PHASED ARRAYS USING SEQUENTIAL ROTATION AND PHASING TECHNIQUES

Tasuku TESHIROGI*, Masato TANAKA* and Norio TAKAHASHI**
* Communications Research Laboratory, ** University of Electro-Communications
* 4-2-1, Nukui-Kitamachi, Koganei-shi, Tokyo 184, Japan

1. Introduction

A sequentially rotated array (SRA), which is composed of elliptically polarized elements rotated sequentially and fed with differential phase shifts corresponding to the rotations, improves both axial circular polarization purity and impedance matching. This technique was first proposed by the authors [1], and after that further studies have been developed by other authors [2][3].

In this paper, we will show that a SRA provides excellent circular polarization (CP) characteristics in the scanned beam direction of a phased array by a theoretical analysis and furthermore it can reduce mutual coupling effects significantly in comparison with a conventionally fed array (CFA) by computer simulation using the method of moment.

2. Analysis of circular polarization characteristics of sequentially rotated phased arrays

We consider a N-element linear phased array, as shown in Fig. 1. Each element is equally spaced with distance d along the y-axis, and rotated and phase shifted properly based on the SRA principle [1]. Furthermore, a differential phase shift ψ_n is added to the n-th element to direct the beam to θ_b as,

$$\psi_n = kd_n \sin\theta_b . \qquad (1)$$

Assuming element radiation patterns in the E-plane and H-plane as $E_p(\theta)$, and $H_p(\theta)$ respectively, and the relative excitation of the y-polarization to x-polarization of the reference element (i.e. n=1) be $j\alpha$, the radiated field from the reference element is written by

$$E_\theta(\theta,\phi) = E_p(\theta)\{\cos\phi + j\alpha\sin\phi\}, \quad (2a) \qquad E_\phi(\theta,\phi) = H_p(\theta)\{-\sin\phi + j\alpha\cos\phi\} . \quad (2b)$$

For a N-element SRA, a differential phase shift and a rotation of ϕ_n radians are given to the n-th element, where ϕ_n is given by

$$\phi_n = p(n-1)\pi/N , \qquad (p=1, 2, \cdots, N-1) \qquad (3)$$

In this paper, for simplicity, n denotes both the element number and the sequential rotation number. In general, however, these parameters are not necessary to be expressed by the same variable n. For example, in the case of 4-element array, a set of sequential rotations and phase shifts $\{0, \pi/4, 3\pi/4, 2\pi/4\}$ for n=1, 2, 3, 4 is possible to be taken.

The radiated fields from the N-element SRA can be expressed by

$$E_\theta(\theta,\phi) = E_p(\theta)\sum_{n=1}^{N}\{\cos(\phi-\phi_n) + j\alpha\sin(\phi-\phi_n)\}\exp\{j[\phi_n + \psi_n - kd_n\sin\theta\sin\phi]\} \qquad (4a)$$

$$E_\phi(\theta,\phi) = H_p(\theta)\sum_{n=1}^{N}\{-\sin(\phi-\phi_n) + j\alpha\cos(\phi-\phi_n)\}\exp\{j[\phi_n + \psi_n - jkd_n\sin\theta\sin\phi]\} \qquad (4b)$$

By using the sequential relations[1],

$$\sum_{n=1}^{N}\cos^2\phi_n = \sum_{n=1}^{N}\sin^2\phi_n = \frac{N}{2} , \quad (5a) \qquad \sum_{n=1}^{N}\cos\phi_n\sin\phi_n = 0 , \quad (5b)$$

we obtain the radiation fields in the direction of the main beam as,

$$E_\theta(\theta_b,\pi/2) = N(1+\alpha)E_p(\theta_b)/2, \quad (6a) \qquad E_\phi(\theta_b,\pi/2) = jN(1+\alpha)H_p(\theta_b)/2 , \quad (6b)$$

or as a vector expression,

$$\mathrm{E} = \frac{N(1+\alpha)}{2}[E_p(\theta_b)\mathrm{e}_\theta + jH_p(\theta_b)\mathrm{e}_\phi]. \qquad (7)$$

From the above expression, we can conclude that within the range of θ where the element patterns of E- and H-planes coincide, a SRA provides perfect circular polarization in the scanned beam direction. For a wider angle of scan, however, CP characteristics deteriorates corresponding to inconsistency between $E_p(\theta_b)$ and $H_p(\theta_b)$.

3. Numerical Examples

We consider 6-element sequentially rotated and conventionally fed phased arrays. All the elements are assumed to have axial ratio of 5 dB ($\alpha = 1.78$), and equally spaced with distance of 0.5λ (λ : wavelength). The configuration of the SRA is shown in Fig. 2.

A step of the rotation and differential phase shift is chosen $\pi/3$ (p=2, in Eq.(3)), and ϕ_ns are $\{\phi_1 = 0,\ \phi_2 = \pi/3,\ \phi_3 = 2\pi/3,\ \phi_4 = 5\pi/3,\ \phi_5 = 4\pi/3,\ \phi_5 = \pi\}$. This arrangement provides a symmetric radiation pattern when the beam is directed to the broadside direction.

Fig. 3 shows radiation patterns of the CFA and SRA for 30 degree-scan. The axial ratio at the scanned beam peak is reduced to 0.65 dB for the SRA, although the elements with large axial ratio are used, while for the CFA the axial ratio amounts to 5.65 dB. It can be seen that the SRA can improve axial ratio at the scanned beam peak significantly compared with the CFA. Fig. 4 shows the case of 45-degree scan. The axial ratio at the beam peak are 1.75 dB and 6.75 dB for the SRA and the CFA, respectively. The deterioration of the axial ratio of the SRA compared with the case of 30-degree scan occurs due to much larger inconsistency between $E_p(\theta_b)$ and $H_p(\theta_b)$.

4. Mutual Coupling Effects on Sequentially Rotated Phased Arrays

In the analysis mentioned above, mutual coupling between elements are ignored. In the case of wide scanning arrays, however, because element spacing is chosen to be relatively small to suppress grating lobes, mutual coupling cannot be neglected.

In this section, we will show that a SRA can reduce mutual coupling effects and provide sufficient CP characteristics much better than a CFA. The model antennas under test are 6-element microstrip arrays as shown in Fig. 2. Each element is a circular microstrip patch which is excited by a single-point feed from backside and has two notches to generate circular polarization. In order to clarify the difference of CP characteristics between the CFA and the SRA, almost perfect CP elements with axial ratio of 0.7 dB were designed and used. The numerical calculation is carried out by using the commercial software "HP Momentum" which is based on method of moment [4].

Fig. 5 shows the radiation patterns in the case of the beam not scanned ($\theta_b = 0$). Even in this case, the mutual coupling deteriorates the CP characteristics of the CFA, of which axial ratio is 2.6 dB, much more than that of the SRA with the axial ratio of 1.3 dB.

Fig. 6 shows radiation patterns for 45-degree scan. We can see that in the CFA, a large difference between E_θ and E_ϕ at the beam peak, and a considerable deformation of the main beam happen, while in the SRA, the levels and shapes of the main beams are maintained to be close. From these figures, we can conclude that SRA can reduce mutual coupling and provides excellent CP characteristics for a phased array with small element spacing.

5. Conclusion

We applied the sequential rotation and phasing technique to phased arrays and verified theoretically that excellent CP characteristics can be maintained at the scanned beam. Furthermore, by numerical analysis, we showed SRA is effective to reduce mutual coupling and realize wide-scan phased array with low axial ratio.

References

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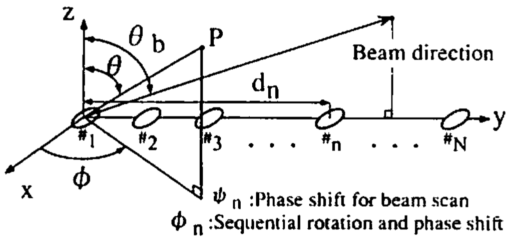
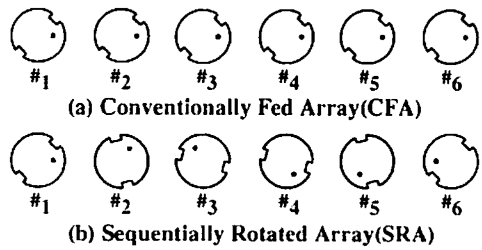


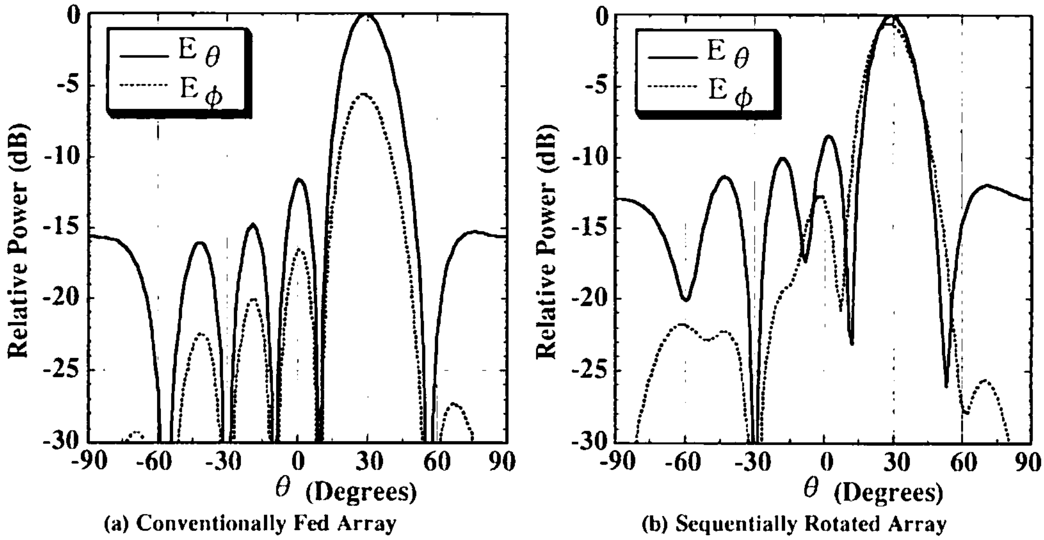
Fig.1 Geometry of a liner phased array



(a) Conventionally Fed Array(CFA)

(b) Sequentially Rotated Array(SRA)

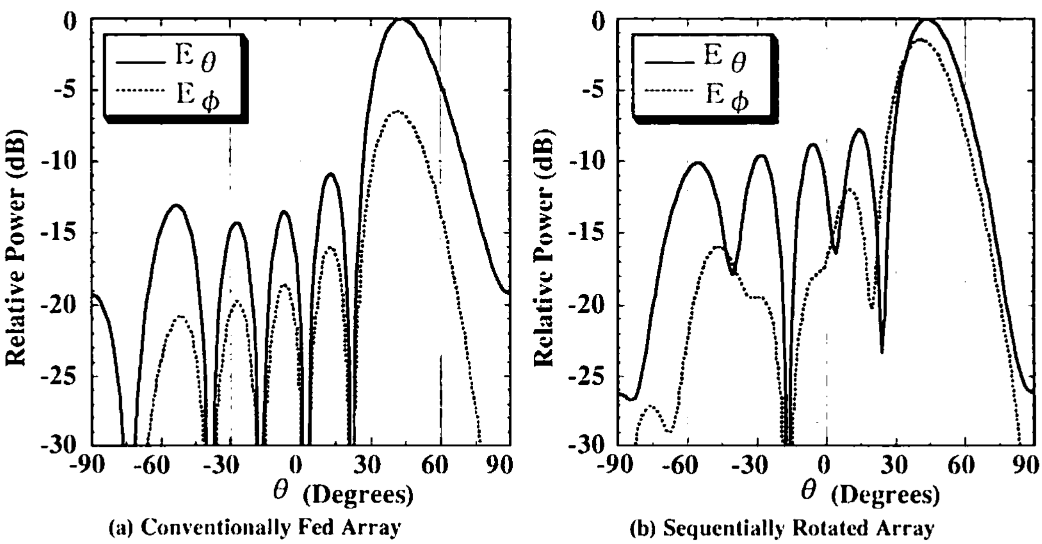
Fig. 2 Configuration of 6-element arrays under test



(a) Conventionally Fed Array

(b) Sequentially Rotated Array

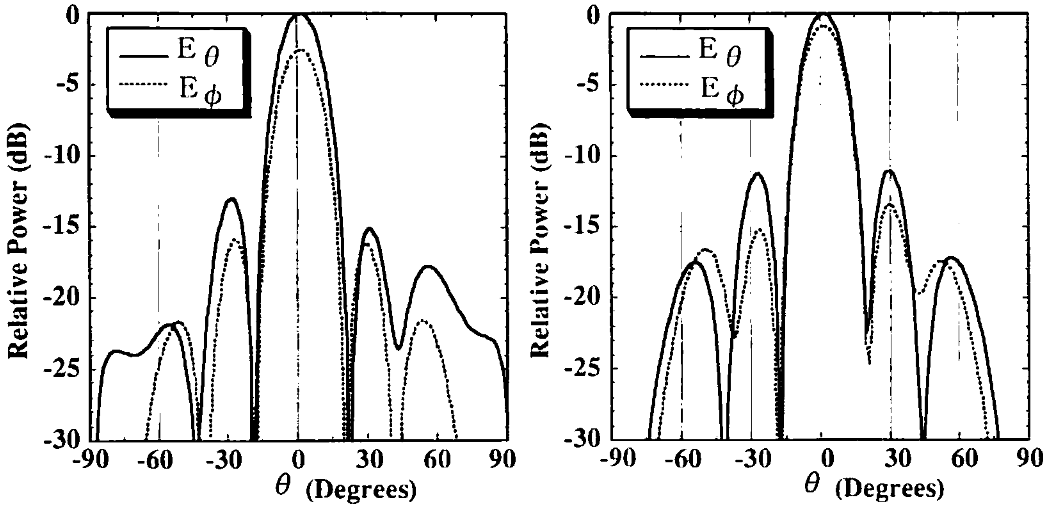
Fig.3 Radiation Patterns of the 6-element arrays
(θ_b=30°, AR of element = 5 dB, Mutual coupling Free)



(a) Conventionally Fed Array

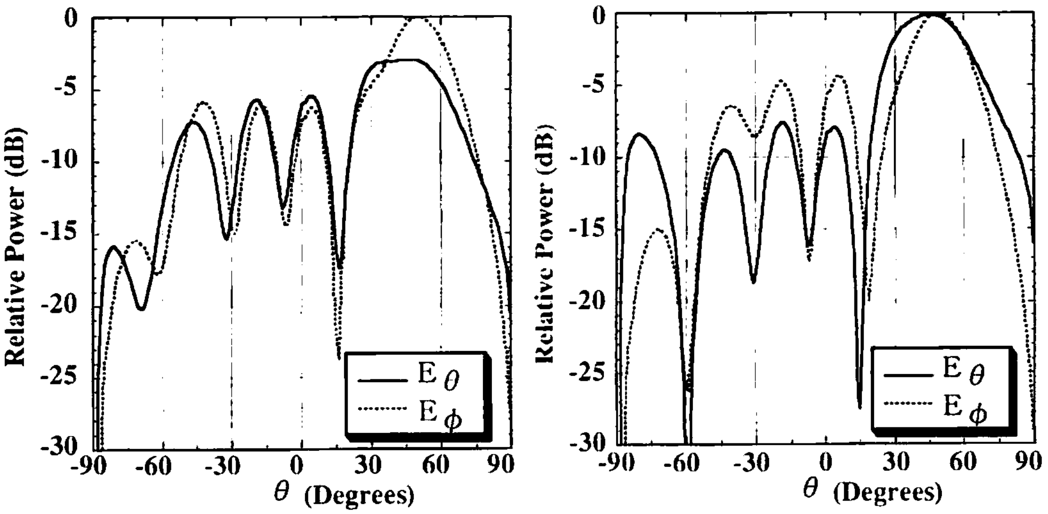
(b) Sequentially Rotated Array

Fig.4 Radiation Patterns of the 6-element arrays
(θ_b=45°, AR of element = 5 dB, Mutual coupling Free)



(a) Conventionally Fed Array (b) Sequentially Rotated Array

Fig.5 Radiation patterns of the 6-element arrays taking account of mutual coupling (θ_b=0°, AR of element = 0.7dB)



(a) Conventionally Fed Array (b) Sequentially Rotated Array

Fig.6 Radiation patterns of the 6-element arrays taking account of mutual coupling (θ_b=45°, AR of element = 0.7dB)