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Investigations of Radiation Characteristics of a Circularly Polarized Conical Beam Spherical Slot Array Antenna*

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SUMMARY This paper presents the radiation characteristics of a circularly polarized conical beam spherical slot array antenna for applying to the mobile satellite communication subscriber. The structure of the antenna is easy to fabricate i.e., a ring of perpendicular slot pairs cut on an outer surface of a concentric conducting spherical cavity enclosed by the conducting conical surface with the simple feeding structure, and a linear electric probe excited at the center of the inner surface of the cavity. Radiation fields of a spherical slot array antenna are calculated by superposing the patterns of all the slots. From the numerical results of the radiation pattern, in both elevational and azimuthal planes, it is obvious that the conical beam is realized. The elevational beam direction is low, which is suitable for installing in the land mobile subscriber unit located far from the equator. The tracking system is not necessary because the azimuthal pattern is omnidirectional. Directivity of the antenna for various spherical radii and angles of slot positions are illustrated as the guidelines for the design. Experimental results are in good agreement with the predictions.

key words: *spherical slot array antenna, mobile satellite antenna, conical beam, circular polarization*

1. Introduction

At present, mobile communication using stationary satellite becomes very popular. Therefore, the investigations of the conical beam antenna are of interest. It has been widely used for the low bit rate or low gain over temperature ratio (G/T) land mobile satellite communication subscriber and broadcasting service [1], [2] in addition to the wireless Local Area Network (LAN) base station [3]. For the land mobile satellite communication subscriber, the antenna is required to radiate right-hand circular polarization with the gain of 6.6 ± 0.9 dBi and the axial ratio less than 2.5 dB [1]. In addition, for the wireless LAN counterpart, the gain of 4.2 dBi is desired [3]. Several types of the conical beam antenna are investigated in literature such as helical [4] and microstrip [5] antennas. The disadvantage of those antennas is the difficulty in fabrication because the power divider and the feeding structure are separated. Recently, the radial line slot antenna (RLSA), which is the circular array of slot pairs cut on the top plate of the radial line waveguide, was developed to radiate circularly polarized conical beam pattern [6], [7]. The merit of that antenna belongs to its simple structure since the power divider and the feeding circuit are integrated into a single structure. However, it was found that the elevational beam direction is relatively high (about 30° from broadside direction). In some applications such as the land mobile subscriber unit located far from the equator, the elevation angle must be lowered. Takada, et al. [8], [9] proposed to feed the radial line slot array antenna by the rotating mode generator, but this effort was achieved at some expenses of gain degradation and more complicated feeding structure. The authors [10] proposed the so-called circularly polarized conical beam spherical slot array antenna which provides the pattern in elevation plane directs toward a low angle direction. This antenna is easy to fabricate i.e., a ring of perpendicular slot pairs cut on an outer surface of the concentric conducting spherical cavity enclosed by the conducting conical surface. The feeding structure is simple, a linear electric probe excited at the inner surface of the cavity and integrated with the power divider. However, the significant drawback of [10] is that the conical beam radiation is not completely realized due to the very deep nulls occured in the azimuthal pattern, since the higher order mode in the cavity is utilized to excite the slot pairs. This paper presents the radiation characteristics of a circularly polarized conical beam spherical slot array antenna to achieve the completely conical beam radiation. The cavity is fed at the center so that axially symmetrical mode is generated. The formulations of the radiation fields of the spherical slot array antenna are derived as the superposition of the fields from individual slot elements. The numerical results appear to be the conical beam radiation pattern i.e., the elevation pattern possesses the null in broadside direction and the azimuthal pattern is omnidirectional. Additionally, the elevational beam direction toward the geostationary satellite is relatively low which is suitable for applying to the land mobile subscriber unit located far from the equator. Contour plot of directivity for various spher-

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ical radii and angles of slot positions are shown as the guidelines for the design of the cavity dimensions and slot arrangements. To eliminate the grating lobes in order to achieve the omnidirectional pattern in azimuthal plane, the azimuthal spacing of the slot pairs must be fixed to be less than one wavelength. This value affects on the grating lobes, and it is fixed throughout the paper. Discussions on the discretization of the spherical radii and angles of slot positions are included to fix the azimuthal spacing of slot pairs. Experimental results are also presented to verify conical beam radiation and are in good agreement with the theoretical ones.

2. Antenna Structure

The structure of a circularly polarized conical beam spherical slot array antenna consists of a number of perpendicular slot pairs cut on an outer surface of a concentric conducting spherical cavity enclosed by the conducting conical surface. The slots in a pair are excited with orthogonal phases to provide the circularly polarized radiation. These slots are arranged as a ring along an azimuthal circumference of the spherical surface at the positions that the adjacent pairs are in phase to form a conical beam. Figure 1(a) shows the local coordinate of the individual slot element. Figure 1(b) shows the top view of the circularly polarized conical beam spherical slot array antenna. The slot length and width are l and α, respectively. Each slot in a pair is separated, along an elevation plane (d_θ), at the distance so that the phase quadrature is obtained [11]. The azimuthal spacing between each slot pair is denoted by s_ϕ. The bottom and perspective views of the antenna are shown in Figs. 1(c) and (d), respectively. One of the slots in a pair is oriented at 45° counterclockwise with the horizontal line of the spherical surface whereas the perpendicular counterpart is oriented at an angle of 135°. The cross-section view of the antenna is shown in Fig. 1(e). The inner and outer radii of the concentric conducting spherical cavity are R_a and R_b, respectively, and this cavity is enclosed by the conducting conical surface at an angle θ_c. The excitation probe is located at the center of the inner surface of the cavity ($R_a \leq$ R $\leq R_b$, $\theta = 0°$, $\phi = 0°$). The center of each slot pair is located at an angle θ_s. Each slot in a pair is offset from the position in opposite direction so that phase quadrature between these slots is obtained.

3. Theory

The radiation fields of a circularly polarized conical beam spherical slot array antenna are formulated in this section. The radiation patterns of the spherical slot array antenna are determined from the combination of the slots in the pairs, and these slot pairs are arranged as the spherical array, subsequently. Let us consider the slot which is located at the local coordi-

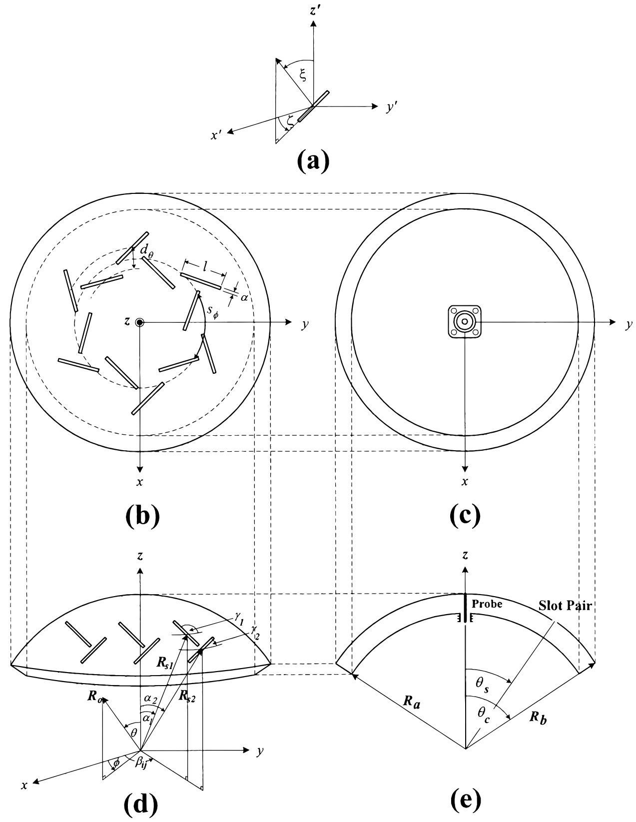

Fig. 1 A circularly polarized conical beam spherical slot array antenna. (a) local coordinates of the individual slot element, (b) top view, (c) bottom view, (d) perspective view, (e) cross-section view.

nate (R_b,ξ,ζ) as shown in Fig. 1(a). The radiation pattern of a slot on a spherical conductor surface can be derived by solving the electromagnetic boundary value problem. The aperture field distribution along the slot is reasonably assumed to be sinusoidal to simplify in calculation. The radiation fields can be expressed by the summation of eigenfunctions in the spherical coodinates as follows [12]:

$$f_\xi(R_b,\xi,\zeta) = \sum_{m=0}^{\infty}\sum_{n=m}^{\infty} f_m(j)^n \left[\frac{jA_{mn}^{TE}}{\alpha}\frac{1}{h_n^{(2)}(kR_b)} \cdot\frac{dP_n^m(\cos\xi)}{d\xi} + \frac{A_{mn}^{TM}}{\alpha}\frac{kR_b}{\left[kR_b h_n^{(2)}(kR_b)\right]'} \cdot\frac{mP_n^m(\cos\xi)}{\sin\xi}\right]\cos(m\zeta) \quad (1)$$

and

$$f_\zeta(R_b,\xi,\zeta) = \sum_{m=0}^{\infty}\sum_{n=m}^{\infty} f_m(j)^n \left[\frac{jA_{mn}^{TE}}{\alpha}\frac{1}{h_n^{(2)}(kR_b)} \cdot\frac{mP_n^m(\cos\xi)}{\sin\xi} + \frac{A_{mn}^{TM}}{\alpha}\frac{kR_b}{\left[kR_b h_n^{(2)}(kR_b)\right]'}\right.$$

$$\left. \cdot \frac{dP_n^m(\cos\xi)}{d\xi} \right] \sin(m\zeta). \quad (2)$$

The coefficients are given as follows:

$$f_m = \begin{cases} \frac{1}{\pi k R_b}(1-\cos(kl)) & ; \quad m=0 \\ \frac{1}{\pi R_b}\sin(kl) & ; \quad m = kR_b \\ \frac{1}{\pi}\frac{2kR_b}{(kR_b)^2-m^2}[\cos(\frac{ml}{R_b})-\cos(kl)]; & \text{elsewhere} \end{cases} \quad (3)$$

$$A_{mn}^{TE} = -\frac{2n+1}{2n(n+1)}\frac{(n-m)!}{(n+m)!} \cdot \int_{\alpha_i-\frac{\alpha}{2}}^{\alpha_i+\frac{\alpha}{2}} mP_n^m(\cos\xi)\,d\xi \quad (4)$$

and

$$A_{mn}^{TM} = -\frac{2n+1}{2n(n+1)}\frac{(n-m)!}{(n+m)!} \cdot \int_{\alpha_i-\frac{\alpha}{2}}^{\alpha_i+\frac{\alpha}{2}} \frac{dP_n^m(\cos\xi)}{d\xi}\sin\xi\,d\xi, \quad (5)$$

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). To provide the right-hand circular polarization, two perpendicular slots are placed at the distance along the elevation plane of d_θ to achieve the phase quadrature excitation. One of the slots in a pair is oriented at γ_1, and the other one is at an angle γ_2 counterclockwise with respect to the horizontal line of the spherical surface. Let us consider N slot pairs which are arranged as a ring along the circumference of the spherical surface and these slot pairs are excited in the co-phase to make the null appear at the broadside direction in elevation plane. The radiation fields of the spherical slot array antenna can be written as the combination of the field from the total number of slots which are arranged to form the circularly polarized conical beam as [13]–[17]

$$\boldsymbol{E}(\theta,\phi) = \sum_{j=1}^{N}\left[\sum_{i=1}^{2}\boldsymbol{f}(R_b,\xi_{ij},\zeta_{ij})e^{j(kR_b\cos\xi_{ij}+\psi_i)}\right] \quad (6)$$

and

$$\begin{aligned}\boldsymbol{f}(R_b,\xi_{ij},\zeta_{ij}) &= f_\xi(R_b,\xi_{ij},\zeta_{ij})\,[\cos\gamma_i-\sin\gamma_i]\,\hat{\boldsymbol{\xi}}_{ij} \\ &\quad -f_\zeta(R_b,\xi_{ij},\zeta_{ij})\,[\cos\gamma_i+\sin\gamma_i]\,\hat{\boldsymbol{\zeta}}_{ij},\end{aligned} \quad (7)$$

where $\hat{\boldsymbol{\xi}_{ij}}$ and $\hat{\boldsymbol{\zeta}_{ij}}$ are unit vectors along the slot local coodinates, respectively, and ψ_i is the phase of the slot number i. It is noted that the phase difference of the two slots $(\psi_1-\psi_2)$ is assumed to be 90°. Additionally, to express the term of source point $(R_b,\xi_{ij},\zeta_{ij})$ as the term of the observation point (R,θ,ϕ), the help of these coordinate transformations are used:

$$\begin{aligned}\cos\xi_{ij} &= \frac{\boldsymbol{R}_{si}\cdot\boldsymbol{R}_o}{|\boldsymbol{R}_{si}||\boldsymbol{R}_o|} \\ &= \sin\alpha_i\sin\theta\cos\,(\phi-\beta_{ij})+\cos\alpha_i\cos\theta\end{aligned} \quad (8)$$

$$\tan\zeta_{ij} = \frac{\sin\theta\sin(\phi-\beta_{ij})}{\cos\alpha_i\sin\theta\cos\,(\phi-\beta_{ij})-\sin\alpha_i\cos\theta} \quad (9)$$

$$\begin{aligned}\hat{\boldsymbol{\xi}}_{ij} &= -\frac{\sin\alpha_i\cos\theta\cos(\phi-\beta_{ij})-\cos\alpha_i\sin\theta}{\sin\xi_{ij}}\hat{\boldsymbol{\theta}} \\ &\quad +\frac{\sin\alpha_i\sin(\phi-\beta_{ij})}{\sin\xi_{ij}}\hat{\boldsymbol{\phi}}\end{aligned} \quad (10)$$

$$\begin{aligned}\hat{\boldsymbol{\zeta}}_{ij} &= -\frac{\sin\alpha_i\sin(\phi-\beta_{ij})}{\sin\xi_{ij}}\hat{\boldsymbol{\theta}} \\ &\quad -\frac{\sin\alpha_i\cos\theta\cos(\phi-\beta_{ij})-\cos\alpha_i\sin\theta}{\sin\xi_{ij}}\hat{\boldsymbol{\phi}},\end{aligned} \quad (11)$$

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

4. Numerical Results

4.1 Radiation Pattern

To illustrate the radiation pattern of a circularly polarized conical beam spherical slot array antenna, let us demonstrate a model of the slot array oriented at an angle of slot position (θ_s) of 40° on the spherical cavity of the radius (R_b) 1.43λ and the azimuthal spacing (s_ϕ) is 0.481λ. It can be seen that the elevational radiation pattern possesses the null in the broadside direction and the beam peak is about 60° as shown in Fig. 2 by the solid line. Figure 3 shows the azimuthal radiation pattern at $\theta = 60°$ by the solid line. It is evident that the omnidirectional radiation is obtained. The directivity of this antenna is about 6.5 dBi.

4.2 Elevation Angle and Directivity

The contour of directivity as a function of the angle of slot pair position (θ_s) and the spherical radius (R_b) are shown in Figs. 4 and 5, respectively. These contours are plotted in case of the azimuthal spacing is fixed and equal to 0.481λ. Other design parameters are listed in Table 1. By this way, to design a circularly polarized conical beam spherical slot array antenna for a specified directivity, the angle of slot pair position (θ_s) and the spherical radius (R_b) can be determined by using Figs.

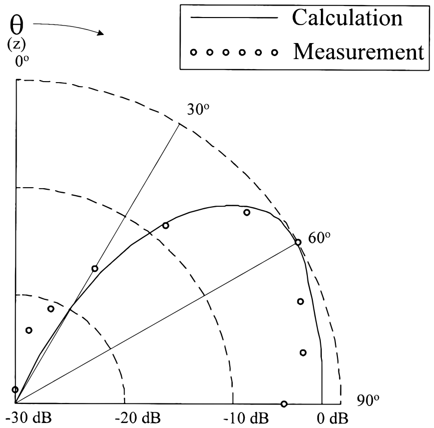

Fig. 2 Elevational radiation pattern.

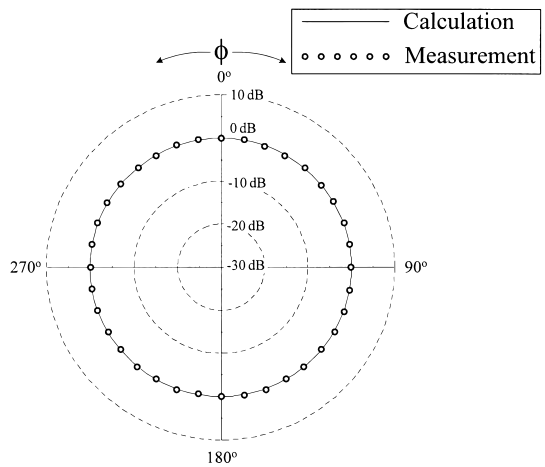

Fig. 3 Azimuthal radiation pattern at $\theta = 60°$.

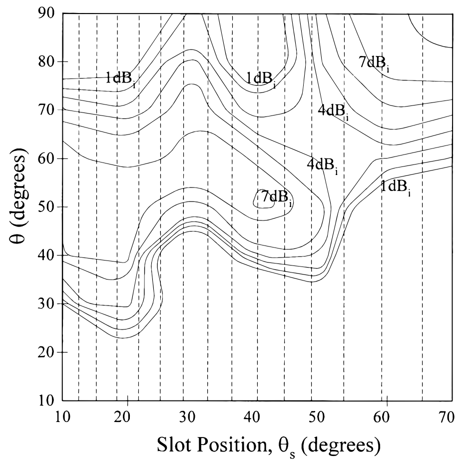

Fig. 4 Contour of directivity as a function of the angle of slot pair position ($R_b = 1.43\lambda$).

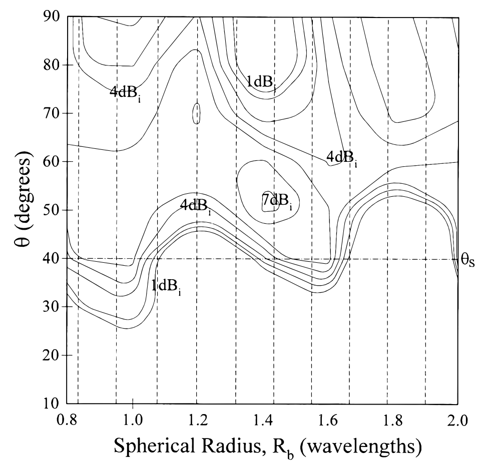

Fig. 5 Contour of directivity as a function of the spherical radius ($\theta_s = 40°$).

4 and 5, respectively. Figure 4 shows the contour of directivity when R_b is fixed at 1.43λ. From this graph, we can observe that the antenna provides a 7 dBi directivity at an angle (θ) of 53° when the angle of slot pair position is at 42°. For example, when the desired directivity is 6 dBi, an appropriate angle (θ) of 60° at an angle of slot pair position (θ_s) less than 40° can be chosen. Figure 5 shows the contour of directivity when θ_s equals 40°. If one chooses the spherical radius equal to λ, a 5 dBi directivity can be obtained at an angle around 40° to 60°. However, when the azimuthal spacing is fixed, the angle of slot position (θ_s) and spherical radius (R_b) can not be arbitrarily varied because the number of slot pairs should be discrete value as the integer. Practically, these parameters (θ_s, R_b) must be chosen according to the discrete value of the slot pair number as shown by using the dashed grid lines in Figs. 4 and 5, respectively. Accordingly, the directivity in a particular direction can be designed from these contours of directivity.

Table 1 Antenna parameters used in the model.

Slot length (l)	5.00 cm (0.5 λ)
Slot width (α)	1.74 mm (0.0174 λ)
Outer spherical radius (R_b)	14.30 cm (1.43 λ)
Inner spherical radius (R_a)	12.70 cm (1.27 λ)
Shorted conical angle (θ_c)	67.34°
Center of slot pair angle (θ_s)	40.00°
Azimuthal spacing between slot pair (s_ϕ)	4.81 cm (0.481 λ)
Elevation distance between each slot in a pair (d_θ)	2.20 cm (0.22 λ)
Number of slot pair (N)	12

5. Experiment

To verify the conical beam radiation, the experiment was set up at the frequency of 3 GHz (available equipment) to measure the elevational and azimuthal radiation patterns. The dimensions of the circularly polarized conical beam spherical slot array antenna which is used in the model are summarized in Table 1. The antenna fabricated consists of two parts of conductor; the outer spherical conductor with a number of slots cut on it and the inner surface with the ring of the shorted conical conductor. The metal plates of those two parts are projected from the spherical prototype, and they are duplicated to the curve surface by compressing with the mold. The slots on outer spherical surface are cut by using the computer-numerically controlled machine. The tolerance of the machine used to fabricate is $\pm 0.1\,\mu$m. The probe of the length 1.6 cm, made of the conductor is connected via N-type connector to feed the antenna at the center of the cavity.

The outdoor field test was done at the deck of the campus building, and the far-field range of 2 m is used. A 10-turn helix with the axial ratio of 0.4 dB was employed to transmit a right-hand circularly polarized wave, and the antenna under test was rotated to receive the transmitted wave at 10° per step. The experimental results of radiation pattern in elevation plane is plotted and compared with the calculation as shown in Fig. 2 by the circles. From this comparison, we saw that these patterns are in good agreement i.e., they yield the null appears in the broadside direction, and the beam peak is about 60°. There are some errors according to the diffraction at the edge of the cavity, the imperfectness of fabrication and the test-site situations. Figure 3 shows the azimuthal pattern of the antenna at the elevational beam peak direction (60°). The theoretical and experimental results are illustrated by using the solid line and the circles, respectively. These results agree very well and are completely omnidirectional. The axial ratio has been measured by using the circular component method [18] and found to be rather high, the level being around 4 dB (cross-polarization discrimination equals 13 dB). This may be because the radiated field is rather linear in polarization since the phase quadrature of the slots is assumed.

6. Conclusions

The radiation characteristics of a new type antenna, a circularly polarized conical beam spherical slot array antenna is investigated in this paper. The structure of the antenna is simple, and suitable for the mass production by using the numerically controlled machine. The numerical study on the radiation pattern is carried out, the conical beam radiation can be obtained, the elevation pattern directs toward the geostationary satellite and makes the null appear in the broadside direction and the radiation pattern in azimuthal plane is completely omnidirectional. The elevational beam direction is relatively low which is suitable for applying to the land mobile satellite communication subscriber unit located far from the equator. It is evident that the elevational beam direction depends on the spherical radius and angle of slot position. The omnidirectional pattern in azimuthal plane can be achieved when the azimuthal spacing is less than one wavelength. The phase quadrature excitation of the slots in a pair is assumed in this paper. To realize this condition, the structure including the length and the position of slots should be optimized taking account of the slot coupling which is under investigation.

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References

[1] J.R. James and P.S. Hall, "Handbook of Microstrip Antennas," Peter Peregrinus, 1989.

[2] H. Kawakami, G. Sato, and R. Wakabayashi, "Research on circularly polarized conical-beam antennas," IEEE Antennas Propagat. Magazine, vol.39, no.3, pp.27–39, June 1997.

[3] Y.J. Guo, A. Paez, R.A. Sadeghzadeh, and S.K. Barton "A circular patch antenna for radio LAN's," IEEE Trans. Antennas & Propag., vol.45, no.1, pp.177–178, Jan. 1997.

[4] Y. Terada and K. Kagoshima, "Conical beam bifilar helical antenna for mobile satellite communications," IEICE Technical Report, AP91-38, June 1991.

[5] T. Hori, Y. Terada, and K. Kagoshima, "Broadband circularly polarized microstrip antenna with a conical beam," IEICE Nat. Conv. Rec., 637, March 1986.

[6] J. Takada, A. Tanisho, K. Ito, and M. Ando, "Circularly polarised conical beam radial line slot antenna," Electron. Lett., vol.30, no.21, pp.1729–1730, Oct. 1994.

[7] J. Takada, A. Tanisho, K. Ito, M. Ando, and N. Goto, "Radiation characteristics of a circularly polarized conical beam radial line slot antenna," 1994 Asia-Pacific Microwave Conf. Proc., pp.101–104, Dec. 1994.

[8] J. Takada, T. Yamamoto, M. Ando, and N. Goto, "Circularly polarized multibeam radial line slot antennas for mobile satellite communication," Proc. IEEE Antennas Propagat. Soc. Int. Symp., pp.1430–1433, June 1995.

[9] J. Takada, T. Yamamoto, M. Ando, and N. Goto, "An azimuthal multibeam radial line slot antennas for mobile satellite communication," Proc. 4th IEEE Int. Conf. on Universal Personal Commun., pp.571–574, Nov. 1995.

[10] M. Krairiksh, C. Phongcharoenpanich, K. Meksamoot, and J. Takada, "A circularly polarized conical beam spherical slot array antenna," Int. J. Electron., vol.86, no.7, pp.815–823, July 1999.

[11] M. Ueno, S. Hosono, M. Takahashi, M. Ando, and N. Goto, "Slot design of a concentric array radial line slot antenna with matching terminating slots," 1994 Asia-Pacifc Microwave Conf. Proc., pp.319–322, Dec. 1994.

[12] Y. Mushiake and R.E. Webster, "Radiation characteristics with power gain for slots on sphere," IRE Trans. Antennas

& Propag., vol.5, no.1, pp.47–55, Jan. 1957.
[13] M. Hoffman, "Conventions for the analysis of spherical arrays," IEEE Trans. Antennas & Propag., vol.AP-11, no.7, pp.390–393, July 1963.
[14] D.L. Sengupta, T.M. Smith, and R.W. Larson, "Radiation characteristics of a spherical array of circularly polarized elements," IEEE Trans. Antennas & Propag., vol.AP-16, no.1, pp.2–7, Jan. 1968.
[15] A.K. Chan, A. Ishimaru, and R.A. Sigelmann, "Equally spaced spherical arrays," Radio Science, vol.3, no.5, pp.401–404, May 1968.
[16] S. Horiguchi, T. Ishizone, and Y. Mushiake, "Radiation characteristics of spherical triangular array antenna," IEEE Trans. Antennas & Propag., vol.AP-33, no.4, pp.472–476, April 1985.
[17] T. Hori, N. Terada, and K. Kagoshima, "Electronically steerable spherical array antenna for mobile earth station," Proc. IEE Antennas Propagat. Conf., pp.55–58, March 1987.
[18] J.D. Kraus, "Antennas," McGraw-Hill Inc., 1988.

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