

Circularly Polarized Beam-Switching Antenna Array Design for Directional Networks

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Abstract—For modern directional communication networks, there is a significant and growing need for advanced antenna array designs that combine the high gain and broadband performance together with the low-cost and lightweight characteristics. In this letter, the beam-switching characteristics of a new 4×8 right-hand circularly polarized long slot antenna (LSA) array were analyzed when fed by an 8×8 Butler matrix. The radiation characteristics were analyzed in terms of bandwidth, beamwidth, gain, cross polarization (x-pol), and axial ratio. Stable radiation patterns were obtained when the main beam directions were within the $\pm 30^\circ$ angle. The beam-switching LSA array has measured gain of 13.5 dBic and beamwidth of 15° with x-pol greater than 10 dB and axial ratio less than 6 dB. Comparative results with a 4×8 stacked patch antenna array are also included for reference.

Index Terms—Beam-switching, circularly polarized (CP), long slot antenna (LSA) array.

I. INTRODUCTION

IN DIRECTIONAL communication networks, directional antenna arrays are used to form and steer radiation patterns to the direction of the communication node. Thus, the directional communication networks provide longer range coverage, are less susceptible to interference, and have better power efficiency compared to the communication networks using omnidirectional antennas. New challenges, however, are introduced in directional communication networks when true energy-efficient directional channels are used rather than a routine implementation of omnidirectional approach using multiple sectoral and simultaneously radiating arrays [1]. These challenges include the continued tracking of mobile users while searching for new ones outside the limits of the directional beam and maintaining connectivity between the communication nodes. In mobile communication node tracking, multipath fading could significantly affect the accuracy of the tracking schemes [2]. To improve the tracking accuracy and mitigate the multipath fading effect, circularly polarized (CP) antennas are desired for directional communication network systems. Over the years, considerable

investigations have been conducted on CP antenna arrays due to their attractive properties of reduced multipath fading effect and the insensitivity to transmitter and receiver orientations. Nonetheless, the majority of the published works on CP antenna arrays has focused on the broadside radiation characteristics and in many cases lacked details of feeding network to support beam-switching or beam-steering [3]–[6]. Methods to realize the beam-switching or beam-steering include digital beamforming and digital control phase shifter. However, they are either costly or have high insertion loss. Other approaches have also been proposed, such as Butler matrix, reflectarray, and transmitarray [7]–[9]. Overall, it is believed that the Butler matrix is the most simple and cost-effective approach. In [7], a beam-switching 1×4 CP array fed by a 4×4 Butler matrix was proposed with reported bandwidth of 29%.

Recently, a broadband CP 4×8 long slot antenna (LSA) array and a low-profile CP 4×8 stacked patch antenna array were developed over the C-band for directional communication network applications [10], and an 8×8 compact broadband single-layer Butler matrix was designed [11]. In [10], the radiation characteristics of these two antenna arrays were compared in the broadside direction in terms of bandwidth, beamwidth, gain, cross polarization (x-pol), and axial ratio. This earlier paper, however, provided preliminary characteristics of these antenna arrays in the broadside directions. This letter, presents an extension to the data provided in the earlier conference paper [10] and specifically focuses on the beam-switching characteristics of the LSA array with new simulation and experimental results describing the CP radiation characteristics in different beam-steering directions.

In Section II, we briefly describe the design of the LSA array and its feed system. Section III presents the broadside radiation characteristics of the LSA array, as well as the simulated and measured CP characteristics of the LSA array while the main beam is steered in different directions. Section IV concludes the beam-switching performance of the LSA array.

II. ANTENNA DESIGN

The schematic of the 4×8 LSA array design is shown in Fig. 1. The antenna array consists of four horizontal and eight vertical slots that divide the metallic patches into 45 sections. The metallic patches are supported by an FR4 substrate with a thickness of 0.4 mm. LSA array is an ultrawideband structure that has an input impedance range from 150 to 377Ω and often requires a complicated feed structure [12], [13]. In this design, the ultrawideband property is compromised by feeding the LSA with 60Ω tapered microstrip lines. To improve the impedance matching, small diagonal slots were created on the metallic patches. As shown in Fig. 1(b), the horizontal and vertical slots were fed by microstrips from the back of the antenna array.

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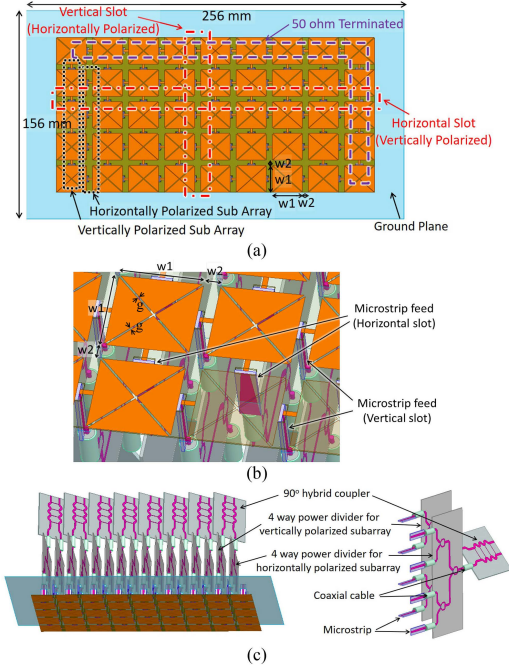


Fig. 1. Schematic of the 4×8 LSA array: (a) front view, (b) zoom-in view of the microstrip feeds, and (c) isometric view with the feed network.

The microstrips were tapered to transform the characteristic impedance from 50 to 60 Ω , where the 60 Ω ends were used to feed the slots. The ground planes of the microstrips were also tapered to minimize the effect of the microstrip feeds on the radiation pattern. In feeding the slots, the center conductors of the microstrips were connected to the metallic patches on one side of the slot, while the ground planes of the microstrips were connected to the metallic patches on the other side of the slot. There are 9 feeds for each horizontal slot and 5 feeds for each vertical slot, which result in a total of 76 feeding ports in the array. To achieve the unidirectional radiation pattern, a ground plane was placed a quarter of a wavelength (at the central frequencies) behind the antenna. From trial and error, the dimensions of the metallic patch width (w_1), the slot width (w_2), and the diagonal slot width (g) were determined to be 20, 4, and 0.5 mm, respectively. Thus, the feeding port spacing is 0.48λ at 6 GHz (highest frequency), where λ is the free-space wavelength. The overall size of the 4×8 LSA array is 256 mm $\times$ 156 mm $\times$ 12 mm. To feed the 4×8 antenna array with the 8×8 Butler matrix, an intermediate feeding network was designed.

As the antenna array only needs to switch the beam direction in the azimuth plane, the antenna feeds were combined vertically to form eight subarrays. For each subarray, a 4-way power divider was used to combine the horizontal slot microstrip feeds to form a vertically polarized subarray, and another 4-way power divider was used to combine the vertical slot microstrip feeds to form a horizontally polarized subarray. The vertically polarized subarray and the horizontally polarized subarray were paired up and fed by a three-stage broadband 90° hybrid coupler that provides stable 90° phase offset over the 4–6 GHz band for the vertically polarized and horizontally polarized subarrays to form a broadband right-hand circularly polarized (RHCP) subarray. As a result, eight RHCP subarrays were formed. The extra feeds were terminated with 50 Ω loads to mitigate the edge effect, as indicated in Fig. 1(a). If the extra feeds were left open, it will slightly affect the beam direction and the axial ratio of the

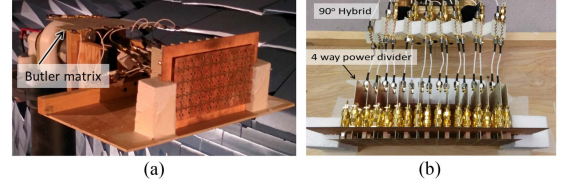


Fig. 2. Fabricated 4×8 LSA array: (a) Isometric view, (b) top view.

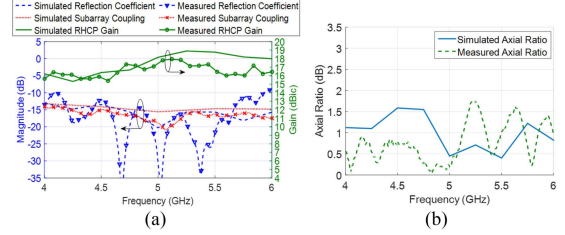


Fig. 3. Simulated and measured broadside radiation characteristics of the 4×8 LSA array: (a) reflection coefficient, RHCP gain, and RHCP subarray mutual coupling; (b) axial ratio.

antenna array. Fig. 1(c) shows the 4×8 LSA array fed by the intermediate feeding network. Coaxial cables were used in the connections between the microstrips and the power dividers, and the connections between the power dividers and the 90° hybrid couplers. The microstrips, the power dividers, and the 90° hybrid couplers were designed on Rogers RO4350B substrate, which has a dielectric constant of 3.66 and a thickness of 0.762 mm.

III. SIMULATION AND EXPERIMENTAL RESULT

A. Broadside Radiation Characteristics

The 4×8 LSA array with the intermediate feeding network was simulated and fabricated. Simulations were performed in HFSS. To simulate the broadside radiation characteristics, the subarrays were excited in-phase. The fabricated LSA array is shown in Fig. 2. An 8-way power divider was connected to the LSA array for broadside radiation characteristics measurement. In the measurement, a linearly polarized horn antenna was used as a transmitter. To measure the RHCP gain and axial ratio of the antenna array, the phase–amplitude method [6], [14] was used with two measurements performed using the horn antenna in the orientation angle of 0° (for E_θ) and 90° (for E_ϕ). The measured E -field was used to calculate E_{RHCP} , E_{LHCP} , and the axial ratio.

The simulation and measurement results of the reflection coefficient, the RHCP gain, the axial ratio, and the mutual coupling between the RHCP subarrays of the LSA array are shown in Fig. 3. The simulated reflection coefficient is below –10 dB across the 4–6 GHz band, which agrees well with the measured result. There are additional resonances in the measured data, which are due to additional cable length in the feeding network as coaxial cables were used to connect the power dividers and the 90° hybrid couplers. Stable RHCP gains are obtained from the simulation and measurement, where the simulated gain ranges from 16.5 to 18.5 dBic and the measured gain ranges from 15.5 to 18 dBic, which are in good agreement. The simulated mutual coupling between the RHCP subarrays is below –13 dB and agrees well with the measured result. Decent axial ratios on the broadside direction are obtained in both simulation and measurement. In both cases, the axial ratios are below 1.8 dB across the frequency band of interest.

TABLE I
LINEAR PHASE INCREMENT AT THE OUTPUT PORTS FOR EACH INPUT PORT OF
THE BUTLER MATRIX

Input port	1	2	3	4	5	6	7	8
Phase increment in output ports (deg)	-22.5	157.5	-112.5	67.5	-67.5	112.5	-157.5	22.5

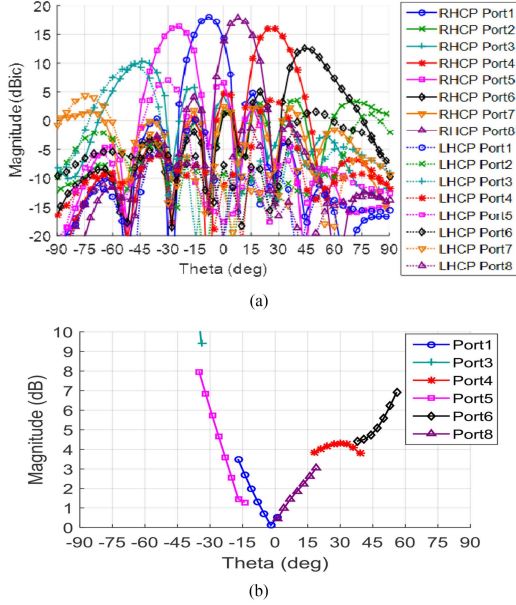


Fig. 4. Simulated radiation characteristics of the 4×8 LSA array for each input port of the Butler matrix at 5 GHz: (a) radiation pattern; (b) axial ratio.

B. Beam-Switching Radiation Characteristics

The 8×8 Butler matrix described in an earlier paper [11] is used to feed the antenna arrays and realize beam-switching. Based on the 8×8 Butler matrix designed in [11], the corresponding phase shift on the output ports for each input of the Butler matrix is shown in Table I. To simulate the radiation characteristics of the antenna array while fed by the 8×8 Butler matrix, the RHCP subarrays of the antenna array were excited with the corresponding phase shift from the 8×8 Butler matrix. The simulated CP radiation characteristics of the 4×8 LSA array at 5 GHz are shown in Fig. 4.

Fig. 4(a) shows the copolarization and x-pol radiation pattern of the 4×8 LSA array while excited with the corresponding phase shift for each input port of the Butler matrix. As shown in Fig. 4(a), at different input ports, the main beam of the antenna array successfully steers to a different direction. The peak gain of the main beam decreases as it steers away from the broadside direction due to the nature of the antenna element. Stable beam patterns are obtained when the main beam direction is within $\pm 30^\circ$, and the change in the peak gain is less than 2 dB. For the main beams within $\pm 30^\circ$ angle, the average peak gain is about 17 dBic with 3 dB beamwidth about 15° and the cross-polarization level more than 10 dB. The corresponding axial ratio on the direction of each main beam is shown in Fig. 4(b). As it may be seen, the axial ratio degrades as the main beam steers away from the broadside direction. For the beam patterns at ports 1 and 8, the axial ratio is less than 3 dB in the direction of the main beam. For the beam patterns at ports 4 and 5, the axial ratio increases to more than 3 dB. Overall, the axial ratio is less than 6 dB within

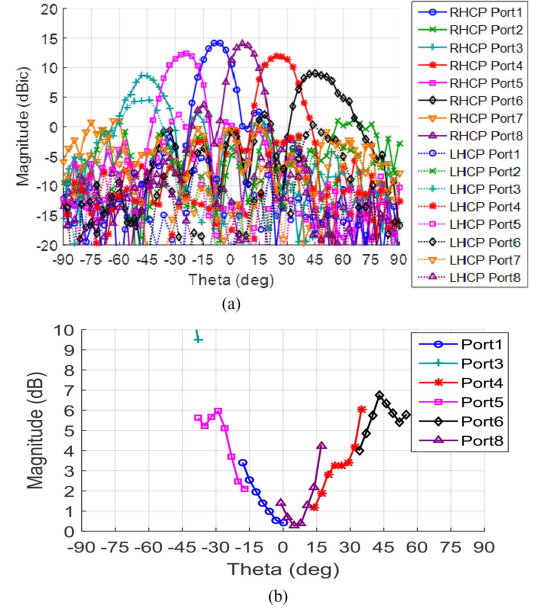


Fig. 5. Measured radiation characteristics of the 4×8 LSA array fed by the Butler matrix at 5 GHz: (a) radiation pattern; (b) axial ratio.

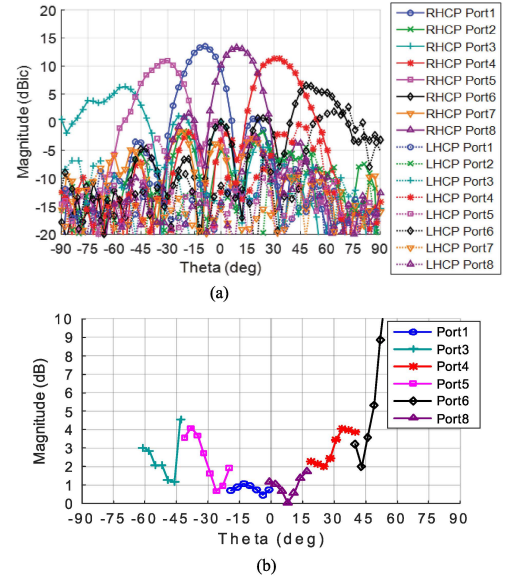


Fig. 6. Measured radiation characteristics of the 4×8 LSA array fed by the Butler matrix at 4 GHz: (a) radiation pattern; (b) axial ratio.

$\pm 30^\circ$ angle. The axial ratio for ports 2 and 7 is not shown in the figure as the axial ratio degrades to more than 10 dB.

The measured radiation pattern and axial ratio of the LSA array fed by the Butler matrix at 5 GHz are shown in Fig. 5. The measured results agree well with the simulation data. The peak gain of the radiation pattern of the LSA array is about 14 dBic. There is about 3 dB decrease in gain compare to the simulation results. The decrease in gain is due to the insertion loss of the Butler matrix.

The measured results at the lower and upper frequencies (4 and 6 GHz) of the LSA array fed by the Butler matrix are shown in Figs. 6 and 7. At 4 GHz, each corresponding main beam steers to a slightly larger angle direction and has wider beamwidth, compared to the results at 5 GHz. This is due to the feeding port spacing being smaller at 4 GHz in terms of wave-

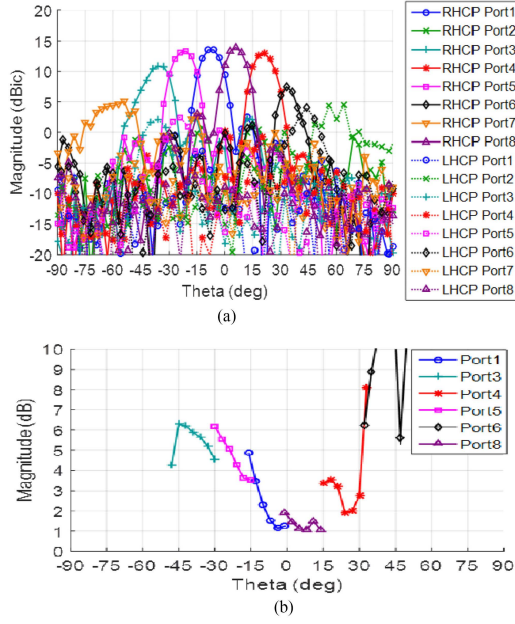


Fig. 7. Measured radiation characteristics of the 4×8 LSA array fed by the Butler matrix at 6 GHz: (a) radiation pattern; (b) axial ratio.

TABLE II
COMPARISON TABLE OF THE 4×8 LSA ARRAY AND THE 4×8 PATCH ANTENNA ARRAY WHEN FED BY THE BUTLER MATRIX AT 5 GHz

Butler matrix input port		1	2	3	4	5	6	7	8
LSA	Theoretical beam direction (deg)	-9	90	-51	28	-28	51	-90	9
	Beam direction (deg)	-8	64	-47	26	-24	44	-62	6
	Gain (dBic)	14.3	1.2	8.7	12	12.4	9	1.6	14.1
	Axial ratio (dB)	1.2	11	12	3.2	4.2	6.6	10.6	0.2
Patch [10]	Theoretical beam direction (deg)	-5	39	-27	16	-16	27	-39	5
	Beam direction (deg)	-5	37	-25	14	-15	26	-38	4
	Gain (dBic)	14.6	12	13.3	13.6	13.6	12.4	11.6	13.9
	Axial ratio (dB)	1.5	2.5	3.2	1.5	1.7	3.4	1.8	1

length. In this case, stable beam patterns are obtained when the main beam directions are within $\pm 40^\circ$. The 3 dB beamwidth is about 17° . The peak gain is about 12.5 dBic with cross-polarization level more than 10 dB. The axial ratio is less than 4.5 dB when the main beam directions are within $\pm 40^\circ$. The improvement in axial ratio at lower frequency end is due to the fact that radiation fields are less sensitive to the asymmetric feeds of the LSA array (longer wavelength), and this helps in improving the balance between the two polarization components. Similarly, at 6 GHz, stable beam patterns are obtained when the main beam directions are within $\pm 30^\circ$. The 3 dB beamwidth is about 13° . The peak gain is about 13.5 dBic with cross-polarization level more than 10 dB. The axial ratio is less than 6 dB when the main beam directions are within $\pm 30^\circ$.

Similar measurements were also performed on the 4×8 patch antenna array [10] when fed by the Butler matrix at the patch antenna array and having operating bandwidth from 4.5 to 5 GHz. Stable beam patterns are also obtained within the $\pm 30^\circ$ angle. The patch antenna array has antenna element spacing of 0.69λ at 5 GHz. Hence, narrower beamwidth (10°) and closer main beam directions are obtained, and grating lobes are also observed on the radiation pattern on ports 2 and 7. Table II shows

the measured beam-switching performance as well as the theoretical beam directions of the LSA and the patch antenna arrays at 5 GHz. In comparison to the patch antenna array, the LSA array has similar gain, wider beamwidth, and wider bandwidth. In the LSA array design, the spacing between the feeds needs to be less than or equal to half-wavelength at the highest operating frequency [12], which causes wider beamwidth and the beam directions spread out wider while fed by the Butler matrix. On the other hand, the patch antenna array has more freedom on the antenna element spacing and better axial ratio while steering the beam away from the broadside direction.

IV. CONCLUSION

An RHCP 4×8 LSA array was developed for directional networking in the 4–6 GHz bands. Feeding networks were designed for the antenna array to support beam steering in the azimuth plane. The LSA array was fabricated and measured. In the broadside direction, the LSA array has an average gain of about 16.5 dBic with an axial ratio < 1.8 dB. When the LSA array is fed by the Butler matrix, stable radiation patterns and a scanning range of $\pm 30^\circ$ are obtained. The beam-switching radiation patterns have average peak gain of 13.5 dBic and beamwidth of 15° with x-pol > 10 dB and axial ratio < 6 dB.

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