IEICE TRANS. COMMUN., VOL. E78-B, NO. 3 MARCH 1995

PAPER

Enhancement of Band-Edge Gain in Radial Line Slot Antennas Using the Power Divider
—A Wide-Band Radial Line Slot Antenna—

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SUMMARY A Radial Line Slot Antenna (RLSA) is a planar antenna for DBS reception [1]. It is a kind of slotted waveguide arrays. The conductor loss is so small that high efficiency is expected irrespective of the aperture diameter. On the other hand, since a RLSA utilizes the traveling waves, the frequency bandwidth is limited by the long line effect [2], particularly for a larger antenna. A new Wide-Band RLSA (WB-RLSA) is proposed which halves the waveguide length and widens the frequency bandwidth [3]. This paper presents the design and experimental results of a model antenna. A gain of 33.7 dBi is measured at the edge of 800 MHz bandwidth and its high potential is demonstrated.
key words: *RLSA, planar antenna, hybrid structure, power divider, wide-band, waveguide, long line effect*

1. Introduction

A radial line slot antenna (RLSA) is a slotted waveguide planar array developed for receiving a direct broadcast from a satellite (DBS) with 300 MHz bandwidth. Since it utilizes a waveguide as a feed circuit [4], it is free of conductor loss and high efficiency is theoretically expected no matter how large the aperture diameter is. Now a single-layer RLSA (SL-RLSA) [5] realizes the efficiency of more than 87% and a double-layer RLSA (DL-RLSA) [6] has more than 80% efficiency. RLSAs is very attractive from the manufacturing point of view as well; the structure is simpler than those of any other planar antennas.

Nowadays wide-band communications are becoming popular with the advance of an information-oriented society and the wide-band antenna system is required as well. The enhancement of the gain at the edge of the frequency bandwidth, called "the band-edge gain" hereafter, is now urgent requirement.

The high potential of RLSA suggests the application to wide-band communications using high-gain antennas. Though RLSAs are the leading candidates for realizing high gain and high efficiency, they suffer from bandwidth limitation as is always the case with traveling wave antennas. Since the frequency bandwidth is inversely proportional to the feed line length, the bandwidth of the large aperture RLSA is narrow. In order to apply large aperture RLSA for wide-band communications, it is necessary to enhance the band-edge gain.

This paper attempts to widen the bandwidth of RLSA using a novel component of power divider, and enhances its band-edge gain. First, we discuss the long line effect in conventional RLSA and show that only the peak gain increases with the antenna diameter while the band-edge gain decreases after taking its maximum at some diameter. Then the structure of a new WB-RLSA is shown to remedy it. It is a hybrid structure of SL- and DL-RLSA; widening the bandwidth is realized by halving the feed line length. We estimate the band-edge gain enhancement by the array analysis, which takes the slot coupling and the termination loss into account. Ideal power divider is assumed in this calculation. A prototype antenna of 0.6 mϕ is fabricated and measured to confirm the design of maximizing the band-edge gain for 800 MHz bandwidth as an example. The effectiveness of WB-RLSA is verified and its high potential is demonstrated by experiment.

2. Single and Double Layer RLSA

Figure 1 shows a structure of radial line slot antenna (RLSA). The operation of a SL-RLSA is summarized first. The power is fed at the center by a coaxial transmission line and is transferred into a rotationally symmetrical outward traveling wave. Slots on the top plate consisting of many pairs, each one of which is a unit radiator of circular polarization, are arrayed along a design spiral. The waveguide is filled with dielectric to suppress the grating lobes from the array. The slot design is performed to satisfy the uniformity of the aperture field distribution at the design frequency; the slot length becomes longer and the pitch S_ρ between slot pairs in radial direction becomes shorter toward the aperture periphery. S_ρ is determined analytically, while S_ϕ is determined arbitrarily. In DL-RLSA, three plates compose a twofold radial line waveguide. Slots cut on the top plate is excited by

Manuscript received May 30, 1994.
Manuscript revised August 19, 1994.
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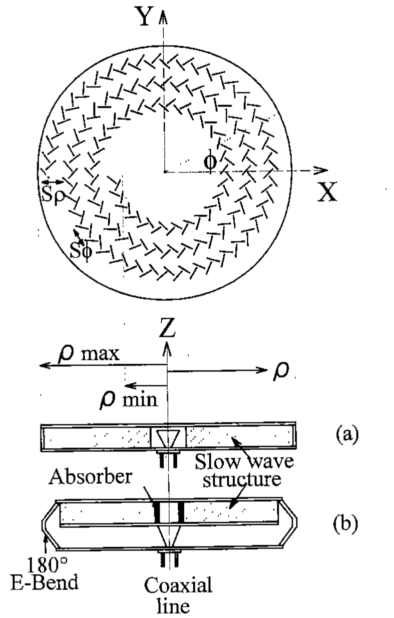


Fig. 1 Radial line slot antennas.
(a) SL-RLSA.
(b) DL-RLSA.

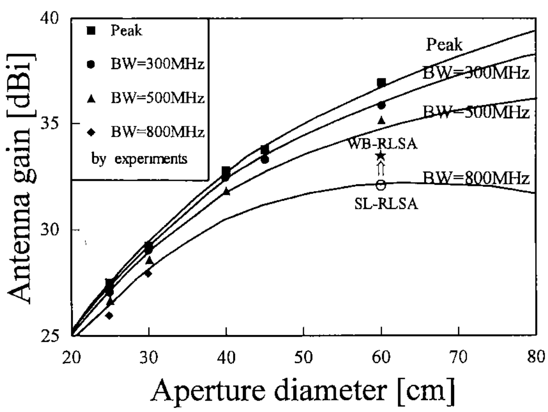


Fig. 2 Band-edge gains of SL-RLSA vs. aperture diameter. solid line: calculated results.

a radially inward traveling wave transferred by the E-bend at the outermost edge of radial waveguide.

Here, the long line effect is explained. If the frequency shifts from the design, the guide wavelength of TEM wave varies and an aperture phase distribution which consists of the phase of the inner field sampled at the slot positions is deviating from the uniform one. Since the change of phase is proportional to the propagation length, the large aperture antenna becomes narrow banded.

The band-edge gain of a SL-RLSA is calculated as a function of the antenna diameter and is presented in Fig. 2. In the figure, the peak gain is the maximum gain within the frequency bandwidth BW and the band-edge gain corresponds to the gain at the edge of

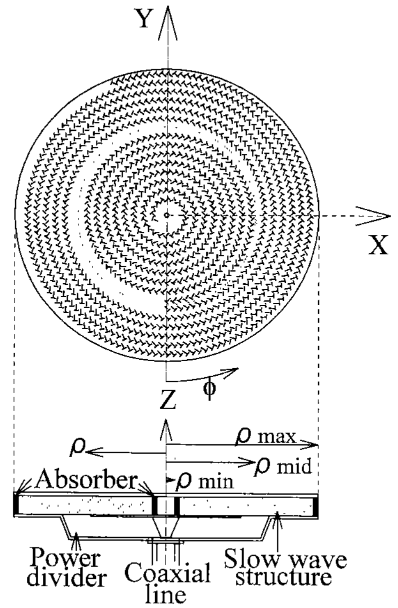


Fig. 3 Wide band radial line slot antenna.

$f=f_0 \pm BW/2$ where the center frequency and the bandwidth are f_0 and BW respectively. The analysis takes the array factor, the coupling between slots and TEM wave in parallel plate waveguide and termination loss into account. It is taken up in 4.2 in detail again. The experimental results are also plotted in Fig. 2 and they are in good agreement with the analysis. The peak gain increases with the aperture diameter while the band-edge gain of 800 MHz bandwidth does not increase with it. The long line effect is dominant and is a disadvantage of traveling wave antennas. The calculated results ★ of 800 MHz band-edge gain of this novel WB-RLSA, is denoted in the same figure. Its calculation method will be discussed in 4.3.

3. Wide-Band RLSA

Figure 3 shows the basic structure of a WB-RLSA. The bandwidth of RLSA is increased by halving the feed line length. The aperture consists of the two regions; the inner part is a DL-RLSA and the outer part is a SL-RLSA. The power is fed at the center by a coaxial cable and is transferred into a rotationally symmetrical outward traveling wave in the lower waveguide. At the divider, the power splits into two components; radially outward and inward traveling waves in the upper waveguide. Both traveling waves excite the slots on the top plate. The upper waveguide is filled with dielectric to suppress the grating lobes from the array. Slots in the inner and the outer regions are excited by inward and outward traveling wave respectively. They are arranged along the reverse spiral. The slot length and the radial spacings between pairs are varied over the aperture as discussed in 4.2.

The residual power at the innermost and the outermost terminal is dissipated by the absorber. The significance of this hybrid structure is that the feed line length of each region is about one half of the aperture radius and that the frequency bandwidth would be widened. This design is general in that it is applicable for RLSA with arbitrary bandwidth requirement, arbitrarily polarization and arbitrarily size. In this paper, we apply this design to 0.6 mϕ circularly polarized RLSA to maximize the band-edge gain for 800 MHz bandwidth as an example.

4. Antenna Design

4. 1 Design of Power Divider

The power divider to be placed in the middle of the radial line is a novel component in WB-RLSA. The finite element method FEM analysis is conducted to realize low reflection and the specified power dividing ratio.

The analysis model is shown in Fig. 4. Since ρ_{mid}, the radial distance of the divider, is large compared with the wavelength, the curvature in ϕ direction is neglected; a two-dimensional structure is considered. The waveguide heights D_u, D_l and the slit width W_1 should be less than 1/2 wavelength for suppression of undesired higher-order transmission modes others than a TEM wave in the waveguide. The thickness T of the inner disk is set to be 2 mm in view of mechanical strength. The relative permittivity ε_r of 1.59 is assumed. The design objectives are as follows:

(1) The reflection from the divider (P_r/P_i) should be sufficiently small.

(2) The desired power dividing ratio ($A_{in}=P_1/P_i$) should be realized. In principle, the power dividing ratio A_{in} should be equal to $(\rho_{\mathrm{mid}}/\rho_{\mathrm{max}})^2$ to realize uniform illumination.

The dominant design parameters are the width of the slit W_1 and the taper angle of the wall W_2. In FEM, linear triangular elements are adopted to formulate a set of linear equations about the potentials at all nodes. The mesh size of 1/20 wavelength is adopted to obtain sufficient convergence for reflection coefficient.

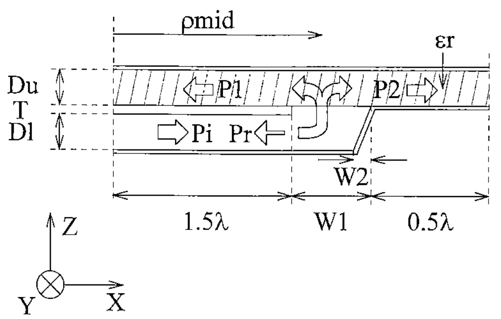


Fig. 4 Analysis model of power divider for WB-RLSA.

Figures 5(a), (b) show the contour map of the reflection coefficient and the power ratio of the inward traveling wave A_{in} as functions of W_1 and W_2 respectively. When $W_1=7.7$ mm and $W_2=2.6$ mm, the reflection below -30 dB is realized and A_{in} is about 0.36 from those figures. This analysis demonstrates the reflection below -25 dB is feasible provided $0.33 \leqq A_{in} \leqq 0.38$ is satisfied. In other words, A_{in} must be chosen in this range and can not be designed arbitrarily. The position of the divider ρ_{mid} should also be chosen carefully because optimum ρ_{mid} which maximize the band-edge gain is determined as a function of A_{in} in 4.3. Anyway $A_{in}=0.36$, $W_1=7.7$ mm and $W_2=2.6$ mm are the proper choice in terms of reflection suppression.

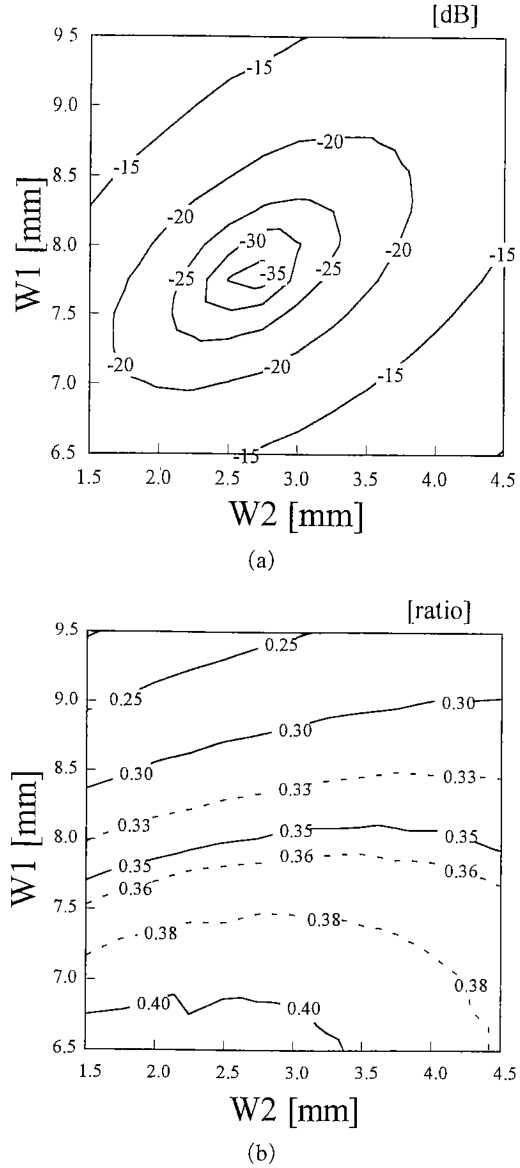


Fig. 5 (a) Reflection from the power divider as functions of W_1 and W_2 ($f=11.85$ GHz).
(b) Power dividing ratio as functions of W_1 and W_2 ($f=11.85$ GHz).

In addition, the authors already confirm that the reflection coefficient and power dividing ratio are stable over more than 1 GHz by calculation and experiment.

4.2 Slot Design for Uniform Illumination

Now we explain the slot design for uniform aperture illumination. Since a RLSA utilizes radially traveling waves, slots with non-uniform length are adopted. On the basis of the continuous attenuation model [5], the slot coupling of each part is determined. First, the coupling factor α is introduced as the decay factor of the traveling wave in the guide [7]; slot coupling causing radiation gives rise to cylindrical waves with exponential decay in the form of $e^{\pm\rho\alpha}/\rho$ where $\pm$ sign corresponds to radially inward and outward traveling wave, respectively. Non-uniform slot length results in that the coupling factor varies with the position. The coupling factor $\alpha_S(\rho)$ at ρ on the single-layer part is given as [5]:

$$\alpha_S(\rho)=\frac{\rho}{\dfrac{\rho_{\max}}{\alpha_{\max}}+\rho_{\max}^2-\rho^2}=\frac{\rho}{\dfrac{\rho_{\max}^2-t_S\cdot\rho_{\mathrm{mid}}^2}{1-t_S}-\rho^2} \qquad (1)$$

while, the coupling factor $\alpha_D(\rho)$ on the double-layer part is given as:

$$\alpha_D(\rho)=\frac{\rho}{\dfrac{\rho_{\min}}{\alpha_{\min}}-\rho_{\min}^2+\rho^2}=\frac{\rho}{\dfrac{t_D\cdot\rho_{\mathrm{mid}}^2-\rho_{\min}^2}{1-t_D}+\rho^2} \qquad (2)$$

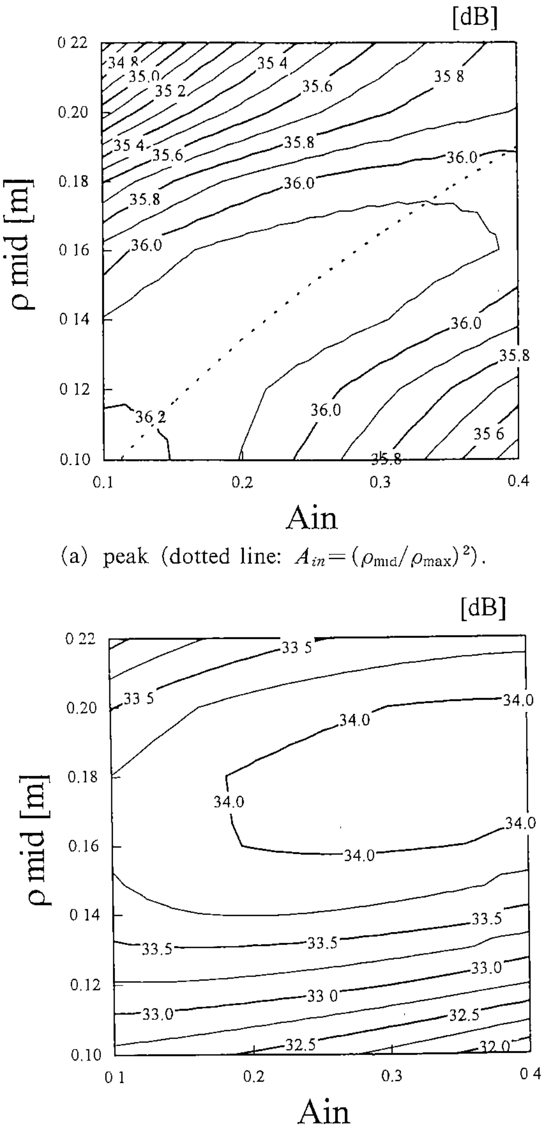
where t_S and t_D correspond to the power dissipated at the outermost and innermost termination, respectively. The parameters $\rho_{\max}$, ρ_{mid} and $\rho_{\min}$ are the antenna radius, the position of the divider and the innermost slots respectively. The coupling factors at $\rho=\rho_{\max}$ and at $\rho=\rho_{\min}$ are expressed by $\alpha_{\max}$ and $\alpha_{\min}$ respectively.

The coupling between slots and TEM wave in the waveguide can not be increased arbitrarily. Furthermore in RLSA, we must keep the coupling smaller so as not to excessively perturb the rotational symmetry of the field. The measured maximum usable coupling factor is about 15-25 [1/m] [2]. The factor $\alpha_S(\rho)$ takes its maximum at $\rho_{\max}$ and is denoted by $\alpha_{\max}$. On the other hand, the factor $\alpha_{\min}$ at $\rho_{\min}$ in the double layer part is chosen arbitrarily within the limits of the coupling factor. Once ρ_{mid} is specified, $\alpha_S(\rho)$ and $\alpha_D(\rho)$ are determined in (1) and (2) provided $\alpha_{\min}$ is determined so as to maximize the antenna gain. This is the design of slot coupling distribution for the uniform illumination in WB-RLSA.

After specifying the slot coupling distribution over the aperture, a rectangular waveguide model with periodic boundary wall [5], [8] composed of two identical slots is analyzed by Moment Method and the slot length and the slot spacings are determined over the aperture, where the perturbation due to the slot coupling is taken into account. The slot pairs thus designed are arrayed spirally. As shown in Fig. 3, annular blocking exists just above the divider, since slots in two regions are arrayed along spirals in reverse direction.

4.3 Enhancement of Band-Edge Gain

The enhancement of the band-edge gain for this wide-



(a) peak (dotted line: $A_{in}=(\rho_{\mathrm{mid}}/\rho_{\max})^2$).

(b) 800 MHz.

Fig. 6 Gain as functions of the inward power ratio and the location of the divider ($f=11.85$ GHz).

band structure is estimated and the location of power divider $\rho_{\rm mid}$ as well as the power dividing ratio A_{in} is optimized. During this calculation, the slots are designed according to the rules stated above and the reflection from the power divider is assumed to be zero. The inward and the outward power ratio A_{in} and A_{out} are related by $A_{in}+A_{out}=1$. The calculation of gain utilizes the slot excitation coefficients given by the Moment Method. The simulation takes the termination loss t_S and t_D at $\rho_{\rm min}$ and $\rho_{\rm max}$ into account as well. Moreover the calculation of gain reflects the effect of the annular blocking region just above the divider as well.

Figures 6(a), (b) show the peak gain and the 800 MHz band-edge gain for the aperture with 0.6 mϕ at 11.85 GHz respectively. In these figures, the left-and-downward portion ($\rho_{\rm mid}=\rho_{\rm min}=0.02$ m, $A_{in}=0$) corresponds to a SL-RLSA. Since the peak gain takes its maximum when the aperture illumination is uniform, relatively high gain is realized for $\rho_{\rm mid}/\rho_{\rm max}=\sqrt{A_{in}}$ which is indicated by a dotted line in Fig. 6(a). More precisely, the peak gain is larger for smaller values of $\rho_{\rm mid}$ and A_{in}; SL-RLSA has the highest gain, since blocking area above the power divider increases with $\rho_{\rm mid}$ and causes the decrease of the antenna gain. Therefore the left-down part; almost a SL-RLSA in the figure, takes the higher gain. On the contrary, the contour of 800 MHz band-edge gain is running somewhat horizontally in Fig. 6(b); the band-edge gain depends upon $\rho_{\rm mid}$ rather than A_{in}. In the figure, the band-edge gain takes its maximum at $\rho_{\rm mid}\approx 0.18$ m, which is larger than $\rho_{\rm max}/2=0.15$ m. It is noted that the band-edge gain of 34.0 dBi is realized for $\rho_{\rm mid}=0.18$ m, $A_{in}=0.36$, which is 1.5 dB higher than that of SL-RLSA as indicated in Fig. 2 by ⊙ and ★ respectively. This design of $\rho_{\rm mid}$ and A_{in} is also the best choice in terms of low reflection of power divider as shown in Fig. 5. In other words, keeping the antenna peak gain being relatively large, we can enhance the 800 MHz band-edge gain in this design. At this time, reflection from power divider can be suppressed by finding the optimum W_1 and W_2 in Fig. 5.

Table 1 Antenna parameters.

Design frequency;f0	11.85[GHz]
Relative permittivity; ε r	1.59
Antenna diameter;2ρmax	0.6[m]
Power divider radius; ρmid	0.182[m]
Blocking radius; ρmin	0.02[m]
Inward power ratio;Pi	0.36
Outward power ratio;Po	0.64
Lower waveguide height;Dl	6.2[mm]
Upper waveguide height;Du	4.0[mm]
Thicness of the disk;T	2.0[mm]
Number of slots;N	2136

The parameters of the antenna which has the excellent characteristics in terms of the band-edge gain are shown in Table 1. The reflection from power divider is less than −20 dB from Fig. 5(a) at 11.85 GHz when these parameters in Table 1 are used. The blocking occupies 4% of the aperture in the model antenna. The termination loss of both edges of this antenna is larger than the conventional type RLSA; the sum of them calculated from Eqs. (1) and (2), is about 15% at design frequency. The model antenna as indicated in Table 1 is fabricated and tested by experiment.

4.4 Model Antenna Design

From Eqs. (1), (2), we can obtain the coupling factor for an aperture with 0.6 mϕ, as a function of the radius in Fig. 7(a) as an example. Here, $\rho_{\rm mid}$ is determined from the relation $A_{in}=0.36=(\rho_{\rm mid}/\rho_{\rm max})^2$. Figure 7 (b) depicts the slot length as a function of the radius. It is clearly recognized that the slot coupling increases with the slot length. The slot length increases from the divider toward the aperture outermost edge and approaches the resonance length of about 11.5 mm. On the contrary in the double-layer part, from the divider to the aperture center, it is almost uniform. Figure 7

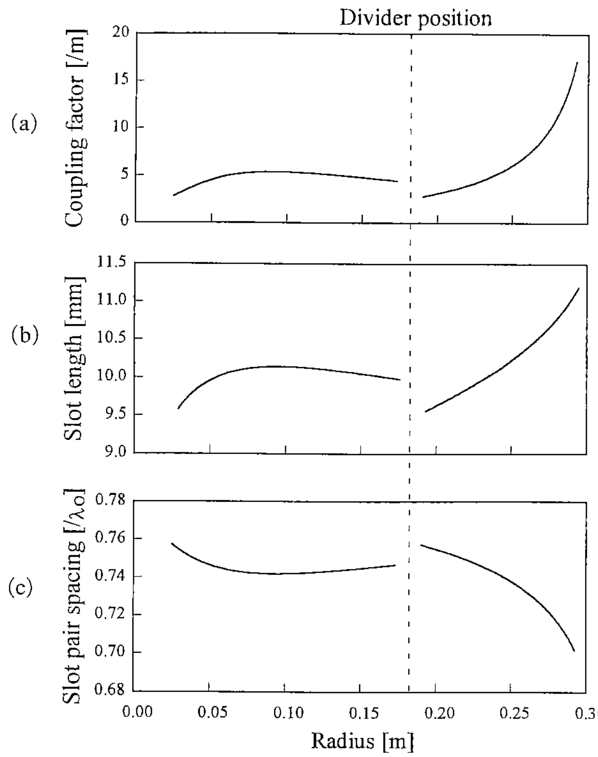


Fig. 7 (a) Radius vs. coupling factor.
(b) Radius vs. slot length.
(c) Radius vs. slot pair spacing in radial direction.

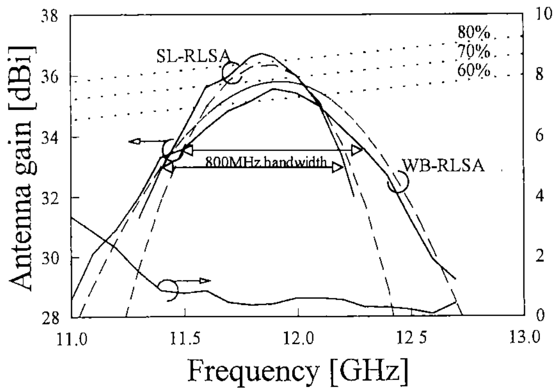


Fig. 8 Antenna gain, efficiency and axial ratio.
solid line: calculated results.
broken line: experimental results.
dotted line: aperture efficiency.

(c) depicts the radial spacing S_ρ between the slot pairs as a function of the position. The value $S_\rho=\lambda_0/\sqrt{\varepsilon_r}$ is adopted on the divider. It decreases from the divider toward the aperture outermost edge. On the contrary, it is almost uniform in the inner part of the aperture. The change in S_ρ reflects the slow-wave effect of wavelength; since the perturbation of slots is stronger as the slot length is longer, the slot radial spacing is smaller for the longer slot. Then in the double-layer part, since the slot length is almost uniform, the slot radial spacing is almost uniform as well. From Figs. 7 (b) and (c), the change in the length and the spacing of slots are small in the double layer part of aperture; uniform slots with equal spacings may be used there. On the other hand, the non-uniform length slot design is inevitable in the single layer part of the aperture.

The practical design of slot plate is shown in Fig. 3. The frequency characteristic of antenna gain in Fig. 8 is calculated in this model antenna using those design parameters. The peak gain of 35.5 dBi, which is 1.5 dBi lower than that of a conventional RLSA, is predicted; while the 800 MHz band-edge gain of 34.0 dBi, which is 1.5 dBi higher than that of a conventional antenna, is expected.

5. Experimental Results

5.1 Input VSWR

A WB-RLSA is fed by a coaxial transmission line through an N-type connector. The experimental result of the antenna return loss is presented in Fig. 9. In frequency range of 11.5–12.5 GHz, the reflection less than -15 dB is realized. This reflection consists of the contribution from the coax-to-radial line adapter and power divider. The above result confirms the validity of the design of feed circuit with the power divider.

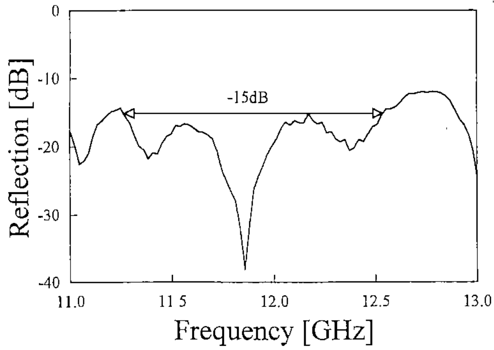
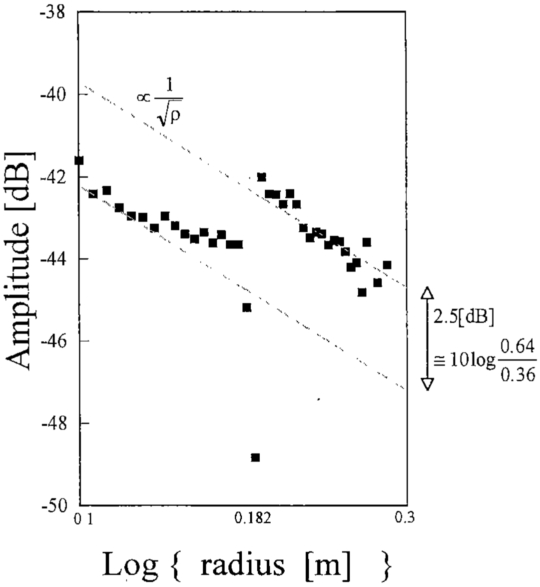
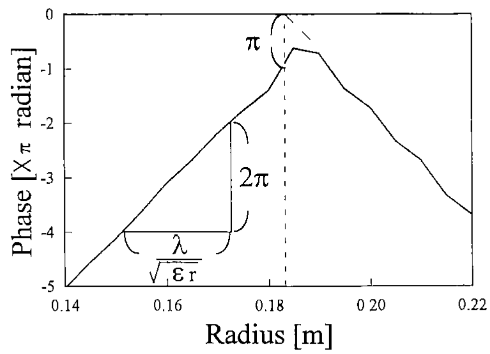


Fig. 9 Measured reflection.



(a)



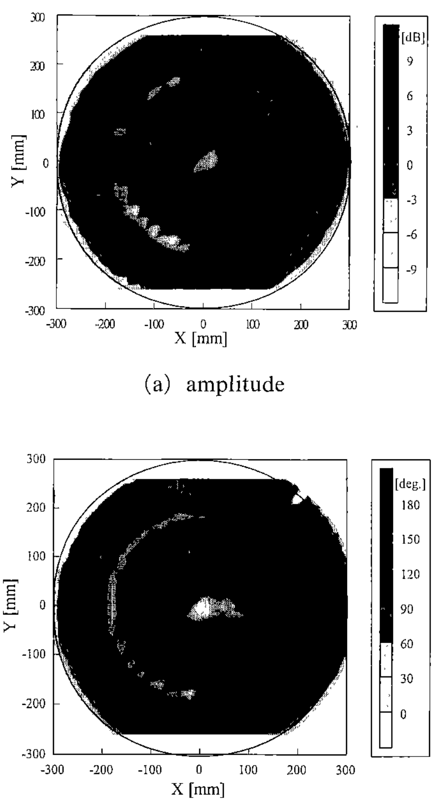
(b)

Fig. 10 (a) Measured power dividing ratio near power divider ($f=11.85$ GHz).
(b) Measured phase distribution near power divider ($f=11.85$ GHz).

5.2 Characteristics of Power Divider

In order to evaluate the operation of the power divider, the amplitude and phase distribution of electric field in the upper waveguide were measured. The electric field in the upper waveguide is measured by inserting the probe into the holes on the conductor top plate which replaces the slot plate. Only the desired traveling wave components are extracted by using time gating techniques of network analyzer. Furthermore, we attach the absorber at the innermost and outermost waveguide walls so that undesirable reflection from the terminations is suppressed. The measured amplitude of the field in the upper waveguide is shown in Fig. 10 (a). Two straight lines show the amplitude decay of $1/\sqrt{\rho}$ associated with the cylindrical wave. The difference of two lines indicates the power dividing ratio. The experimental result indicated by ■ is in good agreement with the calculated one, though small errors are observed at the position of the divider (ρ= 0.182 m). Furthermore, we already confirmed that the power dividing ratio is stable over more than 1 GHz by experiment.

The measured phase distribution is shown in Fig. 10(b). The two oblique lines indicated that the inward and the outward traveling waves are generated. The phase progress is 2π per $\lambda/\sqrt{\varepsilon_r}$ which verifies the propagation of TEM waves. The phase jump by π just above the slit corresponds to the change of the electric field direction at this point. From those measurements, the operation of the power divider is confirmed.



(a) amplitude

(b) phase.

Fig. 11 Aperture field distribution (f=11.85 GHz).

5. 3 Aperture Field Distribution

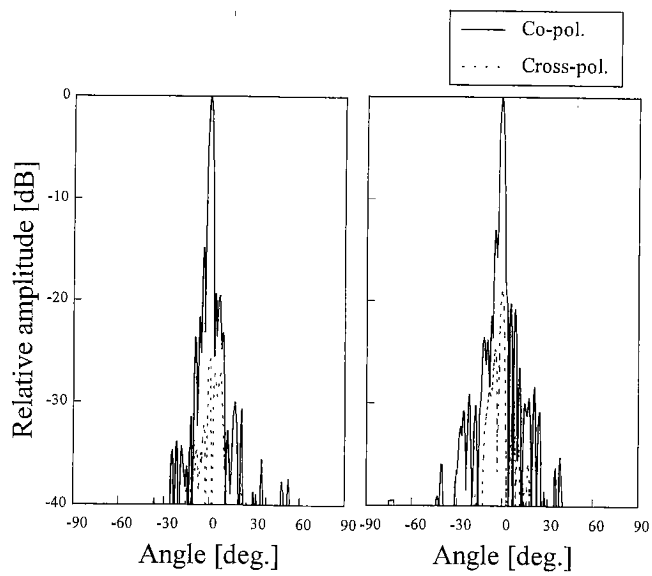
The aperture field distributions measured above the slot aperture are given in Figs. 11 (a), (b). They show the amplitude and phase distribution of co-polarization components at 11.85 GHz. The region without slots (blocking) exists at the aperture center and at the divider ($\rho=\rho_{\rm mid}$). However, the aperture distributions of both parts are well balanced and almost uniform illumination is realized over the full 0.6 mϕ aperture.

5. 4 Radiation Pattern

Figures 12(a), (b) present the examples of Fresnel radiation patterns of co- and cross-polarization component in ϕ=90° and ϕ=0° plane respectively. The co-polarization pattern is almost symmetrical. The first sidelobe levels are about −15 dB that becomes asymmetry as a result of the slot arrangement as well as the blocking; the radiation patterns depend upon each cutting plane because of the same reasons. The cross-polarization components are well suppressed below −25 dB and intolerably large sidelobes do not appear.

5. 5 Antenna Gain and Axial Ratio

The measured frequency characteristics of the gain, efficiency and axial ratio of WB-RLSA are included in Fig. 8. Those for conventional RLSA are also presented. They are in reasonable agreement with the calculated ones. In the figure, the dotted line 60%, 70%



(a) ϕ=90°. (b) ϕ=0°.

Fig. 12 Radiation pattern in Fresnel region (r=7 m, f=11.85 GHz).

and 80% denote the aperture efficiency. The maximum gain of 35.5 dBi and efficiency of 65% are measured at center frequency for WB-RLSA. The discrepancy in predicted and measured peak gain of WB-RLSA is about 0.5 dB and is mainly due to following reasons;
(1) Slots cut just above the power divider may disturb the illumination uniformity. It may result in the discrepancy between theory and the measurement.
(2) Structure is a bit complicated than SL-RLSA and is more sensitive to manufacturing errors.

On the contrary, at 800 MHz bandwidth, the band-edge gain of 33.7 dBi is realized at the edge of the frequency bandwidth between 11.5 GHz and 12.3 GHz. It is about 1 dB larger than that of the conventional SL-RLSA. The excellent axial ratio less than 1 dB is realized over wide frequency range. It is a bit increasing at lower frequency. The slot coupling is weaker at the low frequency and the residual power reflected at both terminations radiate undesirable cross polarization wave.

6. Conclusion

This paper proposed a WB-RLSA to widen the frequency bandwidth. It is a hybrid of single and double layer RLSA. The feed line length is about one half of the aperture radius and the frequency bandwidth would be widened. The low reflection power divider is designed for this antenna. A prototype antenna with 0.6 mϕ aperture is fabricated and measured to confirm the design maximizing the band-edge gain for 800 MHz bandwidth. The effectiveness of the WB-RLSA is verified and its high potential is demonstrated by experiment. The antenna gain of about 33.7 dBi was obtained at 800 MHz bandwidth by experiment. This band-edge gain is 1 dB higher than that of a conventional SL-RLSA. This result of enhancement of band-edge gain can be applied to linearly polarized RLSA as well. The antenna efficiency at the center frequency is 65% and a bit lower than the prediction. Further improvement of the band-edge and the peak gain is expected if the annular slot design is adopted which reduces the aperture blocking [9]. Moreover, it is attractive to introduce the matching slot placed at the aperture periphery for reducing the termination loss of about 15% is important future study.

Acknowledgment

The authors are deeply indebted to Mr. Hasegawa of Panasonic for the FEM analysis, and Mr. Hagiwara and Mr. Yamamoto of NTT DoCoMo for their help of this antenna design. Thanks are also due to the RLSA group of TOPPAN printing company and TAISEI for the fabrication of the model antenna.

References

[1] Goto, N. and Yamamoto, M., "Circularly polarized radial line slot antennas," *IECE Technical Report*, AP80-57, Aug. 1980.
[2] Takahashi, M., Takada, J., Ando, M. and Goto, N., "Characteristics of small-aperture, single-layered, radial line slot antennas," *IEE Proceedings-H*, vol. 139, no. 1, Feb. 1992.
[3] Yamamoto, K., Hagiwara, S., Takahashi, M., Takada, J., Ando, M. and Goto, N., "A wide band radial line slot antenna," *Proceeding of ISAP'92*, Sep. 1992.
[4] Goebels, F. J. and Kelly, K. C., "Arbitrary polarization from annular slot planar antennas," *IRE Trans. Antennas & Propags.*, vol. AP-9, pp. 342–349, Jul. 1961.
[5] Takahashi, M., Takada, J., Ando, M., Goto, N., Suzuki, M., Okazaki, Y. and Numano, Y., "A small aperture single-layered radial line slot antenna for DBS reception," *7th International Conference on Antennas & Propagation*, 15C-4, (York), Apr. 1991.
[6] Hirokawa, J., Ando, M. and Goto, N., "An analysis of slot coupling in a radial line slot antenna," *Proceeding of ISAP'89*, Aug. 1989.
[7] Ando, M., Sakurai, K., Goto, N., Arimura, K. and Ito, Y., "A radial line slot antenna for 12 GHz satellite TV reception," *IEEE Trans. Antennas & Propag*, vol. AP-33, no. 12, Dec. 1985.
[8] Takahashi, M., Takada, J., Ando, M. and Goto, N., "Efficiency enhancement of radial line slot antennas by aperture illumination control," *Proceeding of ISAP'92*, Sep. 1992.
[9] Ueno, M., Takahashi, M., Hirokawa, J., Ando, M., Goto, N. and Arai, H., "A rotating mode radial line slot antenna—concentric array—," *IEICE Technical Report*, AP93-43, Jun. 1993.

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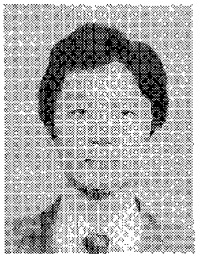

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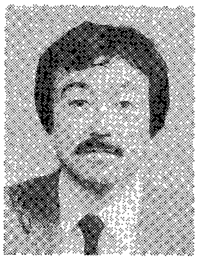

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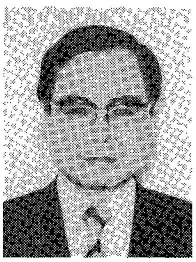

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