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A Steerable Spherical Slot Array Antenna

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ABSTRACT This paper investigates the principle of a steerable spherical slot array antenna. By combining the advantages of a spherical array in which the beam shape can be kept constant as it is steered in any direction, a simple beam steering mechanism of an active array antenna and a simple array element, a cost effective steerable antenna can be achieved. This antenna is useful in a mobile communication system.

KEYWORDS: spherical array, slot antenna, cavity-backed slot, active antenna.

INTRODUCTION

Spherical array antenna has been continuously investigated because the significant characteristic of this antenna type is that the constant radiation pattern, as it is steered in any directions, can be achieved.[1] Therefore, this antenna is suitable for military radar and satellite applications. A number of researches about array element on spherical surface have been conducted subsequently such as using dipoles,[2-3] turnstiles[4-5] and microstrip patches.[6-7] These array elements are complicated and difficult to fabricate. To solve these drawbacks, the authors proposed to use the slot as the array element of the spherical array antenna.[8] This antenna is nominated as a spherical slot array antenna.

Although the spherical array has the interesting characteristics, its cost is too high to be widely used. This might due to sophisticated feeding network. Thus, the applications of this antenna are restricted to the military use and high technology service. Recently, the spherical array antenna has been developed to use in the mobile satellite communication system.[7] However, the feeding network is still complicated. To simplify the feeding network, many researches in the early of this decade have been devoted to the active phase array such as[9-12] which oscillating antennas are injection locking to spatially synchronize the power and the main beam can be steered simply. All of the works are mainly focused on the linear and planar arrays which were found that the beam steering is limited in the range of $\pm 30^\circ$. The advantage of a wide range beam scanning of the spherical array and a simple beam scanning mechanism of the active phase array motivate the authors to investigate a so-called spherical active phase array antenna.

The objective of this investigation is to obtain the wide range beam scanning using a simple scanning mechanism. Moreover, the simple structure is essential to the future implementation. Accordingly, a segmented spherical cavity backed slot active antenna is chosen as an array element. This paper presents the principle of the steerable spherical slot array antenna. The radiation characteristics are illustrated and verified by experiments.

RADIATION CHARACTERISTICS OF A SPHERICAL SLOT ARRAY ANTENNA

Since a spherical cavity-backed slot antenna is used as an element of the spherical array antenna, consequently, the radiation fields of a slot on spherical surface will be realized in this section.

Let us consider a slot of length "l" and width "α" located on a conducting spherical cavity of the radius R_0 as shown in Fig 1 (a). In this paper, the slot width is narrow so that the sinusoidal aperture distribution is reasonably applied. By solving the boundary value problem and using the asymptotic expression of spherical Hankel function, the far field pattern of this slot can be expressed as the superposition of the field in transverse electric (TE) and transverse magnetic (TM) modes:[13,14]

$$\bar{E}_t(r,\theta,\phi) = \sum_{m=0}^{\infty} (E_{mr}\hat{\gamma} + E_{m\theta}\hat{\theta} + E_{m\phi}\hat{\phi}), \qquad (1)$$

where each component of this electric field can be written as

$$E_{m\theta}(r,\theta,\phi) \approx 0 \qquad (1a)$$

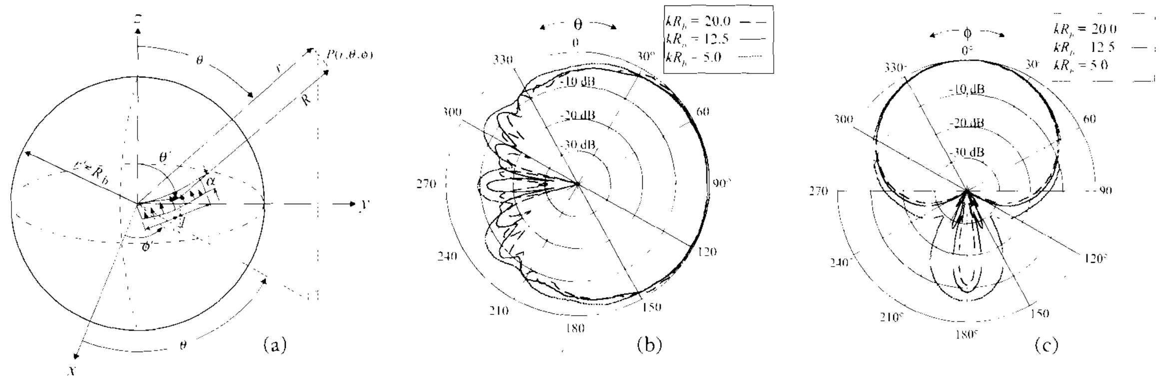

Fig 1. A slot on conducting spherical surface. (a) Geometry of the problem (b) E-plane pattern (c) H-plane pattern

$$E_{m\theta}(r,\theta,\phi) \approx -\frac{e^{-jk_0r}}{r}E_{m0}\sum_{n=m}^{\infty}(j)^n\{\frac{jA_{mn}^{TE}}{\alpha}\frac{1}{h_n^{(2)}(k_0R_b)}\frac{dP_n^m(cos\theta)}{d\theta}+\frac{A_{mn}^{TM}}{\alpha}\frac{k_0R_b}{[k_0R_bh_n^{(2)}(k_0R_b)]'}\frac{mP_n^m(cos\theta)}{sin\theta}\}cosm\phi \tag{1b}$$

$$E_{m\phi}(r,\theta,\phi) \approx \frac{e^{-jk_0r}}{r}E_{m0}\sum_{n=m}^{\infty}(j)^n\{\frac{jA_{mn}^{TE}}{\alpha}\frac{1}{h_n^{(2)}(k_0R_b)}\frac{mP_n^m(cos\theta)}{sin\theta}+\frac{A_{mn}^{TM}}{\alpha}\frac{k_0R_b}{[k_0R_bh_n^{(2)}(k_0R_b)]'}\frac{dP_n^m(cos\theta)}{d\theta}\}sinm\phi\cdot \tag{1c}$$

The coefficients are given as follows:

$$A_{mn}^{TE} = -\frac{2n+1}{2n(n+1)}\frac{(n-m)!}{(n+m)!}\int_{\phi'-\frac{\alpha}{2}}^{\phi'+\frac{\alpha}{2}} mP_n^m(cos\theta)d\theta \tag{1d}$$

and

$$A_{mn}^{TM} = -\frac{2n+1}{2n(n+1)}\frac{(n-m)!}{(n+m)!}\int_{\phi'-\frac{\alpha}{2}}^{\phi'+\frac{\alpha}{2}} \frac{dP_n^m(cos\theta)}{d\theta}sin\theta d\theta, \tag{1e}$$

where $h_n^{(2)}(\cdot)$ denotes the spherical Hankel function of the second kind of order n, and $P_n^m(\cdot)$ denotes the associated Legendre function of order (n,m). The primed bracket designates for the derivative of the function in the bracket with respect to the argument (kR_b).

Knowing $\bar{E}_t(r,\theta,\phi)$, the radiation characteristics of a slot on spherical surface can be obtained. Figs 1(b) and 1(c) show radiation patterns in electric and magnetic planes for different spherical radii, when θ' and ϕ' is equal to $90°$ and $0°$, respectively. We can see that when the spherical radius is large, the beamwidth is narrower than that of the small one. Furthermore, the larger the radius the lower the backlobe are observed.

Next, a spherical array of the radius R_b with MxN slots, arranged as rings on the spherical surface will be considered as shown in Fig 2. Each slot is oriented at an angle γ_i with respect to the horizontal line. The

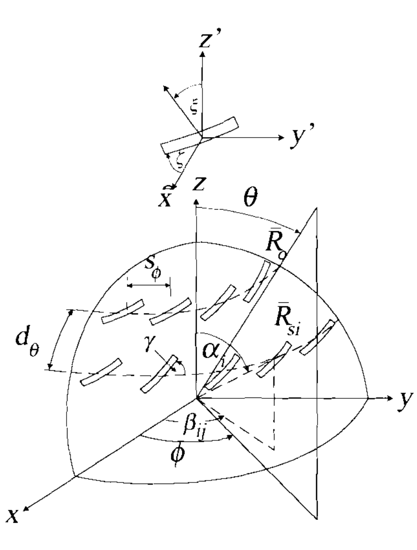

Fig 2. A spherical slot array antenna.

azimuthal spacing between adjacent slot in each ring and the distance in elevation direction between the two rings are denoted by s_ϕ and d_θ, respectively. The radiation pattern of this antenna is the summation of the field from each slot, which was derived in the previous subsection. It can be expressed as[2]

$$\bar{E}(\theta,\phi)=\sum_{j=1}^{N}\left[\sum_{i=1}^{M}\bar{E}_t(R_b,\xi_{ij},\varsigma_{ij})e^{j(kR_b\cos\xi_{ij}+\varphi_{ij})}\right] \tag{2}$$

and

$$\bar{E}_t(R_b,\xi_{ij},\zeta_{ij})=E_\xi(R_b,\xi_{ij},\zeta_{ij})[\cos\gamma_i-\sin\gamma_i]\hat{\xi}_{ij}+E_\varsigma(R_b,\xi_{ij},\zeta_{ij})[\cos\gamma_i+\sin\gamma_i]\hat{\varsigma}_{ij} \tag{2a}$$

where $\hat{\xi}$ and $\hat{\varsigma}$ are unit vectors along the slot local coordinates, respectively, and φ_{ij} is the phase of slot number i in the ring number j, respectively. Additionally, to express the term of source point (R_b,ξ,ζ), as the term of observation point (r,θ,ϕ), the helps of these coordinate transformations are used:

$$\cos\xi_{ij}=\frac{\bar{R}_{si}\cdot\bar{R}_o}{|\bar{R}_{si}||\bar{R}_o|} \tag{3a}$$

$$=\sin\alpha_i\sin\theta\cos(\phi-\beta_{ij})+\cos\alpha_i\cos\theta \tag{3b}$$

$$\tan\varsigma_{ij}=\frac{\sin\theta\sin(\phi-\beta_{ij})}{\cos\alpha_i\sin\theta\cos(\phi-\beta_{ij})-\sin\alpha_i\cos\theta} \tag{4}$$

$$\hat{\xi}_{ij}=\frac{-\sin\alpha_i\cos\theta\cos(\phi-\beta_{ij})-\cos\alpha_i\sin\theta}{\sin\xi_{ij}}\hat{\theta}+\frac{\sin\alpha_i\sin(\phi-\beta_{ij})}{\sin\zeta_{ij}}\hat{\phi} \tag{5}$$

$$\hat{\zeta}_{ij}=\frac{-\sin\alpha_i\sin(\phi-\beta_{ij})}{\sin\xi_{ij}}\hat{\theta}-\frac{-\sin\alpha_i\cos\theta\cos(\phi-\beta_{ij})-\cos\alpha_i\sin\theta}{\sin\zeta_{ij}}\hat{\phi} \tag{6}$$

where $\bar{R}_o$ is the position vectors of the observation point, R_{si} is the position vectors of the location of slot number i of the ring number j, α_i is the elevation angle of slot number i, and β_{ij} is the azimuthal angle of slot number i in the ring number j, respectively.

In order to direct the main beam to the direction (θ_o,ϕ_o) the phase excitation of each slot must be

$$\varphi_{ij}=-kR_b\left[\sin\theta_o\sin\alpha_i\cos(\phi_o-\beta_{ij})+\cos\alpha_i\cos\theta_o\right] \tag{7}$$

If the spherical dimension is fixed such that R_b equals 2λ and a single ring of eight slots located at α_i equals 45°, β_{ij} equals 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315°, repectively. The main beam direction is steered to θ_o equals 45° and ϕ_o is in the direction of 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5°, 180°, 202.5°, 225°, 247.5°, 270°, 292.5°, 315° and 337.5°, repectively, the phase distribution is shown in Table 1.

It is obvious in Table 1 that in order to steer the main beam of the antenna to the sixteen directions, each element (slot) is excited by using only six stages, *ie*, 0°, 27.4°, 105.4°, 222.2°, 254.5° and 332.6°. In this regard, if we use a phase shifter, the three-bit phase shifter will be employed.

The azimuthal and elevation power patterns of this antenna are shown in Fig 3 (a) and Fig 3 (b), respectively. The gain of 10.26 dBi is achieved and the deviation from this value when switching to the new beam is approximately 3 dB. It is observed that sidelobe level is relatively high. In this paper, instead

Table 1. Phase distribution of the element in each steered beam.

φ_{ij} of element at → / ϕ_0 ↓	0°	45°	90°	135°	180°	225°	270°	315°
0°	0°	105.4°	0°	254.5°	0°	254.5°	0°	105.4°
22.5°	27.4°	27.4°	222.2°	222.2°	332.6°	332.6°	222.2°	222.2°
45°	105.4°	0°	105.4°	0°	254.5°	0°	254.5°	0°
67.5°	222.2°	27.4°	27.4°	222.2°	222.2°	332.6°	332.6°	222.2°
90°	0°	105.4°	0°	105.4°	0°	254.5°	0°	254.5°
112.5°	222.2°	222.2°	27.4°	27.4°	222.2°	222.2°	332.6°	332.6°
135°	254.5°	0°	105.4°	0°	105.4°	0°	254.5°	0°
157.5°	332.6°	222.2°	222.2°	27.4°	27.4°	222.2°	222.2°	332.6°
180°	0°	254.5°	0°	105.4°	0°	105.4°	0°	254.5°
202.5°	332.6°	332.6°	222.2°	222.2°	27.4°	27.4°	222.2°	222.2°
225°	254.5°	0°	254.5°	0°	105.4°	0°	105.4°	0°
247.5°	222.2°	332.6°	332.6°	222.2°	222.2°	27.4°	27.4°	332.6°
270°	0°	254.5°	0°	254.5°	0°	105.4°	0°	105.4°
292.5°	222.2°	222.2°	332.6°	332.6°	222.2°	222.2°	27.4°	27.4°
315°	105.4°	0°	254.5°	0°	254.5°	0°	105.4°	0°
337.5°	27.4°	222.2°	222.2°	332.6°	332.6°	222.2°	222.2°	27.4°

of using three-bit phase shifters, an active phase array using different frequencies of each element according to the injection locking technique is used.

Active Spherical Slot Array Antenna

This section describes an active phase array, which a segmented spherical cavity-backed slot antenna, as shown in Fig 4 (a), is employed as a load of an active device (here is the field effect transistor (FET)) to perform as an oscillator. Fig 4 (b) shows the principle of the injection locking technique in a spherical array. In order to obtain the phase distribution as described in Table 1 in the previous section, each oscillator has to oscillate the frequency within the injection bandwidth such that[10]

$$\omega = \frac{d\theta}{dt} = \omega_o[1 - \frac{1}{2Q}\sum_{j=1}^{N}\varepsilon_{ij}\frac{A_j}{A_i}\sin(\phi_{ij}+\theta_i-\theta_j)], \quad (8)$$

where ω_o is the free-running angular frequency of the oscillators, Q is the quality factor of an oscillator circuit, and ε_{ij} is the coupling factor between the element i and j, and θ_i and θ_j are the phase distribution of element number i and j, respectively.

For a load of an oscillator, the measured input impedance of a segmented cavity-backed slot antenna, with the dimensions of ΔR_b, $\Delta\theta$ and $\Delta\phi$ equal to 0.5λ, 22.5° and 45°, respectively, are measured at the frequency of 2.45 GHz. The variation of impedance as a function of probe length is shown in Fig 5. At a probe length of 20 mm, for instance, the impedance is $40+j57\ \Omega$.

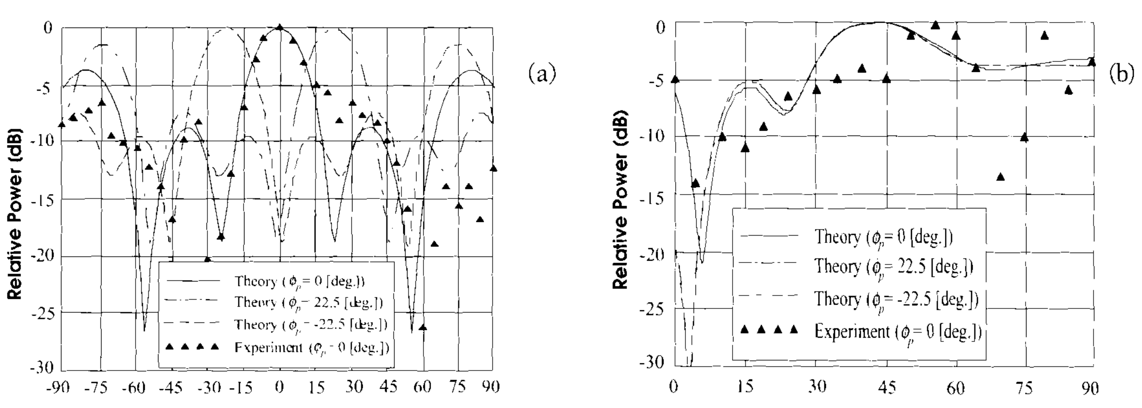

Fig 3. Power pattern of the antenna. (a) azimuthal plane at $\theta = 45°$ (b) elevation plane.

For coupling coefficient between each element, we measured the S_{ij} of the element in the array and plotted it in term of ε_{ij} as shown in Fig 6.

The active spherical slot array antenna was fabricated to test its characteristic. To do so, each oscillator was designed according to the design procedure as described in.[15] The *2SK571GaAs MESFET* was used as an active device and the microstrip matching network was designed on a Teflon substrate. Its ε_r equals *2.45* and the thickness is *1.6* mm. For the frequency 2.45 GHz, the circuit is shown in Fig 7. The Q of the resonator can be measured from the oscillator circuit. In this work, it was measured that Q is *206*. From the measured Q and ε_{ij}, the frequency of each element can be calculated from.[8] According to the phase in Table I, the frequency of each oscillator will be shown in Table II.

In order to measure the power pattern, the experiment was set up as described in[16] to measure the power pattern. The calculated elevation and azimuthal power patterns are compared with the measured results as shown in Fig 3 (a) and Fig 3 (b). The main beam can be steered to the desired direction, but the beam shape is not exactly fit to the calculated results.

Discussions and Conclusions

This paper proposed a steerable spherical slot array antenna which combines the advantage of a spherical array antenna and an active phased array antenna. Therefore, its pattern can be steered to any directions, with constant pattern, very easy by changing the frequencies of each element properly.

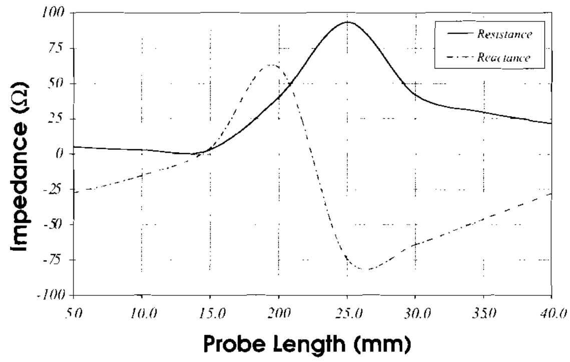

Fig 5. Measured input impedance of a segmented cavity-backed slot antenna for various probe lengths.

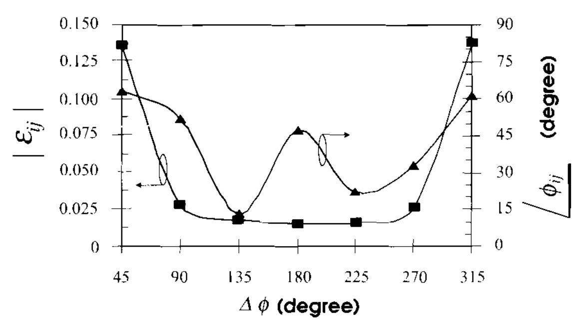

Fig 6. Coupling coefficients between slots on spherical surface.

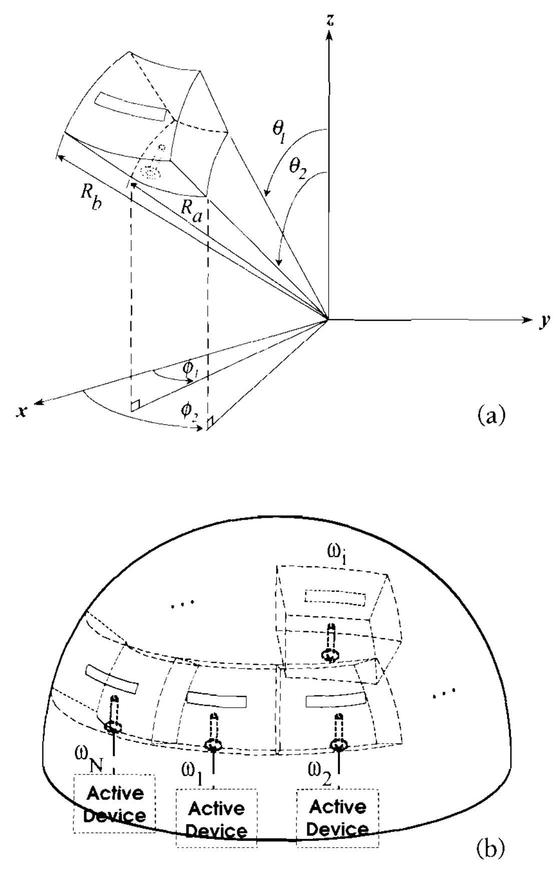

Fig 4. (a) A segmented cavity-backed slot element.
(b) Active spherical slot array antenna.

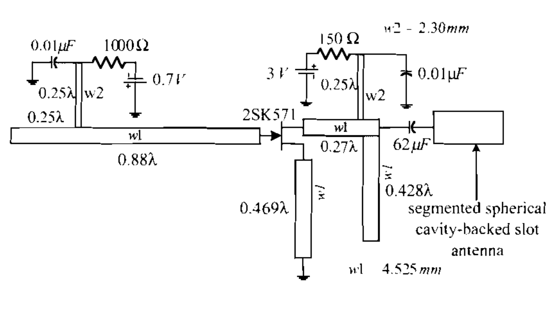

Fig 7. Oscillator circuit.

Table 2. Frequency of the oscillators.

f(GHz) / $\phi_0 \downarrow$	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
0°	2.449	2.450	2.452	2.449	2.452	2.449	2.450	2.451
22.5°	2.449	2.449	2.448	2.449	2.450	2.450	2.449	2.450
45°	2.451	2.450	2.451	2.451	2.450	2.451	2.450	2.450
67.5°	2.449	2.449	2.448	2.449	2.450	2.450	2.450	2.450
90°	2.450	2.450	2.450	2.452	2.450	2.449	2.450	2.450
112.5°	2.449	2.449	2.448	2.448	2.450	2.449	2.450	2.450
135°	2.450	2.451	2.451	2.449	2.452	2.449	2.450	2.451
157.5°	2.450	2.448	2.450	2.449	2.449	2.450	2.450	2.449
180°	2.451	2.450	2.450	2.452	2.448	2.450	2.450	2.450
202.5°	2.450	2.449	2.450	2.450	2.449	2.451	2.450	2.449
225°	2.450	2.450	2.451	2.450	2.452	2.451	2.451	2.451
247.5°	2.450	2.449	2.449	2.450	2.450	2.450	2.449	2.448
270°	2.450	2.451	2.451	2.449	2.450	2.450	2.450	2.451
292.5°	2.449	2.450	2.448	2.450	2.450	2.449	2.449	2.448
315°	2.451	2.450	2.450	2.452	2.449	2.450	2.451	2.449
337.5°	2.449	2.450	2.448	2.450	2.450	2.448	2.449	2.449

The prototype antenna was designed and fabricated to test its characteristic. It was found that there was difficulty in tuning the oscillating frequencies, but the experimental results can verify the proposed idea. Currently, an optimum condition is not available, consequently, the sidelobe level is high. This problem is left for further study. In this work, we employ measured data in the design. Analysis by using Finite-Difference Time-Domain (FDTD) method to investigate the impedance of a spherical cavity backed slot antenna which is used as an array element is under investigation in addition to the coupling coefficient between each slot. The data are essential in the design of a cost effective steerable antenna in mobile communication system.

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References

1. Sengupta DL, Smith TM and Larson RW (1968) Radiation characteristics of a spherical array of circularly polarized elements. *IEEE Trans Antennas Propagat* 16, 2-7.
2. Chan AK, Ishimaru A and Sigelman RA (1968) Equally spaced spherical arrays. *Radio Sci* 3, 401-4.
3. Chan AK and Sigelman RA (1969) Experimental investigation on spherical arrays. *IEEE Trans Antennas Propagat* 17, 348-9.
4. Horiguchi S, Ishizone T and Mushiake Y (1984) Improvement on polarization property of turnstile spherical array antenna. *Trans IEICE of Japan* 67, 451-3.
5. Horiguchi S, Ishizone T and Mushiake Y (1985) Radiation characteristics of spherical triangular array antenna. *IEEE Trans Antennas Propagat* 33, 472-6.
6. Stockton RJ and Hockensmith RP (1977) Application of spherical array - a simple approach. *Digest of 1977 IEEE Symp Antennas Propagat*, 202-5.
7. Hori T, Terada N and Kagoshima K (1987) Electronically steerable spherical array antenna for mobile earth station. *Proc IEE Int Antennas Propagat Conf.* 55-8.
8. Krairiksh M, Thongsopa C and Phongcharoenpanich C (1998) A steerable active spherical slot array antenna. *Proc of the 1999 Progress in Electromagnetics Research Symp. Taipei*, vol 1, p 483, March 1999.
9. Stephan KD (1986) Inter-injection-locked oscillators for power combining and phased arrays. *IEEE Trans Microwave Theory Tech* 34, 1017-25.
10. Liao P and York RA (1993) A new phase-shiftless beam-scanning techniques using arrays of coupled-oscillators. *IEEE Trans Microwave Theory Tech* 41, 668-71.
11. Navaro JA, Fan L and Chang K (1993) Active inverted stripline circular patch antennas for spatial power combining *IEEE Trans Microwave Theory Tech* 41, 1856-63.
12. Lin J and Itoh T (1994) Active integrated antennas. *IEEE Trans Microwave Theory Tech* 42, 2186-94.
13. Mushiake Y and Webster RE (1968) Radiation characteristics with power gain for slots on a sphere. *IRE Trans Antennas Propagat* 16, 47-55.
14. Leekpai C, Phongcharoenpanich C and Krairiksh M (1998) Theoretical investigation of a slot on spherical surface. Proc *EECON'98*, 513-6.
15. Collin RE (1992) Oscillators and Mixers. In: *Foundations for Microwave Engineering*, pp 831-875. McGraw-Hill, Inc. Singapore.
16. Navaro JA and Chang K (1996) Power comhining. In: *Integrated Active Antennas and Spatial Power Combining*, pp 69-99. John Wiley & Sons, Inc, New York.