency range from 4.2 to 8GHz (C Band application). The proposed circular polarized circular slot antenna array has a measured peak gain of 8.7 dBic at 5.95 GHz. The CPSA array gain was between 7.4 - 8.7 dBic across 4.2 to 9GHz. The measured gain in +z ($\theta=0^\circ$) is shown in Fig. 6. For measuring the Gain of the fabricated antenna, one LP antenna is used in two orientations, the partial gains, G_{TV} and G_{TH} are combined to yield the total gain as,

$$G_T = 10 \log (G_{TV} + G_{TH}) \text{ [dBic]} \quad (1)$$

Note that a printed slot antenna is a bidirectional radiator, hence the gain in -z-direction ($\theta=180^\circ$) will be the same. It is interesting to notice that the proposed antenna array has 3dB axial-ratio bandwidths (ARBW_s) at 4.7 to 6.6GHz. The normalized radiation patterns results of the proposed CPSA array in two orthogonal planes at 5.5 GHz are shown in Fig.7. Since the printed slot antenna is a bidirectional radiator, the radiation patterns at both sides of the antenna will be similar with contrary CP. In this figure, the proposed antenna presents RHCP radiation in the +z-axis direction and LHCP radiation in the -z-axis direction.

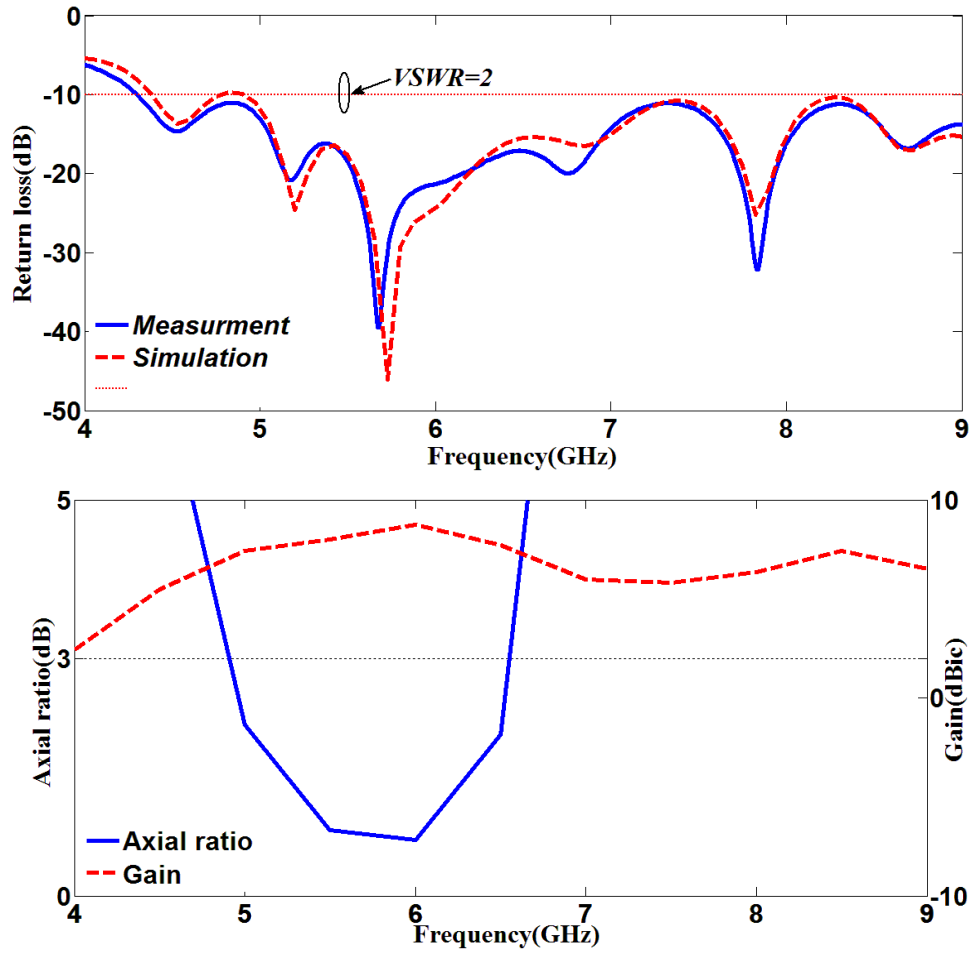


Figure 6. Comparison between measured and simulated S_{11} results of proposed CPS antenna array and measured gain and axial ratio results

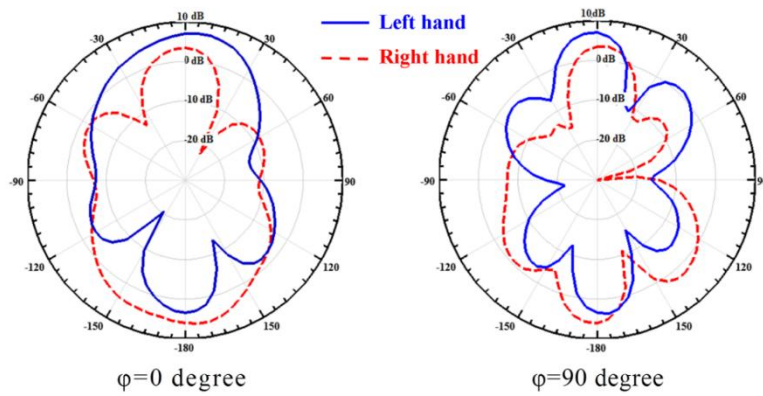


Figure 7. The measured RHCP and LHCP radiation patterns at 5.5 GHz. The right and left hand normalized radiation patterns with red dash line and blue solid line at $\text{PHI}(\phi) = 0$ and 90 deg, respectively.

TABLE II
COMPARISON OF THE PROPOSED FEED NETWORK STRUCTURE AND MEASURED CHARACTERISTICS WITH OTHER ARRAY ANTENNAS. THE IMPEDANCE BANDWIDTH (BW) IS THE FREQUENCY RANGE WHERE THE $VSWR \leq 2$; AND ARBW IS THE 3-dB AXIAL-RATIO BANDWIDTH.

Ref.	Feed Network	BW (freq. range) (GHz)	ARBW (freq. range) (GHz)	PG (dBic)	Substrate
[18]	Asymmetric CPW	0.80 (1.1-1.9)	0.80 (1.1-1.9)	~8	FR4
[19]	Aperture Coupled	0.80 (1.6-2.4)	0.60 (1.7-2.3)	~15	RT/Duroid 5880
This work	Microstrip	3.80 (4.2-8)	1.90 (4.7-6.6)	8.7	FR4

The size of the antenna array is $120\text{mm} \times 120\text{mm}$. The comparison of the proposed design and the previous CPSA array structures with sequential feed network and arc feed-line is presented in Table II, and it shows a significant increase in impedance bandwidth and axial-ratio bandwidth, i.e. the impedance and AR bandwidth are, respectively, more than three and two fold wider than the previous designs.

V. CONCLUSION

Four-element antenna array comprising of sequentially rotated CPSA elements and employing microstrip-line feed network to the slot antenna has been presented. The attributes of the proposed CPSA array includes: a relatively simple structure, a low cost fabrication, and broadband operation across 4.2-8 GHz. The measured results show that the impedance bandwidth is 62% for $VSWR < 2$, and axial-ratio < 3 dB is 33.6%. The broadband CPSA array used seven quarter-wave transformers sections that are curved and linked together in a consecutive sequence to form a four-port network. The measured maximum antenna gain is 8.7dBic.

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