Novel Single-Layer Waveguides for High-Efficiency Millimeter-Wave Arrays

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***Abstract*—This paper presents novel single-layer waveguides for challenging design of high-gain, high-efficiency, and mass-producible planar slotted arrays for millimeter wave. The key feature of three types of waveguides as well as state-of-the-art performance of arrays using these are surveyed. A model antenna realizes 35-dBi gain and 64% efficiency at 60.2 GHz.**

***Index Terms*—Millimeter-wave array, mm-wave array, TEM node waveguide array.**

I. High-Gain Application of Millimeter-Wave Antennas

THE variety of radio systems with high-frequency and high-gain antennas at present and in the near future are summarized in Fig. 1. These include high-speed wireless local area network (LAN), automotive collision-avoidance radar in 60–80-GHz bands, 20-GHz-band entrance radio relay systems for connecting mobile base stations, and various types of millimeter-wave subscriber radio systems [1], [2]. A unique program of communications and broadcasting engineering satellite in Japan (COMETS) has several systems covering 20–50-GHz bands. In the design of high-gain planar antennas, the loss in feeding lines determines the antenna efficiency, while the choice of radiating elements as well as the waveguiding structure affects the manufacturing cost. It is roughly estimated that the efficiency of microstrip or triplate line arrays with 35 dBi would be lower than 30% in, for example, 60 GHz [3]. Since the loss is negligible in the waveguide, and slots are cost effective, a slotted waveguide array is a leading candidate for high-gain flat antennas. However, slotted-waveguide arrays have never been used commercially, with the few exceptions of military or professional applications. The key problem has been the highest manufacturing cost of the waveguides. Authors have developed several types of single-layer waveguide arrays in 12- and 20-GHz bands which realize high efficiency and mass produceability [3], [4]. This paper extracts the advantages and the drawbacks of these waveguides in terms of antenna efficiency and manufacturing cost. The latest challenges for millimeter-wave applications are also demonstrated for confirming the potential in high frequency. Fig. 1 also includes the state-of-the-art efficiency of slotted waveguide arrays as functions of the gain and frequency. The efficiency at 35-dBi gain is about twice as high as that of other types of arrays [1].

At first, single-layer waveguides are classified into three, in terms of modes in the waveguides. Then, the design, excellent characteristics, as well as the difficulties of arrays using each single-layer waveguide are presented.

II. Single-Layer Waveguides

Fig. 2 presents varieties of single-layer waveguides which are suitable for mass production. Parallel-plate waveguides operating in TEM wave excitation are already commercially mass produced in the form of radial-line slot antennas (RLSA's) for 12-GHz DBS reception, as shown in Fig. 3(a) [3]. The parallel-plate structure [5]–[7] is oversized and has no sidewalls; it assures the lowest transmission loss among the three. This becomes the important advantage even in high-gain range, where other types of planar structures suffer from serious conductor loss. Furthermore, it is the most simple structure without a wall, and is the leading candidate for the cost-effective waveguide arrays. One difficulty of TEM waveguides is that the scattering from slots, which excites higher modes, must be taken into account in the design or must be suppressed; this implies that the design flexibility is slightly sacrificed. Single-mode waveguides in Fig. 3(b) are excited in-phase by π junctions, as shown in Fig. 4(a). They are also commercialized for mobile direct broadcasting from satellite (DBS) reception [4], [8], [9]. This structure consists of only two components, i.e., a slotted plate and a base plate with corrugation. Single-mode waveguides bring us design flexibility, although it is more expensive than an oversized one. A drawback as applied for high frequency is that the electric contact between the bottom plate and the slot plate should be perfect [1]. A cost-effective process for this contact has never been established. Single-mode waveguides with alternating phase excitation, shown in Fig. 3(c), may be regarded as the mixture of (a) and (b) [10]. Adjacent waveguides are fed out of phase by 180° through T-junctions, shown in Fig. 4(b), which are compared with the π junctions in Fig. 4(a). Noteworthy is that the electrical contact between the narrow walls and the slot plate is not necessary for the alternating phase waveguides [1], [10]. Thus, reduction of loss as well as cost for fabrication would be expected. A test antenna was fabricated and the basic operation without the electric contact has been confirmed.

The above observation for three types of single-layer waveguides is summarized in Fig. 2, in terms of mass producibility and designability.

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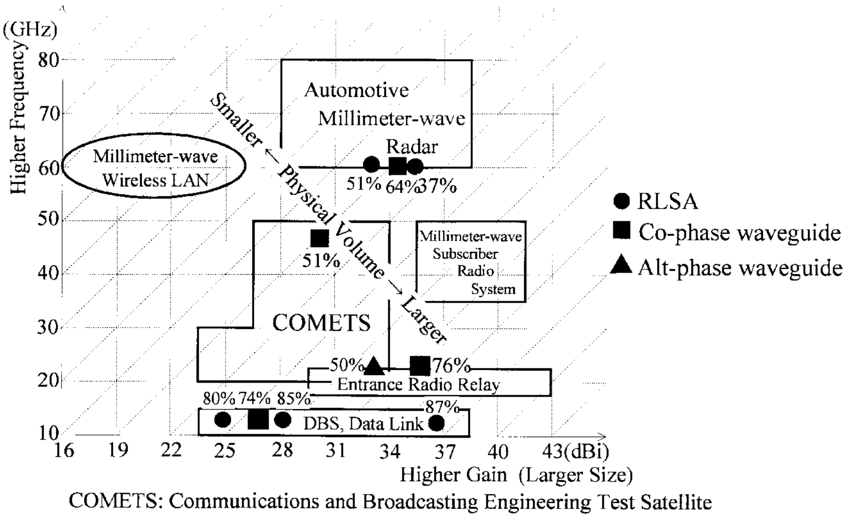


Fig. 1. High-gain applications in millimeter wave.

Modes	Single-mode		Multi-mode
Waveguide Structure	Co-phase	Alternating Phase	
Loss Mass-production	△	?	◎
Designability Stability	◎	?	△
Application Example	• Mobile DBS • Entrance Radio	(Tech. Rep. IEICE AP90-130 AP93-145 EMT-89-119)	• RLSA • Paralell Plates (Traveling-wave)

◎:Excellent △:Marginal ?:Promising

Fig. 2. Single-layer waveguides for planar arrays.

III. Single-Mode Waveguides

A. Single-Mode Waveguide In-Phase

The single-mode waveguide with co-phaseal excitation is the most popular structure, except that the feeding waveguides are also in the same layer as those for the radiating waveguides. The unique power-dividing element of π junctions, shown in Fig. 4(a), realizes this simple structure as well as mass productivity [4]. The slot and waveguide design techniques are already mature in 12-GHz bands. Various antenna functions have been reported successfully, such as circular or linear polarization, boresite or tilted beams, and two beams antennas [1], [4], [9], [11]. The waveguide has the negligible conducting loss and provides the way to high-efficiency antennas even in high-gain and high-frequency use. Challenges for higher frequency and excellent efficiency include the followings.

1) Entrance Radio Relay Systems in 22-GHz Band: A two-dimensional slot array is fabricated for experiments in 22-GHz band. A radiating waveguide is an array of resonant shunt slots on the broad wall and is designed to realize uniform distribution on the aperture [12]. The size of the array is presented in Fig. 3(a). The electrical contact between the slot plate and the narrow walls is realized by a time-consuming brazing technique. The peak gain of 35.9 dBi is obtained and the antenna efficiency is 75.6% at 22.15 GHz. This efficiency is about two times higher than those of other planar arrays in this frequency and gain range [1].

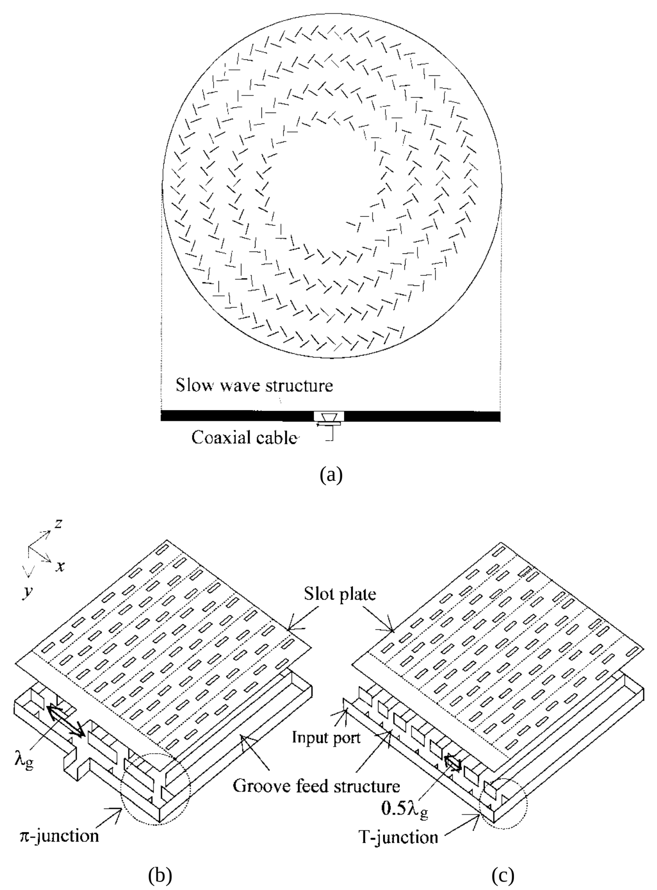


Fig. 3. Single-layer waveguide arrays. (a) RLSA. (b) Single mode (in phase). (c) Single mode (alternating phase).

2) 60-GHz-Band Single-Layer Waveguide Arrays for Car Collision-Avoidance Radar: A 35-dBi test antenna at 60 GHz has the size of about 105 mm × 120 mm × 5 mm, 600 resonant shunt slots on 24 waveguides of 3.22 mm × 1.88 mm [1]. The typical size of slot is 3 mm × 0.3 mm. Relatively large reflec-

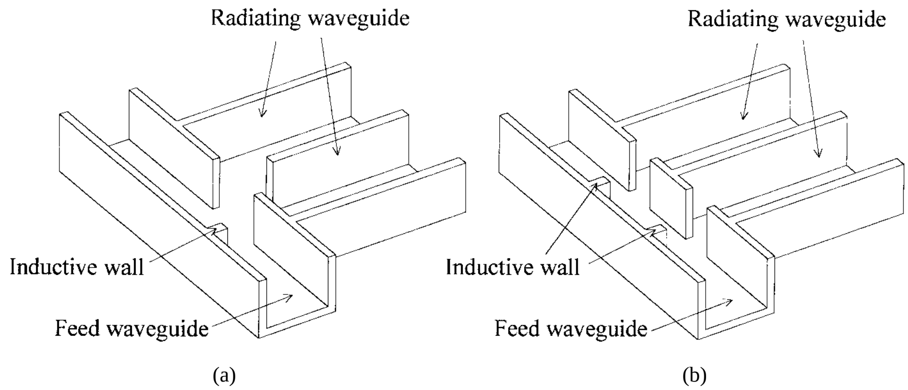


Fig. 4. Power dividers for single-layer waveguide. (a) π-junction. (b) T-junction.

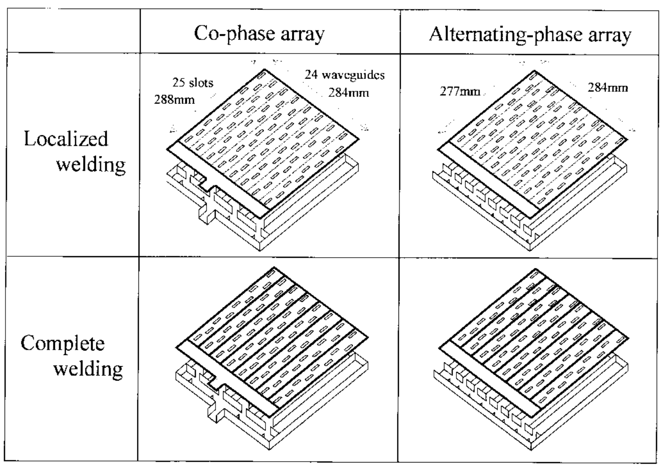


Fig. 5. Two types of laser welding for test antennas.

tion of -5 dB was observed at 59.7 GHz. The highest gain of 35 dBi and the efficiency of 64% were observed at 60.2 GHz. This efficiency is very high and is, again, about two times larger than that predicted for other types of antennas [13].

3) Leaky-Wave Antennas for Satellite Mobile Communications in COMETS [14]: Circularly polarized leaky-wave antennas with a large-beam tilting angle of about 46° are manufactured for mobile reception of satellite signals in 21-, 31-, and 46-GHz bands. It has the size of about 110 mm $\times$ 95 mm $\times$ 5 mm. Typical gain and efficiency of antenna is 23.8 dBi and 63% at 21.0 GHz, 26.3 dBi and 54% at 30.8 GHz and 30.2 dB and 51% at 46.9 GHz, respectively.

Serious difficulty of co-phase waveguide (A) is the realization of an electrical contact between the slot plate and the narrow walls. To demonstrate the importance of the contact, two types of laser welding contacts are tested in 22-GHz-band antennas. The center column in Fig. 5 shows the area of welding in co-phase waveguide arrays by bold lines. Complete welding indicates the model with all the walls welded, while the localized welding is that with only the periphery of the aperture as well as the power-dividing waveguide welded; the latter is much attractive in terms of mass productivity. Fig. 6(a) shows the measured phase distribution over the aperture of complete and localized welding models. Small-beam tilting design, about 6° in $+z$-direction, accounts for linearly tapered distribution. The aperture phase of the latter is seriously deformed from the uniform one observed for the former. Fig. 7(a) compares the antenna gain for two antennas. The antenna with localized welding is losing gain and a bit frequency shifted. These suggest that the mechanical contact is not sufficient for the co-phase waveguide walls.

B. Single-Mode Waveguides With Alternating Phase

The alternating-phase waveguides dispense, in principle, with the electric contact between the slot plate and the narrow walls. This is of great advantage in mass production. Two more antennas with almost the same dimension as the co-phase ones are fabricated to evaluate the importance of electric contact. Test antennas with complete and localized welding are shown in the right column of Fig. 5. The aperture phase illumination and the antenna gain are presented in Figs. 6(b) and 7(b), respectively. As is expected, the gain as well as the phase illumination remains unchanged even if the narrow wall contact is omitted [1], [10].

In Fig. 7, the theoretical peak gain as well as the measured gain of alternating phase waveguide is lower than that of co-phase waveguide arrays by about 0.5–1 dB. This degradation for alternating phase ones is due to the grating lobes of about -25 dB appearing in diagonal planes. They are associated with the slot arrangement, not periodic, but symmetrical with respect to narrow walls, as shown in Fig. 3(b). This gain reduction may be eliminated by the beam tilting in $-z$-direction or the use of dielectric material filling the waveguide. The beam tilting in $-z$-direction or the use of dielectric material filling the waveguide may eliminate this gain reduction. The predicted aperture efficiency is compared in Fig. 8 as functions of the dielectric constants for the beam tilting of 8° in $-z$-direction. The gain reduction is only 0.3 dB, even for empty waveguide ($\varepsilon_r = 1$).

Another interesting feature of alternating phase waveguide is that narrow walls can be reduced, in principle, at the center frequency [2], [15]. Fig. 9 shows the possible configurations of waveguide with reduced narrow walls. If the frequency changes from the design, the null position of the fields moves away from the original wall position. Then the slot excitation changes and gain reduction occurs. A simple calculation was conducted to evaluate the bandwidth narrowing effects for them where the coupling windows in T-junctions are regarded as the magnetic currents radiating into the oversized waveguide with reduced narrow walls. The slot excitation

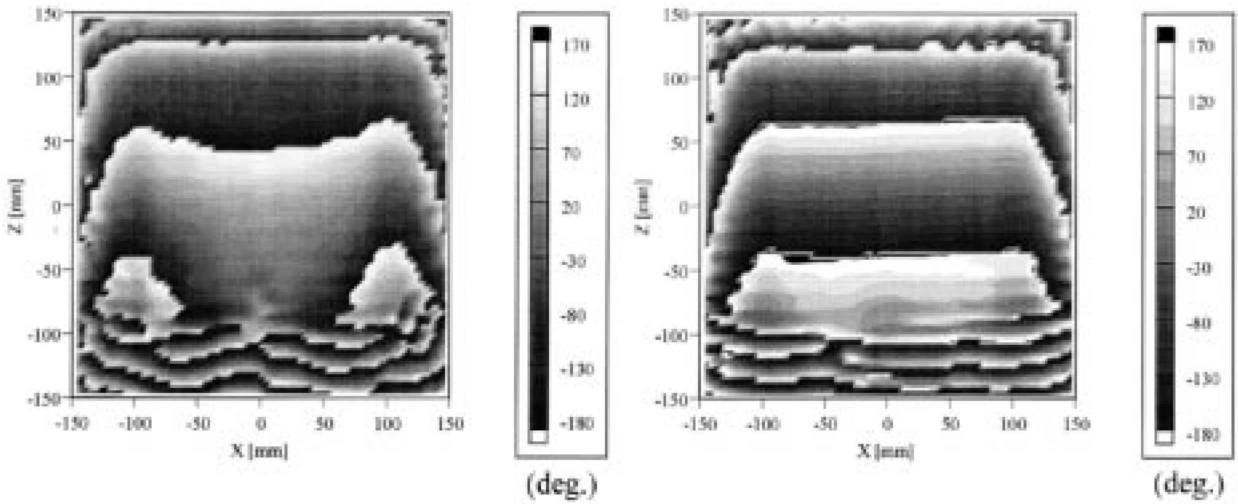


Fig. 6. Measured aperture phase distribution of co-phase waveguides. (a) Localized welding. (b) Complete welding.

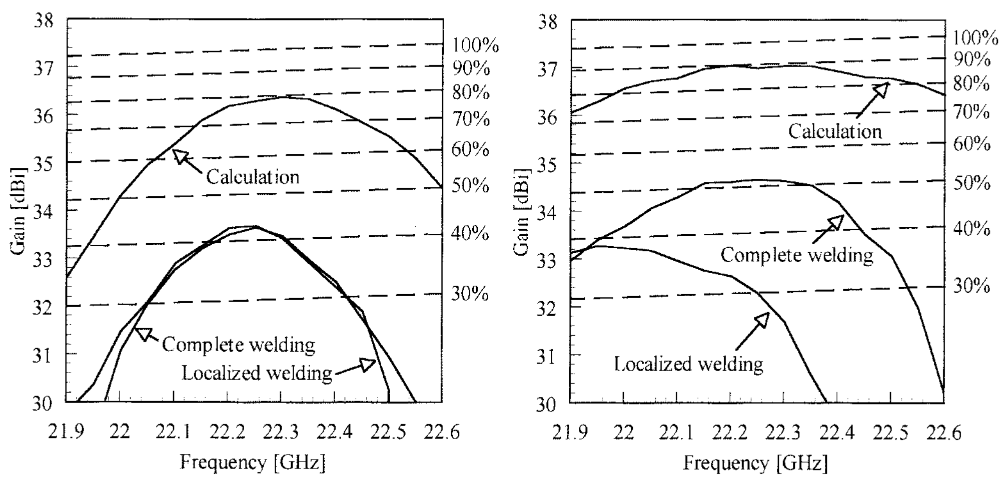


Fig. 7. Gain reduction of single-layer waveguide array due to imperfect electric contact at narrow walls. (a) Co-phase waveguide arrays. (b) Alternating phase waveguide arrays.

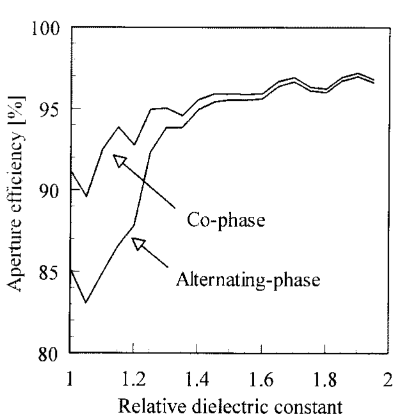


Fig. 8. Efficiency reduction of alternating phase waveguide arrays due to grating lobes.

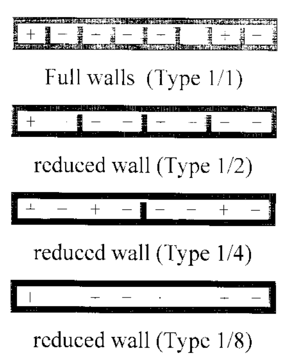


Fig. 9. Alternating phase waveguide with reduced narrow walls.

is assumed to be proportional to the magnetic field at the slot position of interest. Fig. 10 illustrates the field amplitude distribution of highly reduced model of Type 1/8. As the frequency shifts from 22.3 GHz, for which all the windows in T-junctions are designed to be in co-phaseal, the null of standing wave deviates from the initial wall positions. The slot excitation reflects this perturbation of standing wave distribution and uniform illumination breaks down. This results in bandwidth narrowing of the predicted antenna gain, as shown in Fig. 11. The 1-dB down bandwidth for Type 1/8 is about 3% for 24-dB antennas. Nevertheless, the wall reduction

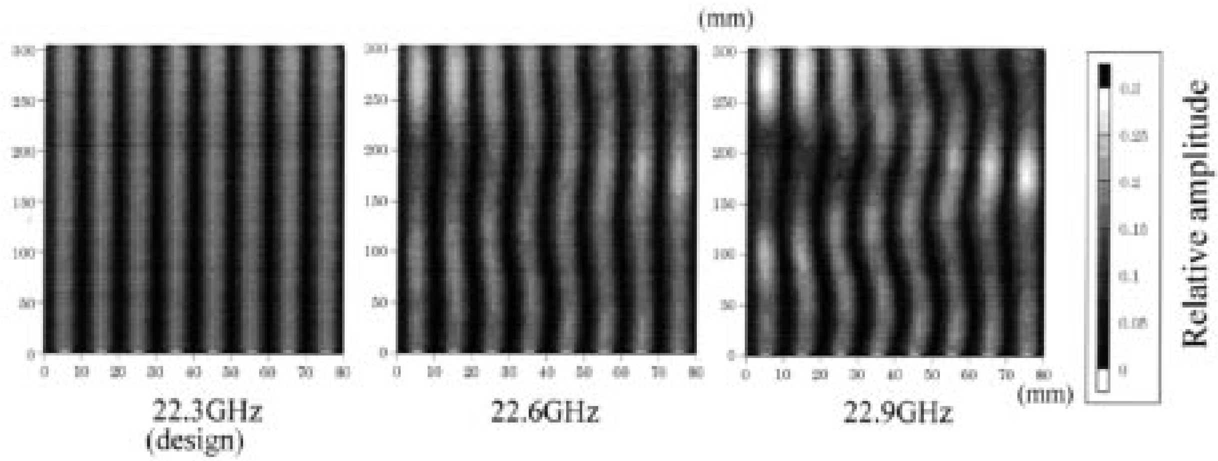


Fig. 10. Amplitude distribution in the waveguide with reduced narrow walls (Type 1/8).

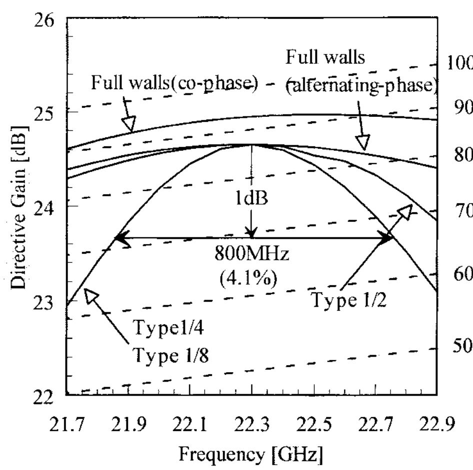


Fig. 11. Bandwidth narrowing of arrays with reduced narrow walls.

in an alternating phase waveguide would be attractive in cost reduction of the antenna if the bandwidth requirement is satisfied.

IV. Parallel-Plate Waveguide

The possibility of high-gain planar antennas for commercial use was first opened up by the RLSA in 12-GHz band by Takahashi *et al.* [3], Goto and Yamamoto [5], and Ando *et al.* [6]. It is a kind of parallel-plate waveguide with a TEM wave and is, at the same time, an oversize waveguide for the scattered or reflected from slots. Therefore, sophisticated slot design, so as not to perturb the dominant TEM traveling-wave operation, has been intensively established. This structure dispenses with narrow walls as well as electric contact. Thus, it seems to be the most promising candidates for millimeter-wave application. The simple scale-down of the lower frequency antenna provides us with millimeter-wave antennas with the comparable efficiency in principle, provided that the fabrication accuracy should be assured. It seems trivial, but should be emphasized in contrast with that other planar structure such as a microstrip line, triplate line, and suspended line, which would suffer from serious degradation in millimeter wave due mainly to conductor loss. The key difference between these lines and waveguide is that the substrate thickness of the former must be kept smaller than that of the latter, so as to suppress the unwanted radiation from the feeder. Smaller thickness results in an increase of conductor loss.

TABLE I
Design Parameter of RLSA'S for LAN

	A	B
Antenna Diameter	25mm	100mm
Number of Turns	3	10
Dielectric Constant	2.20	1.08
Waveguide Height	0.635mm	1.00mm
Design Frequency	60.0GHz	60.0GHz
Number of Slots	134	1290
Beam Shape	Conical	Pencil

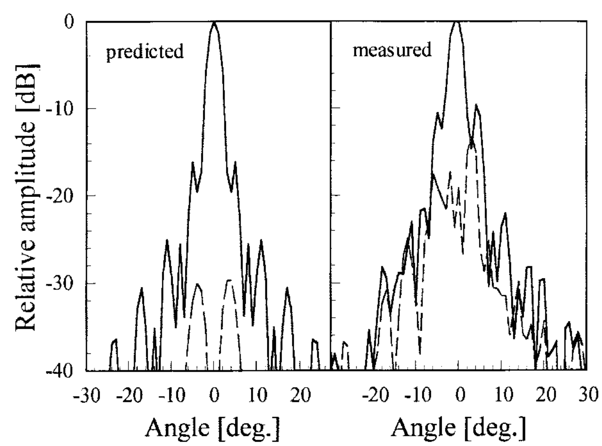
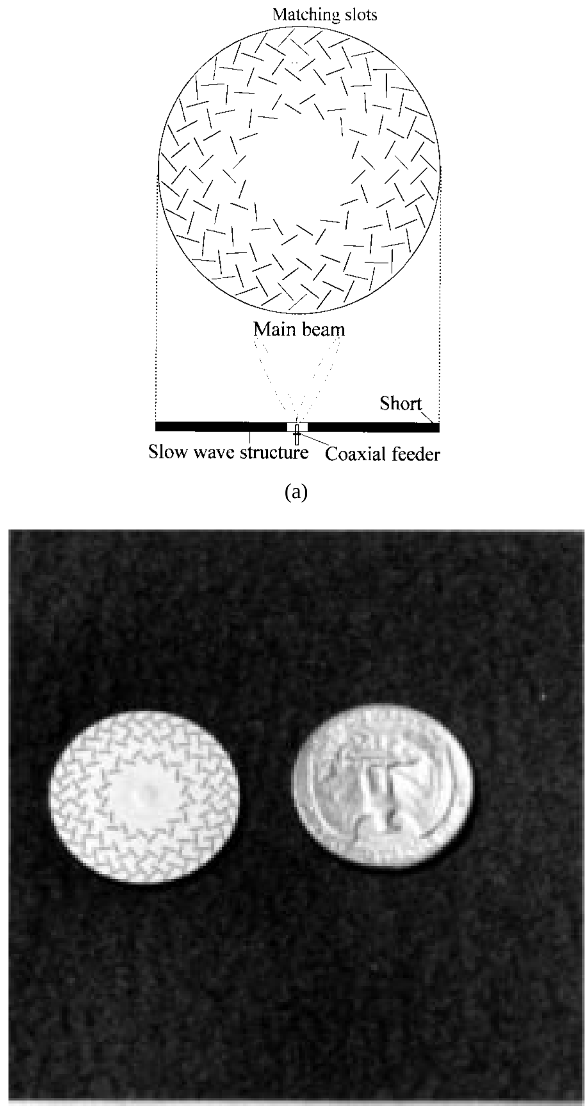


Fig. 12. Predicted and measured radiation patterns of 60-GHz RLSA's (high-gain type B). Solid line: Co-pol. Dashed line: Cross pol.

Several RLSA's are fabricated in 60 GHz. Another unique concept of a through-hole antenna constructed on the substrate is also proposed to realize the mass production of TEM wave antennas [14].

1) 60-GHz-Band RLSA for High-Speed Wireless LAN Systems: Two types of circularly polarized RLSA's are manufactured. Both have the similar structure shown in Fig. 3(c). Slots in the aperture consist of many slot pairs, each one of which has two slots oriented perpendicularly and spaced



(a)

(b)

Fig. 13. A conical beam RLSA for 60-GHz wireless LAN (type A). (a) Concentric array RLSA with coaxial feed. (b) Test antennas for wireless LAN (photo).

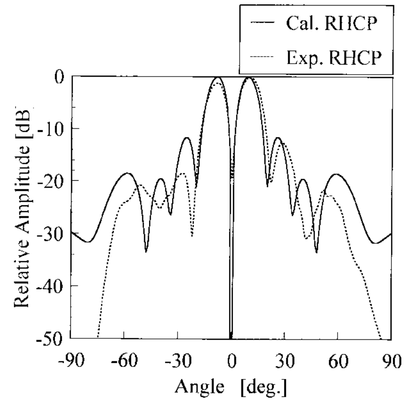


Fig. 14. Measured radiation patterns of three C-turn RLSA's.

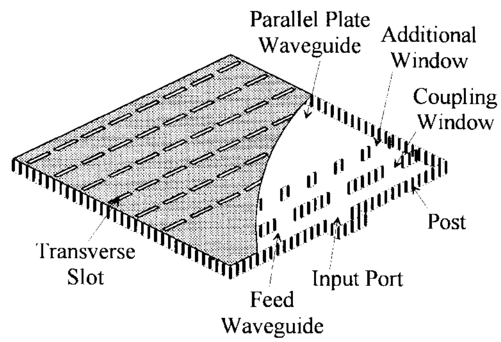


Fig. 15. A post-wall waveguide for TEM wave array.

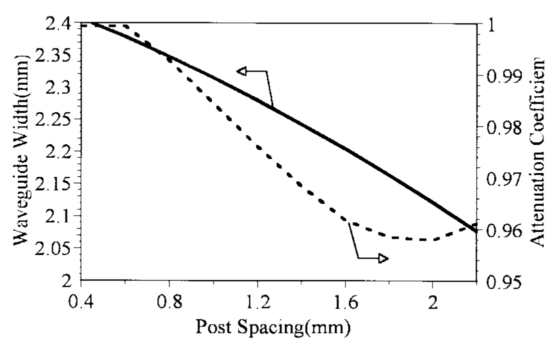


Fig. 16. Attenuation and waveguide width realizing effective width of 2.15 mm.

radially by a quarter-wavelength guide. One pair is a unit radiator of a circularly polarized wave for radially outward traveling-wave excitation by a coax to a radial-line adapter. These slot pairs are arrayed spirally for a pencil beam or concentrically for a conical beam. The design parameters are listed in Table I. One is a 10-cm-diameter high-gain RLSA with a pencil beam, as shown in Fig. 3(c). This is made by simply placing the conducting sheet above the top plate with etched slots, with the foaming spacer put between them. Radiation patterns are presented in Fig. 12. A gain of 33 dBi and the efficiency of about 51% was measured. The reflection at the feed point and the alignment error of the plate should be eliminated for enhancing the efficiency up to 70%. Another example is a 25-mm-diameter RLSA with a conical beam, as shown in Fig. 13 [16]. It has slot pairs arrayed not in spiral, but in concentric arrangement. The Teflon substrate with a thick ground conductor is adopted and the slots are etched on the top conductor, while plating shorts the periphery of the aperture. The dielectric constant is 2.2. Fig. 14 presents the comparison of the predicted and measured patterns. The agreement is reasonable, except the wide angular regions due to errors in near-field measurement technique. Though the VSWR was not good at the center frequency, the discrepancy between measurement and prediction was no more than 2 dB in gain, which suggests the high potential of RLSA's in terms of loss in millimeter-wave frequency. Accurate discussion of the antenna gain is left for further study.

2) Post-Wall Waveguide in Substrate: The authors have proposed a single-layer feed waveguide to excite a plane TEM wave for parallel-plate slot arrays, as shown in Fig. 15 [14]. Instead of conductor walls, densely arrayed through holes are accommodated in the substrate. As the density of through holes becomes higher, they can be regarded as the equivalent narrow walls. Propagation constant of the post-wall straight

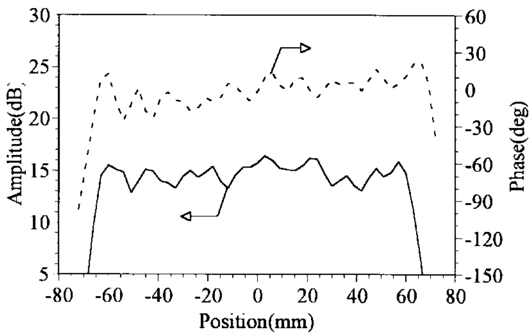


Fig. 17. Measured aperture field distribution of post-wall waveguide.

TABLE II
DESIGN PARAMETERS OF POST-WALL WAVEGUIDE IN 40-GHz BAND

Relative Permittivity of Dielectric		2.17
Substrate Height		1.52mm
Post Diameter	d	0.60mm
Post Spacing	s	1.00mm (max.)
Window-Post Position	h	1.70mm
Post-Wall Width	a_f	4.92mm
PEC-Wall Width	a_e	4.43mm
Window Spacing	a_r	6.30mm
Number of Windows		22
Design Frequency		40.0GHz

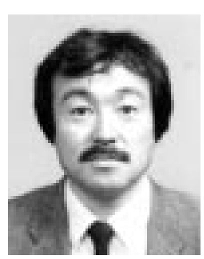
waveguide has been calculated by using Galerkin's method-of-moment analysis as a function of the spacing. At 74 GHz, the post diameter of 0.3 mm and the dielectric constant of 2.17 are assumed for calculation. Fig. 16 demonstrates the results where larger post spacing corresponds to larger loss. It also shows that as the spacing increases, narrower waveguide width is required for realizing the equivalence to a solid-wall waveguide with 2.15 mm. The unit component named as periodic-wall π junction is designed and arrayed in series to constitute a TEM wave exciter into the substrate. Test waveguide, as shown in Fig. 15, is fabricated in 40-GHz band using the parameters in Table II. Fig. 17 shows the power-dividing characteristics measured over the parallel plate along the feed waveguide. Inner field is picked up through slots etched on the top plate. Sufficiently uniform amplitude and phase illumination is observed, and TEM parallel-plate mode excitation is confirmed. This structure can be mass produced by through-hole techniques in the substrate.

V. CONCLUSIONS

Three types of single-layer waveguides are introduced for the planar slotted arrays. Excellent efficiency was demonstrated for single-mode co-phase arrays. RLSA's using oversized waveguides are designed for 60-GHz LAN, and low-loss characteristics are suggested. A noble structure called the post-wall waveguide is also proposed for TEM wave excitation. Alternating-phase waveguide arrays using single-mode waveguides have an attractive advantage: electric contact is not required at the interface between the slot plate and the waveguide narrow walls. Narrow-wall reduction is also possible for narrow-bandwidth applications.

REFERENCES

[1] K. Sakakibara, J. Hirokawa, M. Ando, and N. Goto, "Single-layer slotted waveguide arrays for millimeter wave applications," *IEICE Trans. Commun.*, vol. E79-B, no. 12, pp. 1765–1772, Dec. 1996.
[2] M. Ando and J. Hirokawa, "High-gain and high-efficiency single-layer slotted waveguide arrays in 60 GHz band," presented at the 10th Int. Conf. Antennas Propagat., Edinburg, Scotland, Apr. 1997.
[3] M. Takahashi, J. Takada, M. Ando, and N. Goto, "A slot design for uniform aperture field distribution in single-layered radial line slot antennas," *IEEE Trans. Antennas Propagat.*, vol. 39, pp. 954–959, July 1991.
[4] J. Hirokawa, M. Ando, N. Goto, M. Takahashi, T. Ojima, and M. Uematsu, "A single-layer slotted leaky waveguide array antenna for mobile reception of direct broadcast from satellite," *IEEE Trans. Veh. Technol.*, vol. 44, pp. 749–755, Apr. 1995.
[5] N. Goto and M. Yamamoto, "Circularly polarized radial line slot antennas," IECE, Japan, Tech. Rep. AP80-57, Aug. 1980.
[6] M. Ando, K. Sakurai, N. Goto, K. Arimura, and Y. Ito, "A radial line slot antenna for 12 GHz satellite TV reception," *IEEE Trans. Antennas Propagat.*, vol. 33, pp. 1347–1353, Dec. 1985.
[7] J. Hirokawa, M. Ando, and N. Goto, "Waveguide-fed parallel plate slot array antenna," *IEEE Trans. Antennas Propagat.*, vol. 40, pp. 218–223, Feb. 1992.
[8] N. Goto, "A planar waveguide slot antenna of single layer structure," IEICE, Japan, Tech. Rep. AP88-39, July 1988.
[9] J. Hirokawa, M. Ando, and N. Goto, "A single-layer multiple-way power divider for a planar slotted waveguide array," *IEICE Trans. Commun.*, vol. 75, no. 8, pp. 781–787, Aug. 1992.
[10] K. Sakakibara, Y. Kimura, A. Akiyama, J. Hirokawa, M. Ando, and N. Goto, "Alternating phase-fed waveguide slot arrays with a single-layer multiple-way power divider," *Proc. Inst. Elect. Eng.*, vo. 144, no. 6, pp. 425–430, Dec. 1997.
[11] K. Sakakibara, Y. Kimura, J. Hirokawa, M. Ando, and N. Goto, "A two-beam slotted leaky waveguide array for mobile reception of dual polarization DBS," *IEEE Trans. Veh. Technol.*, to be published.
[12] K. Sakakibara, J. Hirokawa, M. Ando, and N. Goto, "A high gain and high efficiency single-layer slotted waveguide array for use in 22 GHz Band," *Electron. Lett.*, vol. 32, no. 4, pp. 283–284, 1996.
[13] M. Ando, K. Sakakibara, J. Hirokawa, N. Goto, and T. Watanabe, "A 60-GHz band single-layer planar waveguide arrays," in *1996 IEEE AP-S Int. Symp. Dig.*, Baltimore, MD, July 1996, pp. 204–207.
[14] J. Hirokawa and M. Ando, "Single-layer feed waveguide to excite plane wave for parallel plate slot arrays," IEICE, Japan, Tech. Rep. AP97-31, pp. 61–68, 1997.
[15] Y. Kimura, J. Hirokawa, M. Ando, and N. Goto; "Frequency characteristics of alternating-phase single-layer slotted waveguide array with reduced narrow walls," in *IEEE AP-S Int. Symp. Dig.*, vol. 2, Montreal, P.Q., Canada, July 1997, pp. 1450–1453.
[16] A. Akiyama, T. Yamamoto, M. Ando, N. Goto, and E. Takeda, "Design of radial line slot antennas for millimeter wave wireless LAN," in *1997 IEEE AP-S Int. Symp. Dig.*, vol. 4, July 1997, pp. 2516–2519.



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