PAPER

Aperture Illumination Control in Radial Line Slot Antennas

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and **Naohisa GOTO**†, *Members*

SUMMARY A radial line slot antenna (RLSA) is a high gain and high efficiency planar array. A single-layered RLSA is much simple in structure but the slot length must be varied to synthesize uniform aperture illumination. These are now commercialized for 12 GHz band DBS reception. In RLSAs, considerable power is dissipated in the termination as is common to other traveling wave antennas; the uniform aperture illumination is not the optimum condition for high gain in RLSAs. Authors proposed a theoretical method reducing the termination loss for further efficiency enhancement. This paper presents the measured performances of the SL-RLSAs of this design with non-uniform aperture illumination. The efficiency enhancement of about 10% is observed; the measured gain of 36.7 dBi (87%) and 32.9 dBi (81%) for a 0.6 mϕ and 0.4 mϕ antennas respectively verify this technique.

key words: *RLSA, planar antenna, BS, wave-guide array, radial wave-guide*

1. Introduction

Direct broadcast from a satellite (DBS) in 12 GHz band has started in Japan. Subscriber antennas for receiving DBS should possess high gain characteristics of about 32–37 dBi. A radial line slot antenna (RLSA) is a slotted waveguide planar array proposed for it. Predicted conductor loss of RLSA in this range of gain is less than 0.05 dB and almost negligible; high efficiency is expected in principle(1),(2).

A unique feature of RLSA is the use of a radially traveling wave as an excitation of slots. In a conventional RLSA, a radially inward traveling wave in a double-layered radial line has been employed; a almost uniform aperture illumination is obtainable by simply adopting slots with identical length and spacing. Antenna efficiency of the commercialized double-layered RLSA with uniform slots and uniform aperture illumination is more than 75% (33.0–36.3 dBi), which is about twice as high as that of the other planar antennas in this range of gain.(3) The defect in a double-layered RLSA is the relatively complicated waveguide structure.

A single-layered RLSA (SL-RLSA) is much more attractive in terms of structural simplicity.(4) It utilizes non-uniform slots which cancel the tapered aperture-illumination associated with a radially outward traveling wave excitation. The antenna efficiency of 70–81% has been realized for SL-RLSAs with the diameters of 0.3–0.6 m. Some of these antennas are now released for commercial use.(5) Uniform aperture illumination has been adopted in the design of these antennas. Major reduction of efficiency is due to termination loss. This loss becomes notable for smaller antennas and is no less than 20% for a 0.3 mϕ antenna. Recent study(6) suggests the efficiency enhancement by adopting non-uniform aperture illumination, which reduces the termination loss by using the conventional slot elements. As an different approach using novel slot elements, the matching spiral or matching slot have also been proposed to reuse the termination loss and reduce the noise temperature.

This paper presents the measured performances of the SL-RLSAs with non-uniform aperture illumination. Low-cost and mass-producible models of 0.2–0.6 m diameter are fabricated. The measured characteristics agree well with the prediction. The efficiency enhancement of about 10% is observed; the measured gain of 36.7 dBi (87%) and 32.9 dBi (81%), the axial ratio around 1 dB for a 0.6 mϕ and 0.4 mϕ antennas respectively verify this technique.

2. A Single-Layered RLSA

Figure 1 shows the structure of a single-layered RLSA. The power is fed at the center and transferred into rotationally symmetrical outward traveling wave. While propagating outward, part of the power is radiated from slots. Those slots, consisting of many pairs, each one of which is a unit radiator of circular polarization, are arrayed along a design spiral. S_ρ and S_ϕ indicate the spacings between adjacent slot pairs along the ρ and the ϕ directions, respectively. S_ρ is designed to be equal to guide wavelength λ_g while S_ϕ is determined arbitrarily. To suppress the grating lobes from the array, the waveguide is filled with dielectric material and λ_g is set to be smaller than λ_0.

A single-layered RLSA utilizes the outward traveling wave for excitation and has the simplest

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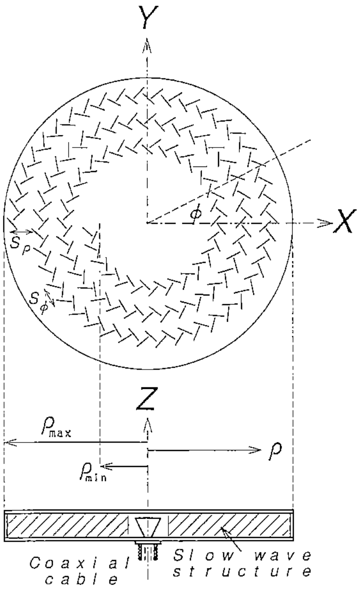

Fig. 1 A structure of single-layered RLSA.

structure. However, it has the disadvantage that the aperture field tends to be steeply tapered off if uniform slots are used, since the slot coupling accelerates the amplitude taper of the radially outward traveling wave. Slot coupling control for uniform aperture illumination was the most important technology in the history of a single-layered RLSA. This design is summarized first.(7) The basic concept is to adopt non-uniform slots which couple weakly and strongly in the inner and outer portions of the aperture, respectively. The slot coupling is maximized at outer position to compensate the unperturbed amplitude taper of $1/\sqrt{\rho}$. Slot lengths and spacings are varied over the aperture. The authors have established a theoretical method to realize the concept stated above.

First, the coupling between slots and the radial waveguide is formulated by full-wave analysis. The coupling factor $\alpha(>0)$ [1/m]and the slow wave factor $\zeta(<1)$ indicating the attenuation per unit length and the wavelength reduction of the inner field due to slot coupling, respectively, are predicted for given slot length L. In RLSA the coupling can not be increased arbitrarily since the rotational symmetry of the field is excessively perturbed. The measured maximum usable coupling factor α, denoted as $\alpha_{\max}$ hereafter, is about 15–25. In the next place, the coupling factor distribution $\alpha(\rho)$ required for uniform aperture illumination is introduced. In Fig. 2, dotted line shows the required coupling factor $\alpha(\rho)$ as a function of ρ. Finally, the slot length and the position are determined over the aperture. For the point at ρ, slot length L is determined to realize $\alpha(\rho)$. Then, the corresponding slow wave factor ζ is used to set the slot radial spacing S_ρ equal to the local guide wavelength $\lambda_g(=\zeta\cdot\lambda_0)$. This procedure is repeated to cover all the aperture. All the design procedure are carried out theoretically. RLSAs in various sizes were designed for practical use by this method. Figure 3 shows the predicted and measured (×) antenna efficiency and the termination loss as a function of antenna size. The predicted values are calculated by array theory. The termination loss is about 15–30% and becomes notable as the aperture diameter decrease. The sum of the termination loss and the antenna efficiency is a bit lower than 100%, and is equal to the aperture efficiency of finite element array with excitations errors due to mutual coupling. When the termination loss is notable, the uniform aperture illumination is no longer the optimum condition for high efficiency.

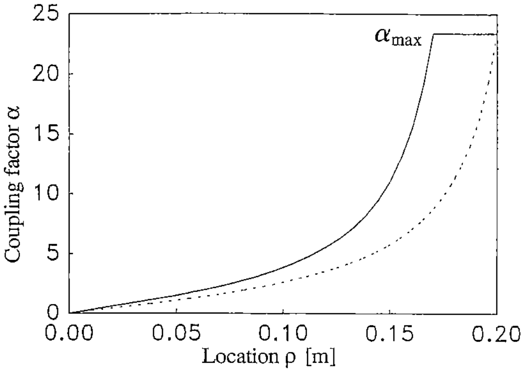

Fig. 2 Coupling factor distribution.
——— Non-uniform aperture illumination
········· Uniform aperture illumination

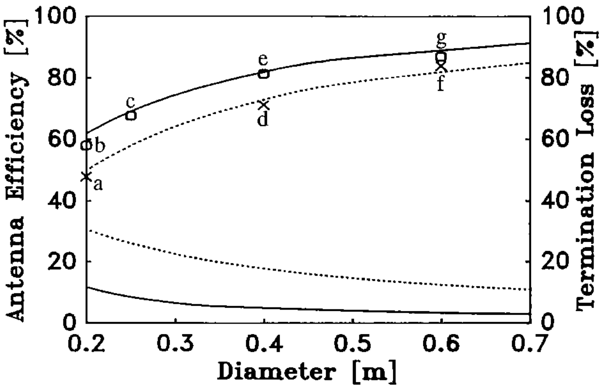

Fig. 3 Antenna efficiency and Termination loss.
——— Non-uniform aperture illumination (○: measured value)
········· Uniform aperture illumination (×: measured value)

3. Non-uniform Aperture Illumination

As a unique difficulty of RLSAs, slot coupling cannot be increased arbitrarily so as not to disturb the rotational symmetry of the inner field excessively.

Consequently, the termination loss power does not vanish in the design of uniform aperture illumination. For further enhancement of efficiency, the reduction of this loss is necessary and non-uniform aperture illumination minimizing the termination loss power have been proposed.(8)

Figure 2 shows coupling factor distribution of this new design. In non-uniform aperture illumination, the uniform slots with maximum coupling are used in outer part of the aperture. In the inner part, the coupling factor distribution is similar to that in uniform aperture illumination design. Calculus of variation stated below shows that this distribution is the optimum condition for maximizing gain under the limited coupling.(9),(10)

The continuous attenuation model due to slot coupling is considered. Under the assumption of the outward traveling wave operation, the following differential equation is obtained for the power density $P(\rho)$ of the inner field and the coupling factor $\alpha(\rho)$ in the radial wave-guide:(7)

$$\frac{d}{d\rho}(\alpha P(\rho))=-2\alpha(\rho)\rho P(\rho) \tag{1}$$

The incident power is normalized as:

$$2\pi\rho_{\mathrm{min}}P(\rho_{\mathrm{min}})=1 \tag{2}$$

where ρ_{min} is the position of the innermost slots. When Eq. (2) is substituted into Eq. (1), the aperture field density $E(\rho)$ is expressed in (3).

$$E(\rho)=\sqrt{\alpha(\rho)P(\rho)}=\frac{\sqrt{\alpha(\rho)}}{\sqrt{\rho}}\exp\left(-\int_{\rho_{\mathrm{min}}}^{\rho}\alpha(r)dr\right) \tag{3}$$

If the phase is uniform in the aperture, the antenna gain $G[\alpha]$ in the boresight is given as a functional of $\alpha(r)$:

$$G[\alpha]=\frac{\left(\int_{\rho_{\mathrm{min}}}^{\rho_{\mathrm{max}}}\int_0^{2\pi}E(\rho)\rho d\phi d\rho\right)^2}{2\pi\rho_{\mathrm{min}}P(\rho_{\mathrm{min}})} \tag{4}$$

where the denominator is 1 from Eq. (2). The condition of the maximum gain is given as:

$$J[u]=\int_{\rho_{\mathrm{min}}}^{\rho_{\mathrm{max}}}\sqrt{\rho u'}\exp(-u)d\rho\rightarrow \text{maximum} \tag{5}$$

$$u(\rho)=\int_{\rho_{\mathrm{min}}}^{\rho}\alpha(r)dr \tag{6}$$

where ρ_{max} is the position of the outermost slots. Since the slot coupling is limited, following constraint exists:

$$0\leqq u'(\rho)\leqq\alpha_{\mathrm{max}} \tag{7}$$

Equations (5) and (7) are solve by the calculus of variations. The augmented function is:

$$F[u]=-\sqrt{\rho u'}\exp(-u)+p_1(y_1^2-u')$$
$$+p_2(y_2^2+u'-\alpha_{\mathrm{max}}) \tag{8}$$

where p_1, p_2 are Lagrange multipliers, and y_1, y_2 are the extra variables. The Euler-Lagrange equation is shown:

$$\frac{\partial F}{\partial u}-\frac{d}{d\rho}\left(\frac{\partial F}{\partial u'}\right)=0 \tag{9}$$

This Euler-Lagrange equation gives three possibilities of the piecewise continuous function for $u'(\rho)$.

$$\text{(I)}\ \ p_1=p_2=0;\ u'(\rho)=\frac{\rho}{K-\rho^2} \tag{10}$$

$$\text{(II)}\ \ y_1=0, p_2=0;\ u'(\rho)=0 \tag{11}$$

$$\text{(III)}\ \ y_2=0, p_1=0;\ u'(\rho)=\alpha_{\mathrm{max}} \tag{12}$$

At the junction between two of these functions, if there are any, the first and the second Erdmann-Weierstrass corner conditions must be satisfied, which read as

① $\frac{\partial F}{\partial u'}\left(=-\frac{1}{2}\sqrt{\frac{\rho}{u'}}\exp(-u)-p_1+p_2\right)$

is continuous at a corner. (13)

② $-F+u'\frac{\partial F}{\partial u'}\left(=\frac{1}{2}\sqrt{\rho u'}\exp(-u)-p_1y_1^2\right.$

$\left.-p_2(y_2^2-\alpha_{\mathrm{max}})\right)$ is continuous at a corner.

(14)

From Eqs. (7) and (13), the possible and non-trivial solution is the combination of type (I) and (III) with one inflection point $\rho=\rho_{\mathrm{Inf.}}$.

$$u'(\rho)=\begin{cases}\dfrac{\rho}{K-\rho^2} & (\rho_{\mathrm{min}}\leqq\rho\leqq\rho_{\mathrm{Inf.}})\\ \alpha_{\mathrm{max}} & (\rho_{\mathrm{Inf.}}\leqq\rho\leqq\rho_{\mathrm{max}})\end{cases} \tag{15}$$

This result is also valid in the case of no inflection point by imposing $\rho_{\mathrm{Inf.}}=\rho_{\mathrm{min}}$ or ρ_{max}. By applying the first and the second Erdmann-Weierstrass conditions, we have

$$u'(\rho_{\mathrm{Inf.}})=\alpha_{\mathrm{max}} \tag{16}$$

and

$$K=\frac{\rho_{\mathrm{Inf.}}}{\alpha_{\mathrm{max}}}+\rho_{\mathrm{Inf.}}^2 \tag{17}$$

As a result of substitution Eq. (15) into Eq. (5), the original problem is reduced to find the maximum of $J(\rho_{\mathrm{Inf.}})$ as a function of $\rho_{\mathrm{Inf.}}$, which imposes the following differential equation:

$$\frac{dJ}{d\rho_{\mathrm{Inf.}}}=0 \tag{18}$$

This is written in the transcendental equation as follows.

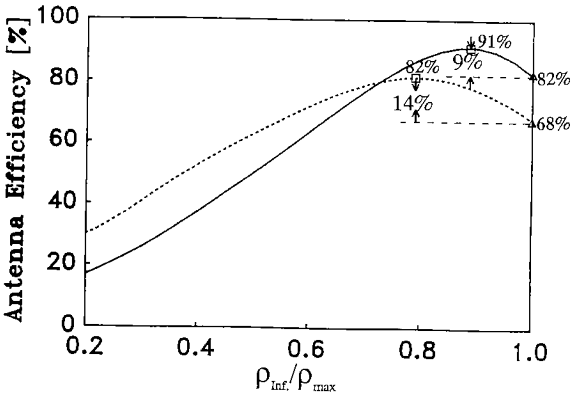

Fig. 4 Antenna efficiency varied the inflection point.
——— 0.6 m diameter antenna
········ 0.3 m diameter antenna
☐: Non-uniform aperture illumination
△: Uniform aperture illumination

$$2\alpha_{\max} \exp\left(\alpha_{\max}\rho_{\text{Inf.}}\right) \int_{\rho_{\text{Inf.}}}^{\rho_{\max}} \sqrt{\rho} \exp\left(-\alpha_{\max}\rho\right) d\rho - \sqrt{\rho_{\text{Inf.}}} = 0 \qquad (19)$$

The solution $\rho_{\text{Inf.}}$ of Eq. (19) maximizes J.

The coupling factor distribution $\alpha(\rho)$ is given from Eqs. (15),(17) as

$$\alpha(\rho) = \begin{cases} \dfrac{\rho}{\dfrac{\rho_{\text{Inf.}}}{\alpha_{\max}} + \rho_{\text{Inf.}}^2 - \rho^2} & (\rho_{\min} \leqq \rho \leqq \rho_{\text{Inf.}}) \\ \alpha_{\max} & (\rho_{\text{Inf.}} \leqq \rho \leqq \rho_{\max}) \end{cases} \qquad (20)$$

where $\rho_{\text{Inf.}}$ and $\alpha_{\max}$ are the location of inflection point defined by Eq. (19) and the maximum coupling factor, respectively. The inflection point $\rho_{\text{Inf.}}$ that is calculated by the continuous model in Eq. (19) is 0.266 m for 0.6 mϕ and 0.118 m for 0.3 mϕ.

To confirm the theory developed by using the continuous attenuation model, we calculate the antenna efficiency for various position of the inflection point $\rho_{\text{Inf.}}$ using array theory.(8) Figure 4 shows the predicted results for 0.3 mϕ and 0.6 mϕ antennas. The results for $\rho_{\text{Inf.}}/\rho_{\max}=1$ correspond to ones for uniform illumination design; the predicted efficiency of 82% (0.6 mϕ) and 68% (0.3 mϕ) reasonable agrees with measured one of 81% and 70%, respectively. In this figure, the optimum $\rho_{\text{Inf.}}$ are 0.271 m for 0.6 mϕ and 0.122 m for 0.3 mϕ, and are in fine agreement with the results from the continuous model. The maximum antenna efficiency predicted in this new design (☐) is 91% and 81% for the diameter of 0.6 m and 0.3 m respectively. These are about 9% (0.6 mϕ)-13% (0.3 m ϕ) higher than one for uniform aperture illumination ($\rho_{\text{Inf.}}/\rho_{\max}=1$: △). The optimized inflection point which is calculated by array theory as a function of antenna diameter is presented in Fig. 5. The ratio $\rho_{\text{Inf.}}/\rho_{\max}$ approaches to unity as the antenna diameter increases. It indicates that uniform aperture illumination sufficiently reduces the termination loss power and is almost optimum for larger antennas. The continuous attenuation model simulates the array beautifully in this case. Figure 6 shows theoretical aperture amplitude distributions for the uniform (a) and non-uniform illumination (b), respectively. The illumination (b) is uniform inside and tapered outside of $\rho_{\text{Inf.}}$. The aperture uniformity is a little bit degraded at the periphery of the aperture, while the illumination level in the uniform region increases and the termination loss is reduced. As the latter effect prevails the former, the antenna efficiency is enhanced. Figure 7 shows the predicted radiation pattern. The pattern as a whole is similar to that of uniform illumination design. As compared with uniform aperture illumination, the envelopes of sidelobes of principal polarization are a little bit lower due to illumination taper. The antenna efficiency and the termination loss of this type of illumination as a function of antenna diameter are

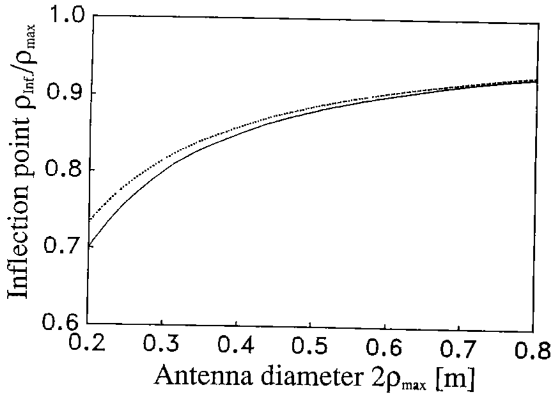

Fig. 5 Location of the optimum inflection point.
——— Array theory
········ Continuous attenuation model

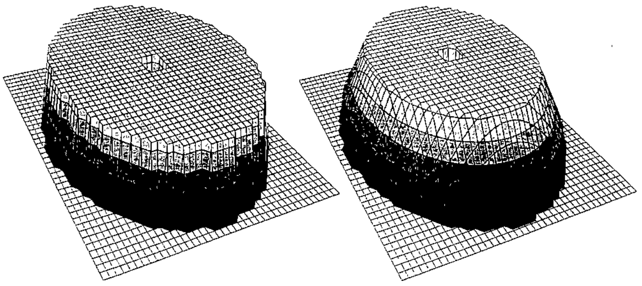
(a) (b)

Fig. 6 Theoretical aperture amplitude distribution.
(a) Uniform aperture illumination
(b) Non-uniform aperture illumination (3 dB/div)

compared with those uniform illumination in Fig. 3. The efficiency enhancement becomes large as the diameter becomes small.

Other important technique to be jointly used with non-uniform aperture illumination is the suppression of cross polarization. In RLSA, the sequential array arrangement is adopted and the axial ratio of the array is better than that of a element slot pair. In the conventional design of uniform illumination, the slot arrangement was determined by neglecting the mutual coupling and the boresite axial ratio still remains acceptable. In this new design, on the other hand, slot coupling is increased over the aperture and mutual coupling effects, especially upon the axial ratio must be taken into account. Figure 8 shows the distribution of axial ratio of a slot pair along ρ. The axial ratio in non-uniform aperture illumination is considerably degraded (~6 dB) if strong mutual coupling is neglected in the slot pair design (design A). If the distance of slots in a pair is re-adjusted (design B), the axial ratio of an element slot pair less than 1 dB is realized as is shown in Fig. 8.

4. Experiments

Based upon the above design, the model antennas were fabricated. The antenna parameters are listed in Table 1. Diameter is 0.2–0.6 mϕ. Their efficiency is compared with the conventional ones with uniform illumination. No absorber is used and the small but still existing residual power is reflected at the conducting wall in these models. In every model, the reflection

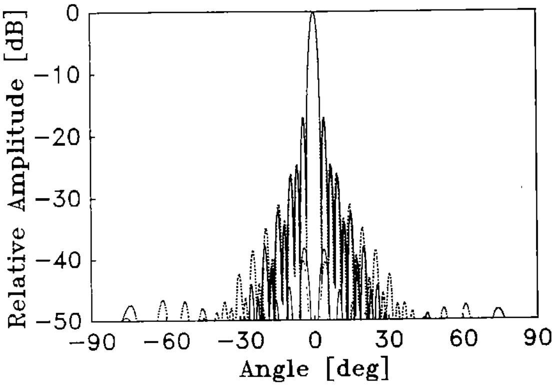

Fig. 7 Theoretical radiation pattern for 0.6 m diameter antenna.
——— Non-uniform aperture illumination
········ Uniform aperture illumination

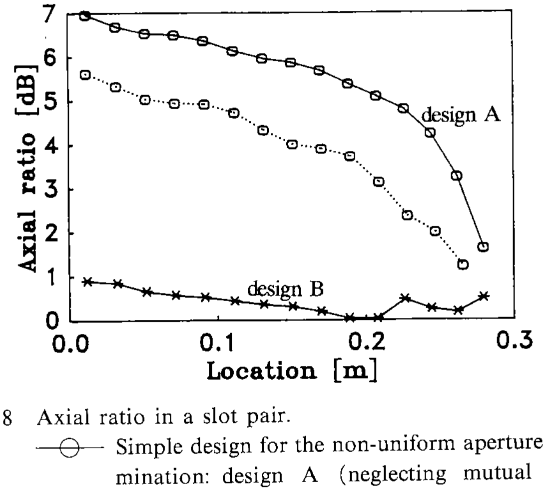

Fig. 8 Axial ratio in a slot pair.
—⊖— Simple design for the non-uniform aperture illumination: design A (neglecting mutual coupling)
···⊖··· Simple design for the uniform aperture illumination (neglecting mutual coupling)
—×— Improved design for the non-uniform aperture illumination: design B (considering mutual coupling)

Table 1 Design parameters of model antennas.

Antenna	Diameter [m]	Inflection point [m]	Aperture distribution
a	0.20	0.100	uniform
b	0.20	0.078	non-uniform
c	0.25	0.095	non-uniform
d	0.40	0.200	uniform
e	0.40	0.167	non-uniform
f	0.60	0.300	uniform
g	0.60	0.266	non-uniform

Permittivity: εr=1.53 Waveguide height: 3.75mm

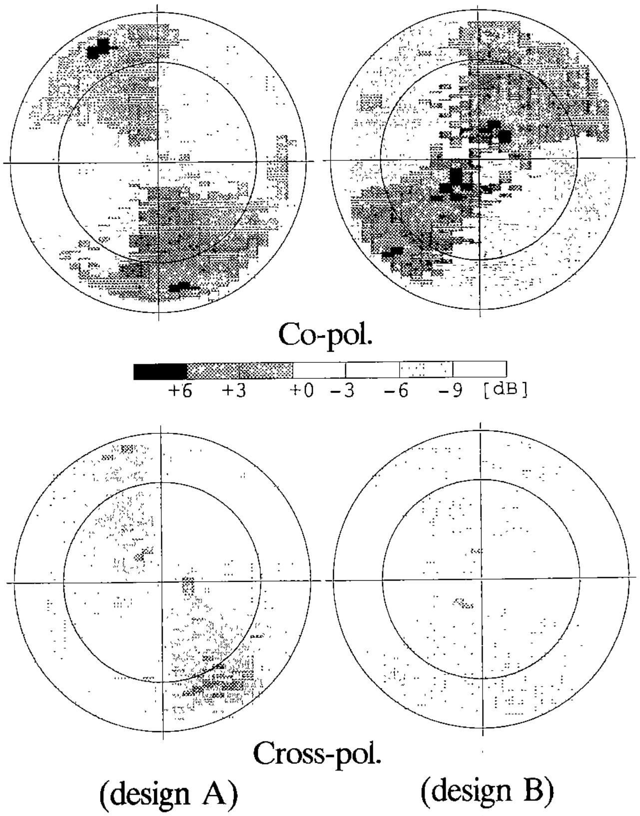

Fig. 9 Aperture amplitude distribution of non-uniform design.
(A) Simple design (neglecting mutual coupling)
(B) Improved design (considering mutual coupling)

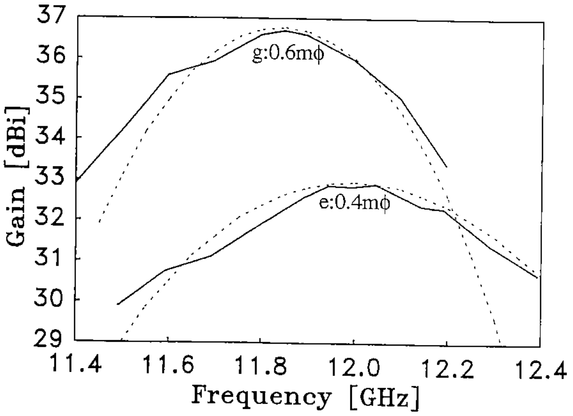

Fig. 10 Measured gain of non-uniform aperture illumination.
——— Measured gain ········ Predict gain

at input port is less than −20 dB. In order to compare design A and design B, Fig. 9 shows examples of aperture amplitude distribution of principal and cross polarization at the design frequency. As for the co-pol. fields, the uniformity along the ρ direction is satisfactory for both design. The rotational symmetry is not perfect but is better for the improved design B than for design A. Noteworthy is that the cross polarization in the improved design B is well suppressed and is much smaller than that in design A. The radiation pattern is symmetrical and the first sidelobe level of about −17 dB indicates the normal antenna operation. The grating lobes, to the endfire direction, are suppressed to less than −35 dB, which does not degrade the antenna gain. The measured gain of the model antennas ($D=$ 0.4 mϕ, 0.6 mϕ) is shown in Fig. 10. The calculated one is also presented, which is in fine agreement with the experiment. Both the gain and bandwidth are fully predictable theoretically. The axial ratio is excellent and is below 1 dB.

Figure 3 includes the measured antenna efficiency of model antennas as a funcion of antenna gain. They are plotted in Fig. 3 by ○ and × for the non-uniform and uniform illumination, respectively. The experiments agree beautifully with theoretical values. Antenna efficiency increases as the diameter becomes larger since the termination loss becomes smaller. The value of efficiency enhancement is 11% (0.2 mϕ), 9% (0.4 mϕ), 6% (0.6 mϕ). The enhancement agrees well with prediction. The efficiency of 87% (0.6 mϕ) and 81% (0.4 mϕ) are observed for model antennas.

5. Conclusion

The efficiency enhancement by the non-uniform aperture illumination is realized. The efficiency of 81% (0.4 mϕ), 87% (0.6 mϕ) are observed for model SL-RLSAs. The high potential of SL-RLSA as well as the validity of the non-uniform aperture illumination design is demonstrated. For smaller antenna, this new design is indispensable. The matching spiral has also been poposed to reuse the termination loss power and reduce the noise temperature.(11) This will be used jointly in future design of extremely smaller antennas, since the rotational symmetry is not perfect due to strongly coupling slot elements in non-uniform aperture illumination design.

Acknowledgment

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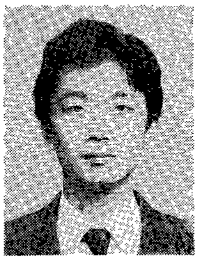

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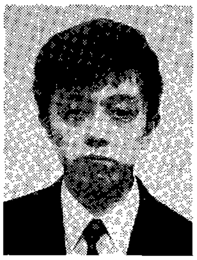

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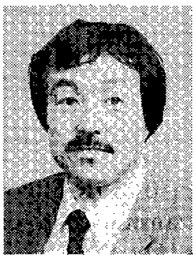

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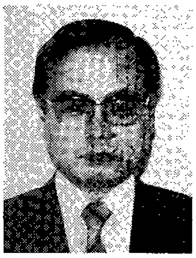

Naohisa Goto was born in Utsunomiya, Japan, on June 8, 1935. He received the B.S., M.S., and D.E. degress from Tokyo Institute of Technology, Tokyo, Japan, all in electrical engineering, in 1959, 1961 and 1964, respectively. From 1966 to 1968 he was an Associate Professor at the Training Institute for Engineering Teachers, Tokyo Institute of Technology. From 1968 to 1975 he was an Associate Professor at Chiba University, Chiba, Japan. From 1975 to 1980 he was an Associate Professor and since 1980 he has been a Professor at Tokyo Institute of Technology. He has been engaged in research and development of array antennas. He has developed a planar slotted waveguide array called "radial line slot antenna," and a ring patch antenna for dual frequency use calld" self-diplexing antenna."