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PAPER

Slot Design of a Concentric Array Radial Line Slot Antenna with Matching Slot Pairs

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SUMMARY A radial line slot antenna (RLSA) is a high efficiency and high gain planar antenna. The efficiency of RLSA becomes lower as the aperture size reduces due to rotational asymmetry of the illumination. A concentric array RLSA (CA-RLSA) was proposed to overcome this difficulty. It adopted three new techniques; (1) not spirally but concentrically arrayed slots, (2) a rotating mode feed circuit, (3) matching slot pairs eliminating termination loss. This paper proposes the basic slot design for (1) and (2) of CA-RLSA. Excellent characteristics of very small CA-RLSAs based upon this design are confirmed by measurements.

key words: *antennas, array, RLSA, CA-RLSA, matching slot pair*

1. Introduction

A radial line slot antenna (RLSA) is a high efficiency and high gain planar antenna for the direct broadcast from satellite (DBS) reception [1], [2]. Two circular disks compose a radial waveguide, the top of which is an aperture with slots arrayed spirally. The predicted conductor loss of a RLSA is small and negligible; High efficiency is expected in principle even in high gain range. Furthermore the simplest structure of RLSA is good for mass-production. Single-layer RLSAs (SL-RLSA) with the diameter of 40 cm to 60 cm have realized the efficiency of more than 80% at 12 GHz and some of these antennas have been released for commercial use [3], [4]. However, smaller ones cannot reach such high efficiency. One reason is termination loss and another is the degradation due to rotational asymmetry of the illumination [5]. The authors have proposed a new concept of a concentric array RLSA (CA-RLSA) to overcome these difficulties. It adopts three new techniques; (1) not spirally but concentrically arrayed slots, (2) a rotating mode feed circuit, (3) matching slot pairs eliminating termination loss [6]–[8].

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This paper presents a basic slot design of CA-RLSA and excellent characteristics of very small RLSAs. The measurement proved that CA-RLSAs have a potential of the high efficiency.

2. Difficulties of Small RLSA's

Figure 1 shows the structure of a conventional SL-RLSA. Two conducting disks compose a radial waveguide and dielectric material is inserted in waveguide as a slow wave structure. The power is fed by the co-axial cable at its center and is transferred into a rotationally symmetrical outward traveling wave. While propagating outward, the power gradually radiates from slots on the top plate. Slots consisting of many pairs, each of which is a unit radiator of circular polarization, are arrayed spirally on a multi-mode waveguide. The unique feature of this antenna has been the combination of rotationally symmetric wave and spirally arrayed elements.

A RLSA is a kind of traveling wave antennas and slot coupling are controlled skillfully to obtain uniform aperture illumination distribution. The excessive coupling of spirally arrayed slots should be avoided to maintain the desired operation in a rotationally sym-

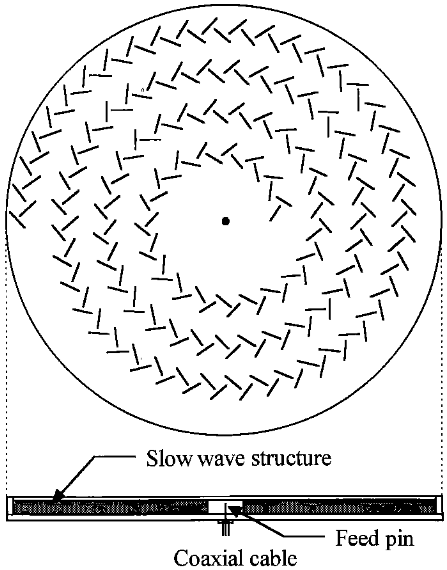

Fig. 1 Single layer (SL)-RLSA.

metrical mode. Accordingly the input power cannot radiate perfectly from slots and a part of it reaches the end of waveguide as termination loss. In a small RLSA the field is seriously disturbed because large coupling slots are necessary.

Figure 2 shows the theoretical and measured efficiency of SL-RLSA in 12 GHz as well as termination loss ratio as functions of aperture diameter. Three types of antennas are compared, that is (a) the conventional one with spirally arrayed slots excited uniformly, (b) spirally arrayed slots with enhanced and non-uniform excitation [3] and (c) the new one with concentric array and matching elements. The loss becomes notable as the antenna diameter decreases. In Fig. 2 the efficiency of conventional uniform design (a) is seriously degraded to less than 70% for the diameter smaller than 40 cm. If the termination loss is taken into account uniform illumination is no longer the optimum design for high efficiency and more strongly coupled slots should be adopted (non-uniform (b)). This concept has been applied successfully in the range of diameter larger than about 30 cm. For smaller RLSA we have proposed matching elements, such as matching slots and matching spiral [9], [10], in order to radiate termination power. However these elements have not worked successfully in RLSA with spiral arrangement since the strong coupling excessively disturbs the symmetry of inner fields. For desired operation of matching elements rotational symmetry is essential.

It is important for a high efficient and small RLSA to radiate termination power by matching elements

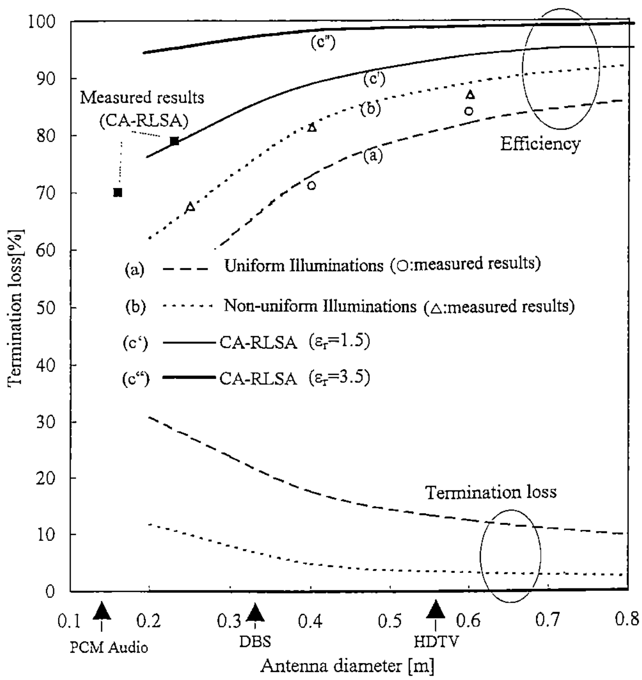

Fig. 2 Antenna efficiency and aperture diameter of RLSA in 12 GHz band.

and to improve rotational asymmetry of illumination at the same time. To solve these problems a new type RLSA has been proposed; a concentric array RLSA (CA-RLSA) [11].

3. Structure of CA-RLSA

Figure 3 shows the structure of CA-RLSA. All of the slot pairs are arranged concentrically and perturbation of slots does not cause rotational asymmetry. The power is fed by the co-axial cable at the center cavity and is transferred into a rotating mode defined by $\exp(j\phi)\ H_1^{(2)}(k\rho)$. This mode is an outward traveling wave with the phase progression along ϕ-direction and is excited as the sum of two TM modes, $\cos\phi H_1^{(2)}(k\rho)$ and $j\times\sin\phi H_1^{(2)}(k\rho)$. The combination of concentric arrangement of array and a rotating mode excitation is the unique feature of CA-RLSA in contrast with the conventional ones utilizing spiral arrangement of slots and a rotational symmetric cylindrical wave excitation. In addition matching elements are jointly adopted at the end of shorted waveguide, which radiate all the residual power and suppress a reflected inward traveling mode of $\exp(j\phi)H_1^{(1)}(k\rho)$. So, quasi-traveling wave operation in $\exp(j\phi)H_1^{(2)}(k\rho)$ is realized.

When a rotating electromagnetic mode is excited in the waveguide and matching elements work perfectly, CA-RLSA will realize much higher efficiency than a conventional one. Figure 2 includes the predicted efficiency of CA-RLSAs (c' and c''). The smaller the antenna diameter becomes, the larger enhancement of the efficiency is predicted. A CA-RLSA with matching slots has the potential to achieve a high efficiency even for extremely small diameter. As for the dielectric constant ε_r, larger ε_r will contribute to reduce the

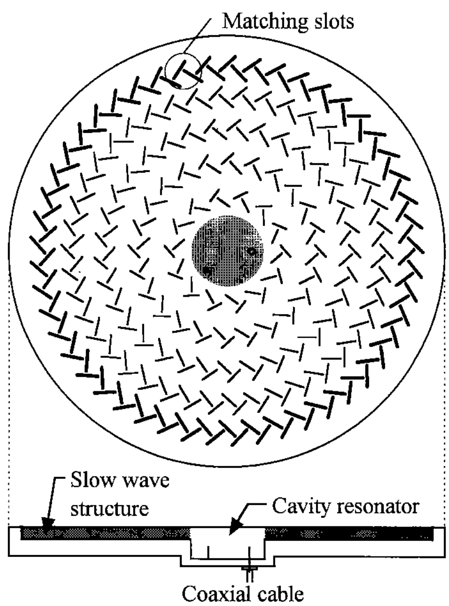

Fig. 3 Concentric array (CA)-RLSA.

element spacing; aperture efficiency of an array approaches to that of continuous aperture, the latter of which takes its maximum of 100% for uniform distribution provided the aperture is large to some extent. As is usual the case with finite sized array, the envelope of side lobes and especially the radiation in wide angular region is suppressed by reducing the element spacing and increasing the element number for given aperture size; a higher efficiency is realized.

4. Slot Design

4. 1 Slots of Inner Section

The slot design was conducted at the design frequency of 11.85 GHz, the center one in DBS bandwidth in Japan. Key procedure is as follows;
1) All the slots are divided into two groups, matching slots and inner slots.
2) Slots of inner section are designed.
3) Matching elements are designed.
4) Radiation phases of two parts are adjusted by radial spacing between them.
This method is very simple because two types of elements are designed independently.

The design of slots of inner section is the same as the conventional one [12], [13], except that the upper limit of slot coupling is removed by the use of matching elements. In the slot design of a SL-RLSA a continuous attenuation model [12] is used assuming operation under the traveling wave condition. For uniform aperture distribution, slot coupling distribution over the aperture is given by the next equations [13].

$$\alpha(\rho)=\frac{\rho}{K-\rho^2},\ K=\frac{\rho_{\mathrm{MAX}}{}^2-t\rho_{\min}{}^2}{1-t} \qquad (1)$$

where t is the termination loss and α is called the coupling factor which represents the attenuation of the inner field due to slot coupling. The desired coupling factor varies with the position. The slot length realizing the above coupling factor in (1) is derived from full wave analysis [14] for given dielectric constants, waveguide height and so on. In the conventional design the maximum coupling factor α is limited around 20–25 [13].

When ideal matching elements are adopted at the end of waveguide, termination loss t is zero. So slot coupling factor α is given by substituting it in (1)

$$\alpha(\rho)=\frac{\rho}{\rho_{\mathrm{MAX}}{}^2-\rho^2} \qquad (2)$$

Consequently in contrast with the conventional RLSA, the coupling factor increases arbitrarily toward the matching elements in CA-RLSA. All the slots including matching slots are excited in the same amplitude by deciding α from (2). Other parameters such as slot length, slot spacing and radiation phase are obtained in the same manner as those in conventional method.

Figure 4 shows the distribution of α. In this design α is larger than conventional one in all the region. At the termination $\rho_{\max}$, slot coupling factor α becomes infinite. Standard paired slots excited by a traveling wave cannot realize such large coupling but matching elements can.

4. 2 Matching Slots

We propose a pair of slots for matching elements of RLSA so that it radiates the circular polarization. The matching slots in the outermost ring have different design and operation from those in the inner part and the conventional design method should be revised.

An analysis model of matching slots is shown in Fig. 5. When antenna radius is large to some extent, cylindrical coordinate system is replaced by Cartesian coordinate system. The input TEM plane wave comes from the z-direction. A waveguide is electrically shorted at $z=s$, the termination of waveguide. The angle of slots is fixed to be 45° as in Fig 5. In Cartesian coordinate system dyadic Green's function is just the same as that of rectangular waveguide. Additionally this model has periodicity in the x-direction which contributes to reduce number of unknowns and parameters.

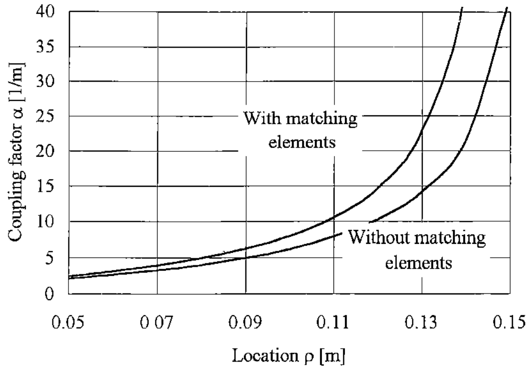

Fig. 4 Distribution of coupling factor α.

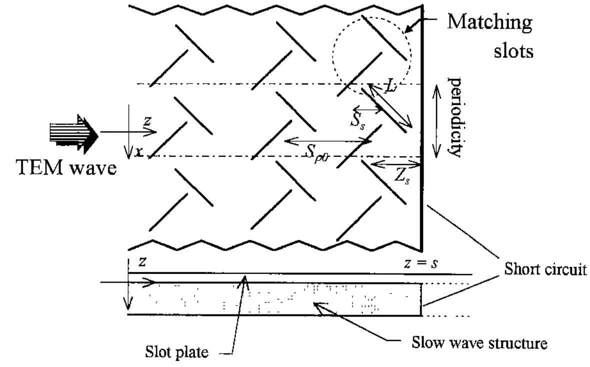

Fig. 5 Analysis model of matching slots.

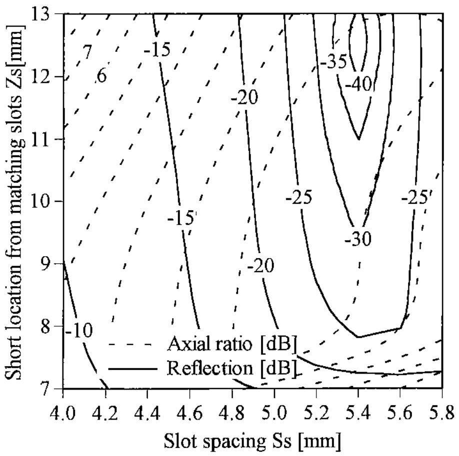

Fig. 6 Predicted axial ratio and reflection of matching slot pairs.

Table 1 Analysis parameters.

Width of periodic wall	14mm
Dielectric constant	1.17
Waveguide height	3.0mm
Frequency	11.85GHz
Length of matching slots	13.5mm

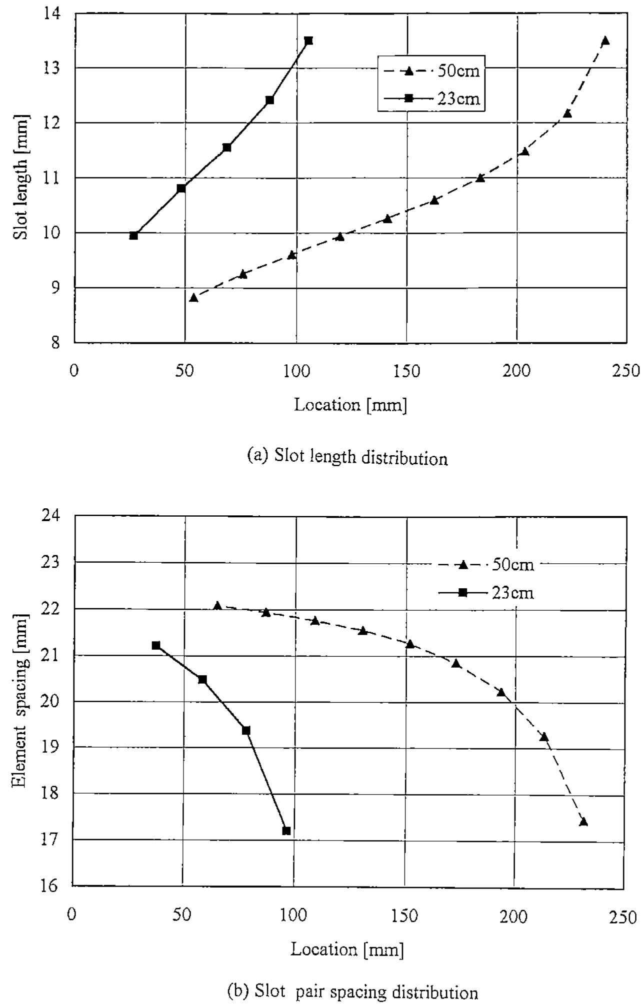

Fig. 7 Distribution of slot parameters.

Matching slots have two roles. Firstly they radiate all the incident power and reduce reflection. Secondly the radiation from them should be circularly polarized in the boresight. Method of moment analysis was conducted to evaluated the slot reflection and the axial ratio for various set of parameters. We first confirmed that the periodicity in the x-direction has small effects upon the characteristics and the design of matching slot pairs; it was set to be about 0.5 wavelength, which is typical spacing in conventional RLSA's [4], [15]. As for the length of matching slots, optimization was conducted assuming that two slots in a pair has the same length. The initial value for the iteration is around the resonance one for traveling wave excitation in the absence of short circuit. For various length of matching slots, two more important parameters, the spacing S_s of matching slot pairs in the z-direction and the distance Z_s to the short are varied and the reflection and the axial ratio of the matching slot are evaluated. After the time consuming but straightforward iterative search, the slot length of 13.5 mm was selected for which both the requirements for the reflection and the axial ratio are satisfied at the same time. Figure 6 shows calculated characteristics of matching slots for the parameters shown in Table 1, where the length of matching slots and periodicity are optimized in above process. In Fig. 6, the horizontal axis is the spacing S_s of matching slot pairs in the z-direction and the vertical axis is the distance between matching slot pair and short location Z_s. Choosing optimum parameters, we can achieve both small reflection less than -20 dB and low axial ratio less than 3 dB. Further calculation shows us that the matching slot pairs have enough bandwidth and the above characteristics are predicted over 300 MHz band.

When matching elements reduce reflection from the termination, slots in the inner part are excited by the traveling wave. The phase of matching slot pairs in the outermost and the inner part of array should be equal and it is realized by controlling the spacing between them which is $S_{\rho 0}$ in Fig. 5. According to the above process all the slots of CA-RLSA are designed.

The slot pattern of Fig. 3 is an example design for an actual array with 23 cm diameter. The shape and the spacing of matching slots are analogous to those in inner parts although they have different operation. Distribution of slot length and slot spacing is shown in Fig. 7. They are changing smoothly in spite of the different design between two groups.

5. Experimental Results

5.1 Aperture Illumination

To verify this method we first fabricate a large CA-RLSA with 50 cm diameter for evaluation of uniformity of aperture illumination. The antenna parameters are shown in Table 2. The feed circuit is an electric wall type dual-feed cavity resonator to excite a rotating mode in radial line [11], [15]. This feeder has two feed pins in phase quadrature excited through 90° hybrid. It can excite an excellent rotating mode but has considerable feed loss in semi-rigid cables from the hybrid. Figure 8 shows an measurement result of aperture illumination. Both amplitude and phase distribution are sufficiently uniform. Subtle asymmetry is due to imperfect excitation of a rotating mode [7]. Figure 9 shows measured radiation pattern in Fresnel region and envelope of calculated ideal pattern of this array. The first side lobe level has some difference because the rotating mode feeder is not perfect. But on the whole measured pattern and calculated envelope are in good agreement.

These results confirm that slots are almost ideally excited and this design method is applicable for uniform aperture CA-RLSA.

Table 2 Antenna parameters.

Antenna diameter	50cm(19.8λ_0)	23cm(9.1λ_0)	16cm(6.3λ_0)
Dielectric constant	1.17	1.17	1.17
Waveguide height	3.0mm	3.0mm	3.0mm
Design frequency	11.85GHz	11.85GHz	11.85GHz
Number of Slots	1346	324	152

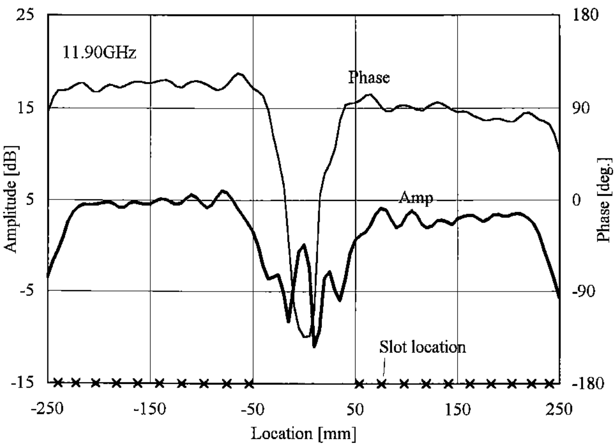

Fig. 8 Aperture distribution of 50 cm antenna.

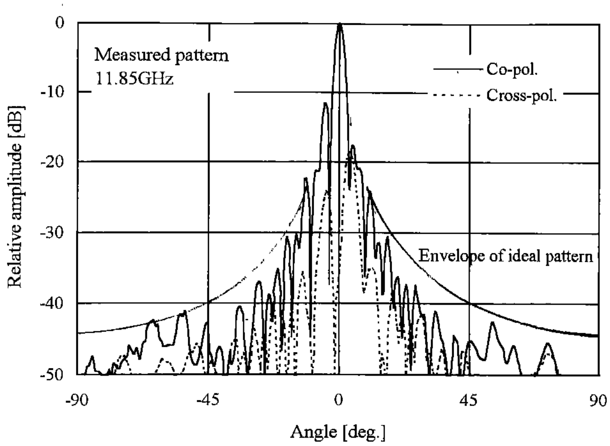

Fig. 9 Fresnel radiation patterns of 50 cm antenna.

5.2 Small CA-RLSA

The most challenging objective of this paper is to apply matching elements to very small aperture. So a small CA-RLSA's with 23 cm diameter is fabricated. Figure 3 shows the slot pattern of the model antenna. Antenna parameters are also shown in Table 2. A feed circuit is a single-feed cavity resonator which has negligible feed loss but has a deformed rotating mode in amplitude [11], [15]. The measured reflection is below −15 dB in more than 1 GHz band width and −20 dB in 400 MHz band width. As is stated later, the center frequency in terms of measured gain is lower than the design one by about 200 MHz. This error is mainly due to wrong estimation of dielectric constant ε_r by about few percent but will be corrected easily in the subsequent design.

The measured aperture distribution in 11.6 GHz is shown in Fig. 10. It has some ripples due to diffraction since the aperture size is small. Figure 11 shows the measured radiation pattern. The XPD in the boresight is about 30 dB and axial ratio is 0.5 dB. The measured gain is shown in Fig. 12. A shift of center frequency of about 200 MHz is observed. The 23 cm antenna has the efficiency of 79%, which is higher than a conventional RLSA by 10% in this small diameter. As another trial, a smaller CA-RLSA with 16 cm diameter is fabricated and it realizes the 70% efficiency. The axial ratio of each antenna is around 0.5 dB and satisfactory.

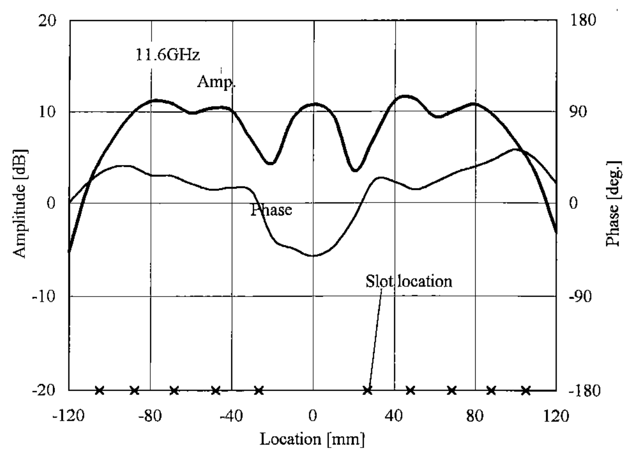

Fig. 10 Aperture distribution of 23 cm antenna.

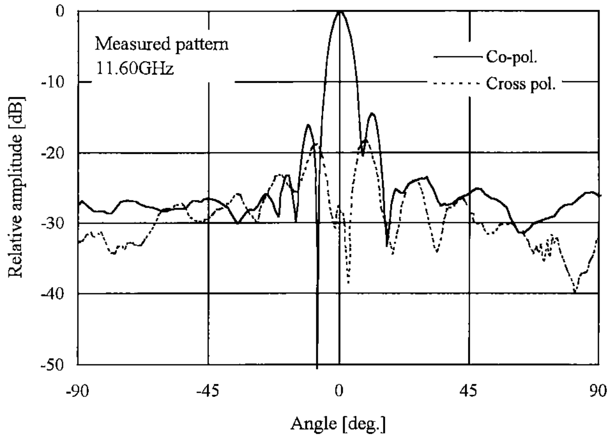

Fig. 11 Radiation patterns of 23 cm antenna.

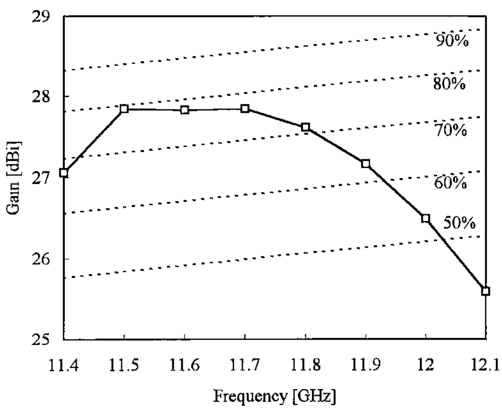

Fig. 12 Measured gain of 23 cm antenna.

These results demonstrate the effect of matching slots.

Lastly these measured results are marked with dots ■ in Fig. 2. The antenna efficiency is drastically improved. We confirm that CA-RLSAs have the potential of high efficiency even if the antenna is small.

6. Conclusion

We propose a basic method to design slots of a CA-RLSA with matching slots. We produce three CA-RLSA's with different diameter by this method. The diameter of the largest antenna is 50 cm, and the smallest one is 16cm. The measured phase of aperture illumination of 50 cm antenna is fine and uniformity of slot excitation is verified. The measured peak gain of the 23 cm antenna is 27.8 dBi at 11.5 GHz and the efficiency is 79%. It is higher than a conventional SL-RLSA by 10% in this diameter. The efficiency of 16 cm antenna is no less than 70%. These results prove that matching slots are effective and that small CA-RLSA's can realize high efficiency.

As another feature of a CA-RLSA, the number of design parameters is small because slots on the same radius have the same parameters. In the future design for the highest gain and for lowest side lobes, complete numerical optimization may be possible.

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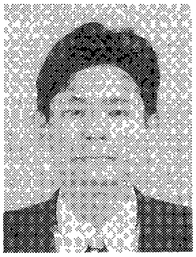

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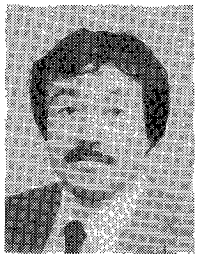

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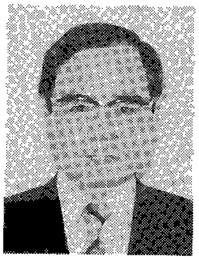

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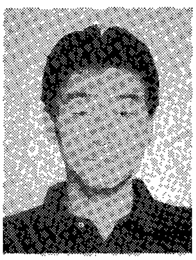

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