On The Design of Sequential-Rotation Arrays Composed of CP-EMCP Elements

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Abstract

This paper first reviews the design principles of sequential-rotation arrays and some significant works that relate to the design technique. Through a series of numerical simulations for various array configurations composed of CP broadband elements, radiation patterns are computed and discussed. A supplementary rule on the senses of spatial angles and phase shifts is deduced.

1. Introduction

The concept of sequentially rotating technique for microstrip patch arrays has a long history. The technique is established at least two decades ago and has its origin in Japan. Most researchers cited in their works that the technique was first presented by Teshirogi *et al.* in the conference of ISAP in 1985 [1]. Our literature research suggested it was pioneered by another two Japanese teams: Haneishi *et al* and Chiba *et al* in 1982 [2], [3]. The former proposed the idea of paired orthogonal elements in circularly polarised (CP) array whilst the latter suggested a sequential multiple-feed for a single patch antenna. Their proposals are similar and effective in improving the boresight axial ratio (AR) by suppressing of high-order modes. At about the same time, Huang [4] employed the sequential-rotation concept for the design of CP array using linearly polarised (LP) elements. A good AR and cross-polarisation discrimination (XPD) can be obtained in the boresight direction but it heavily reliant on the accurate design of the feed network. The sense of circular polarisation is decided not by the elements but critically on the arrangement of amplitudes and phases of the feeders. The use of LP elements is difficult to extend to phased arrays or beam scanning antenna systems that require low AR at wide angles off boresight. Further, the advantages of LP elements are offset by a significant gain reduction due to the high cross-polarised lobes in diagonal planes [5].

In this paper, a design study of a 2x2 sequential-rotation array (SRA) using broadband CP-EMCP elements will be discussed. The study will reveal an interesting design rule that has not been fully reported in the literature and may have also been overlooked by the antenna engineers.

2. Design Principles for 2x2 Planar Array

In 1989 Hall *et al* published a couple of papers [6], [7] on the design principles and applications of the sequential-rotation array (SRA). The papers elaborated that the *n*th element of a *M*-element SRA should have a spatial rotation Φ_{sn} and an excitation phase shift Φ_{en} as given by [6]

$$\Phi_{sn} = (n-1)\frac{p\pi}{aM}$$
$$\Phi_{en} = (n-1)\frac{p\pi}{M} \qquad 1 \le n \le M \qquad (1)$$

where a represents the mode number. When $a = 1$, which is the fundamental mode of the square patch, $\Phi_{sn} = \Phi_{en}$; p is an integer, $1 \le p \le M\text{-}1$, which is the condition for circular polarisation.

For optimum improvement over the effect of phase deviations due to the coplanar feeders, a large M and small p is highly desired [6], [7]. Eqn. (1) is regarded as the first principle in the design of SRA, however, it concerns only the magnitudes of the angles. This seems to be the only necessary conditions for building a SRA. The reason is that both Φ_{sn} and Φ_{en} are positive numbers in the unit of degree or radian. The direction (or sense) of rotation of elements is not specified in the design principle.

If the co-polarisation of the SRA is right-hand circularly polarised (RHCP), the *on-axis* cross-polarisation discrimination (XPD) of an arbitrarily excited array can be expressed as

$$XPD\ [\text{dB}] = 20 \times \log_{10}\left|\frac{E_{\text{R}}\left(\theta = 0^\circ, \varphi, V_1\right)}{E_{\text{L}}\left(\theta = 0^\circ, \varphi, V_3\right)}\right| \qquad (2)$$

Kraft [8], [9] reported that the dependence of XPD, and hence the axial ratio of a SRA, is not just from the structure of array elements but also from the feed network. Hence,

$$XPD\ [\mathrm{dB}] = XPD_{st} + XPD_{f} \tag{3}$$

The first term (XPD_{st}) of Eqn. (3) is regarded as the *polarisation stability factor* whereas the second term (XPD_f) is attributed to the quality of the feed network. XPD_{st} describes the influence of particular antenna geometry as well as the mutual coupling amongst elements. For LP elements of a SRA (e.g [4]-[5]), XPD_{st} is 0 dB due to its large axial ratio. For any geometry of CP elements, XPD_{st} is greater than 10 dB with a sign that indicates the *sense* of CP of the elements. Now, we are going to examine the importance of the *sense* of the spatial angles Φ_{sn} and phase shifts Φ_{en} by using a broadband RHCP elements named as CP-EMCP elements [11]-[12], but excluding the coplanar feed network. A planar feed network is part of radiating structures apart from the array elements.

Consider a planar 2x2 SRA consisting of four ($M = 4$) identical singly-fed CP-EMCP elements, which are sequentially rotated by a multiple of 90° ($p = 2$) *clockwise* about the *z*-axis as shown in Fig. 1. For brevity, the design details and geometries of CP-EMCP elements will not be repeated here, but can be found in [11] & [12]. The SRA elements are arranged in a squared grid size of $2/3\lambda_o$ at 10 GHz as shown in Fig. 1. The elements are excited by four complex voltages (v_1, v_2, v_3, v_4) having the identical amplitudes with different phase shifts according to Eqn. (1).

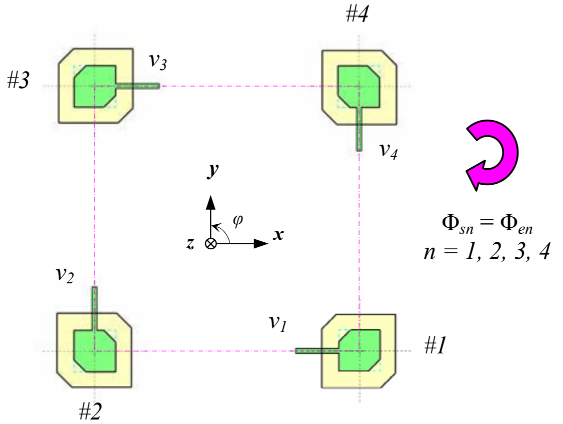

Fig. 1: Geometry of a 2x2 planar array composed of sequentially rotated CP-EMCP elements (#1~#4) in a multiple of 90° *clockwise* ($p = 2$). The elements are arranged in a square grid and fed by the excitation voltages v_1 to v_4 according to the V_1 mode (RHCP). The planar feed network is excluded in the study.

3. Results and Findings

When a SRA composed of CP elements, either LH or RH polarised, the polarisation stability of the array is higher than that obtained from LP elements. Consequently the achievable XPD in the boresight direction of the entire array would be even higher if an optimised coplanar feed network having the same sense of the CP elements was implemented. If the rotation of the element opposes the sense of the phase shift, a reverse hand of polarisation would result. Fig. 2 shows eight possible SRA designs according to the design principles of Eqn. (1). Namely, all CP elements are sequentially rotated by an angle of 90° and fed by a unity voltage with a sequential phase-shift of 90°. However, the rotations or the sequences of the angles Φ_{sn} and Φ_{en} are either clockwise (CW) or counter-clockwise (CCW) in the scenarios (a) to (h). The corresponding radiation patterns obtained from the MoM simulations using an infinite ground-plane are shown accordingly in Fig. 2. The LHCP patterns which oppose the elements polarisation result in cross-polar fields whenever the senses of angles Φ_{sn} and Φ_{en} are opposite, as in scenarios (b), (d) and (e). The generation of the cross-polar radiation is not subject to either sense of the angles. The XPD in the other scenarios are in excess of 30-dB in the range of $\theta = \pm 90°$ due to the exclusion of feed network ($XPD_f = 0$). The highest (60 dB) *on-axis* XPD is obtained in scenario (a) whereas the configuration in scenario (c) gives the best XPD within ±45°, good sidelobe levels (-20 dB) and cross-polarised grating lobe levels (-30 dB) amongst all configurations. This configuration of orthogonal pair is commonly used if RHCP elements are employed in a SRA, which can be found in the literature [2], [10]. Comparing the results from scenarios (h) and (f), where both angles Φ_{sn} and Φ_{en} are in the same direction (CCW), the configuration of SRA in scenario (h) shows that the boresight cross-polar level can be suppressed, and its *on-axis* XPD is enhanced to >45 dB by offsetting elements in 45° *ahead*. Likewise, comparing the configurations in scenarios (g) and (a), the cross-polar levels at ±30° are moved to ±60° by using such an offsetting technique.

4. Conclusion

The technique of sequential rotation of elements inside an array essentially reinforces the wanted hand of rotation of the elements. The basic principle does not indicate the direction of rotation of both angles. The radiation patterns of the SRA configurations in scenarios (a) to (h) show that the reinforcement of the elements can be obtained in either direction as long as the rotation angle Φ_s and phase angle Φ_e are in the same direction of rotations. That is, the reinforcement can be had at a direction which is opposite to the rotation of the CP elements. On this basis, we conclude this to be a *sufficient condition* supplementary to the design principles of SRA composed of identical SFCP elements of any senses.

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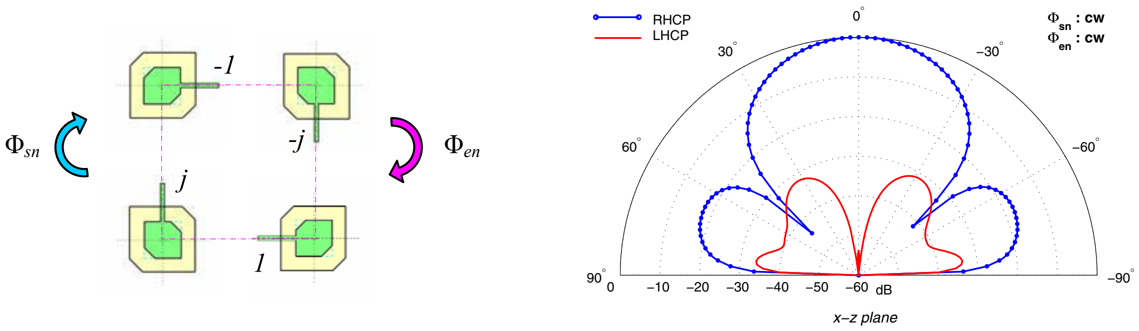
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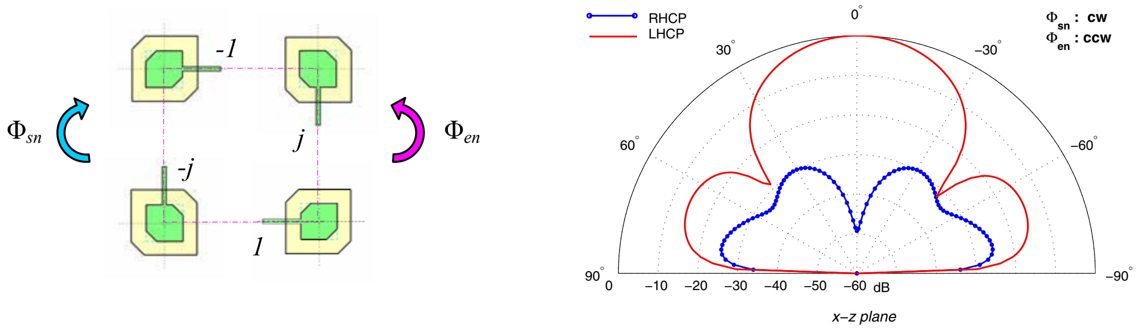
(a)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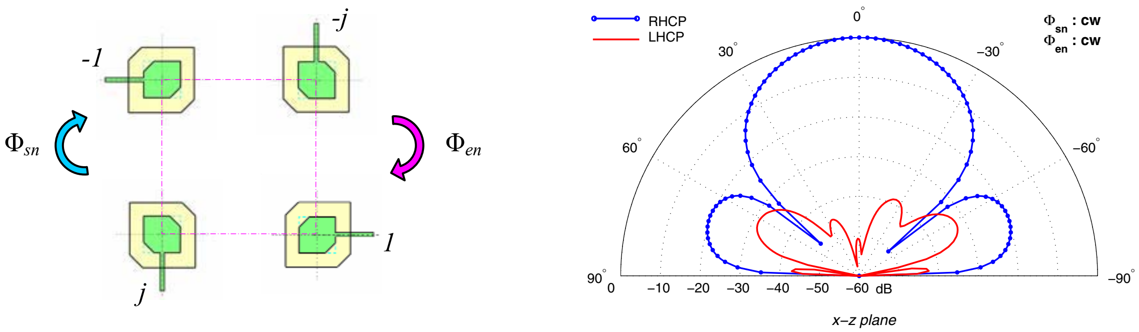
(b)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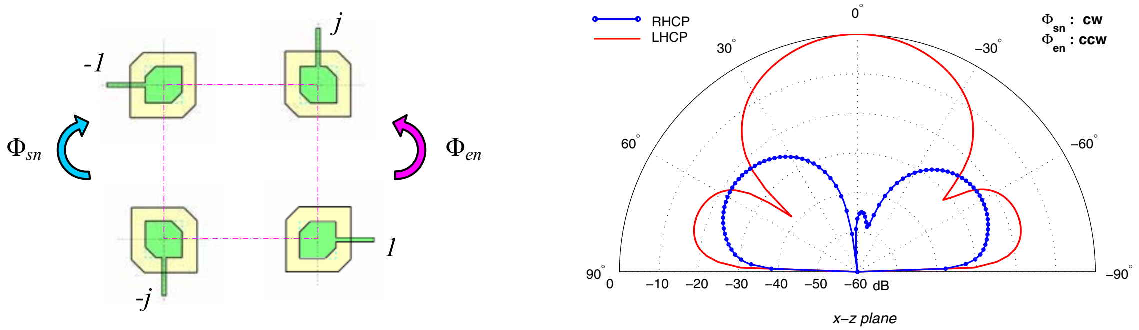
(c)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x–z plane

(d)

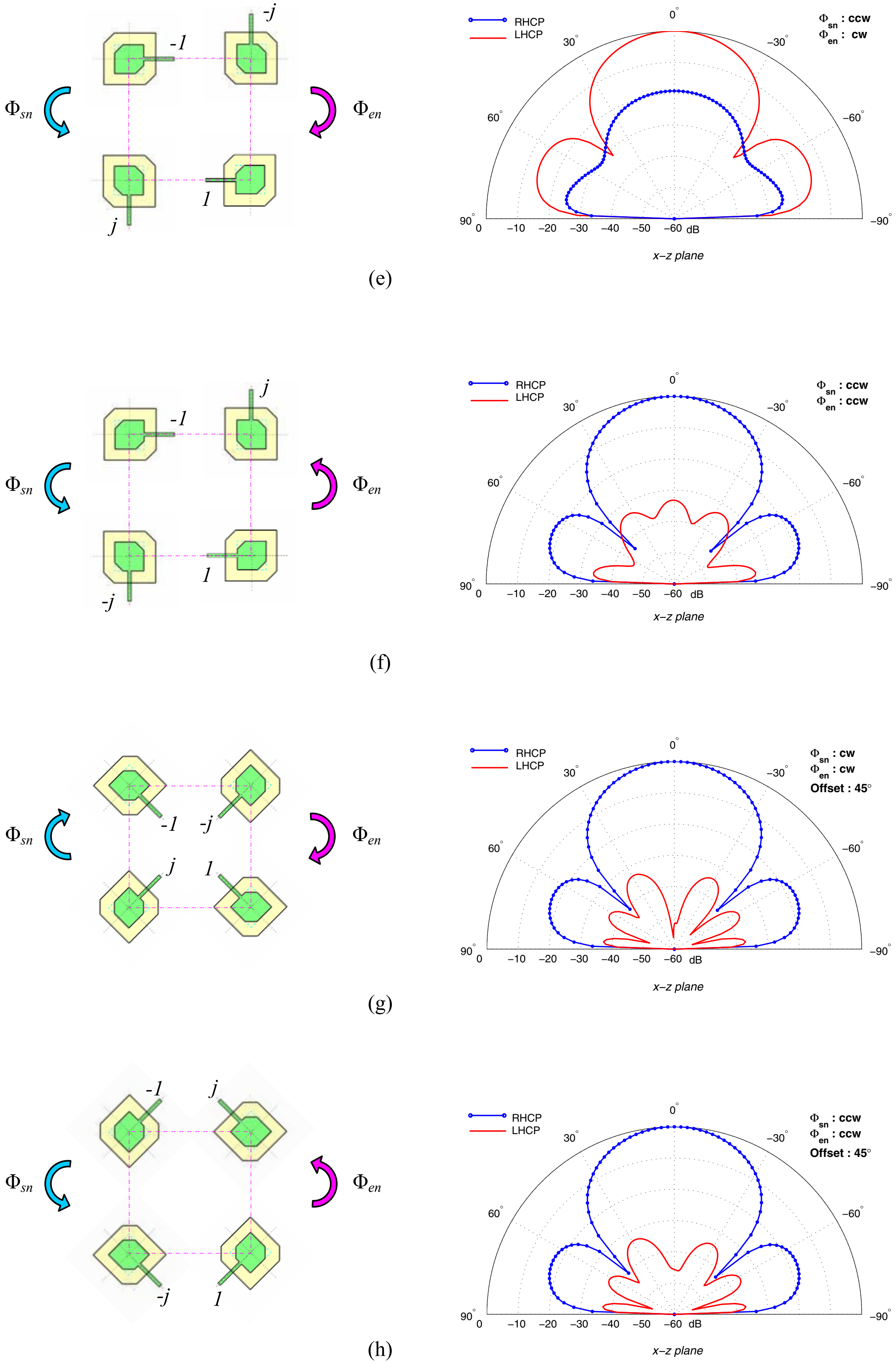

Fig. 2: The eight radiation patterns at 10 GHz in *x-z* plane for the different configurations of the SRA.