Sidelobe Suppression in 76-GHz Post-Wall Waveguide-Fed Parallel-Plate Slot Arrays

Jiro Hirokawa, *Member, IEEE*, and Makoto Ando, *Member, IEEE*

***Abstract*—Sidelobe suppression is demonstrated for 76-GHz post-wall waveguide fed parallel-plate slot arrays for car radar applications. Taylor distribution illumination control is successfully confirmed experimentally in the slot array on the parallel-plate waveguide. Amplitude distribution in the transverse direction is controlled by shaping a quasi-TEM mode and that in the longitudinal direction is realized by the slot coupling control, both in an oversized waveguide. Measured sidelobes are below −22 dB for one-dimensional (1-D) Taylor tapering while those for two-dimensional (2-D) Taylor distribution are below −18 dB. The gain reduction in comparison with that for uniform illumination is less than 1 dB both in the experiment. All these verify the potential of aperture illumination control of the parallel-plate slot arrays.**

***Index Terms*—Millimeter-wave, parallel-plate waveguide, planar antenna, post, sidelobe, slot antenna.**

I. Introduction

A PARALLEL-plate slot array [1]–[9] is an attractive candidate for high-efficiency and mass-producible planar phased array antennas [10], [11] for millimeter-wave applications because the transmission loss is generally small in comparison with other feed lines. A parallel-plate waveguide is a kind of closed waveguides without any radiation loss. Therefore, it can have height or thickness much larger than a microstrip line and can reduce conductor loss. Slots, radiating elements of the array, can be etched on the upper plate easily. We proposed a novel single-layer feed structure of post-walls, as shown in Fig. 1 [9]. The post-wall feed waveguide consists of densely arrayed metal-wall via-holes in a dielectric substrate. The antenna can be produced at low cost by popular techniques such as via-holing, metal plating, and etching. We confirmed the basic operation of the antenna in 40 GHz where a plane TEM wave was successfully excited in the parallel-plate [9]. We also measured 29.7 dBi gain with 44.6% efficiency and −7.5 dB reflection at 76.75 GHz in a 76-GHz antenna with the aperture sized by 52 mm × 49 mm [12].

One unique feature of this antenna is that a quasi-plane TEM wave in an oversized waveguide are utilized for slot excitation; the generation and the control of the dominant mode in this waveguide is the key for the designability of this type of the array though the infinite parallel-plate is assumed and the post-wall short around the periphery is neglected in the present design. It comes that the aperture size and illumination may affect the antenna performance significantly. This background is

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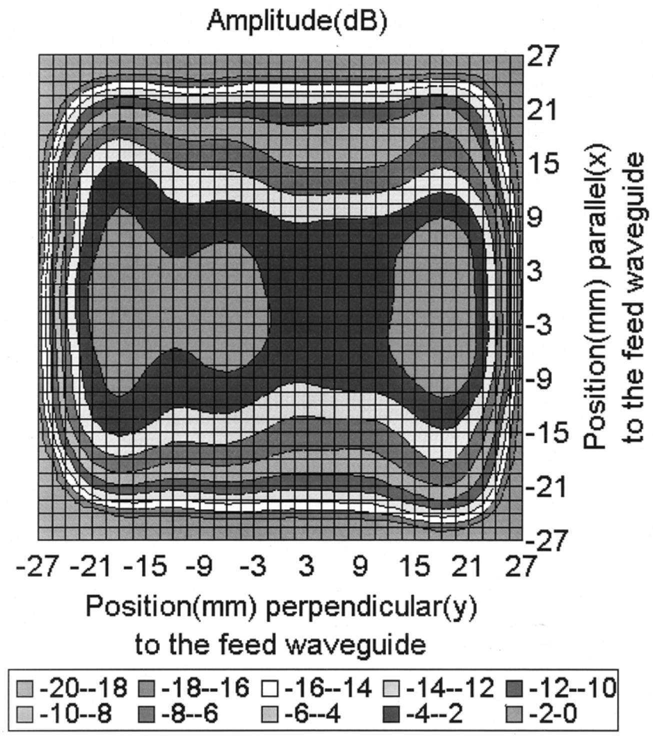


Fig. 1. Post-wall waveguide ted parallel-plate slot array.

different from those for other types of arrays with single-mode feeding systems. Mass productivity and high efficiency are aimed at the possible cost of stability and the designability. The designability, as well as the loss characteristics in terms of the aperture size, is discussed in [12]. This paper demonstrates the designability in terms of the illumination control.

Design for sidelobe suppression is discussed and evaluated for millimeter-wave car radar antennas (76–77 GHz). We design one-dimensional (1-D) (x or y) or two-dimensional (2-D) (x and y) Taylor distribution over the aperture as shown in Fig. 1. The excitation of the array of coupling windows in the feed waveguide and that of the array of slot pairs on the parallel-plates are controlled to shape the illumination along the x and the y axes, respectively. The size of the coupling window and the length of the slot are varied along the x and the y axes, respectively, based upon a field analysis of the moment method. The synthesized field distribution along the x-axis just in front of the array of the coupling windows would suffer from deformation during the propagation in the y direction. This is because the desired distribution consists of plural modes with different propagation constants. Therefore, the field distribution control over a 2-D

(xy) aperture is an important step and worth checking. We fabricate three types of 76-GHz sidelobe-suppressed antennas and measure the aperture-field distributions and the far-field patterns. Taylor distribution is reasonably observed over the aperture. Measured sidelobes are below -22 dB for 1-D suppressing either in the H(xz) or E(yz) planes, and -18 dB for 2-D suppression. The gain reduction as compared with that for uniform illumination is less than 1 dB in the experiment. We present the structure in Section II and the design in Section III. In Section IV, the configuration of the model antennas is explained. The experimental results are shown in Section V. Finally, Section VI is the conclusions.

II. STRUCTURE

Fig. 1 shows the structure [13], [14]. A post-wall feed waveguide is located at the edge of a parallel-plate one. Coupling windows are placed with a spacing of the guide wavelength in the feed waveguide to be excited in phase. Two additional windows are made in the face of each coupling window to propagate a TEM wave [15]. A post is placed behind each coupling window in the feed waveguide to suppress a reflected wave due to the window coupling [14]. An aperture for input port is cut on the bottom of the parallel-plate, which is followed by a T-junction at the center of the feed waveguide. All the radiating slots are paired with a spacing of about a quarter of the wavelength in the parallel-plates for the traveling wave propagation [8], [16], [17]. The slot pairs are arrayed with the spacing of one wavelength to be excited in phase and to radiate a boresight beam. The slot length and the spacing are varied along the y-axis while they are constant along the x-axis. Taylor distribution along the x-axis is synthesized by the inner field distribution excited by the array of coupling windows while that along the y-direction is realized by the slot coupling control. No matched loads are used for the termination of the waveguides: Matching units are designed for 100% coupling or radiation.

III. DESIGN

A. Design of Coupling Windows

In the previous design for uniform aperture field, one coupling window in the post-wall waveguide was analyzed by the method of moments as a unit in a model of a rectangular waveguide with the periodic boundary condition in the narrow walls as shown in Fig. 2 [9]. This analysis model assumed the periodicity of the parallel-plate fields in the transverse direction (x-direction) [18]. In this paper, the same analysis model is used to suppress sidelobes since the amplitude taper between adjacent coupling windows in Taylor distribution is small enough to be neglected provided that the an array is large to some extent. Every coupling window with a post is designed to suppress the reflection. Therefore, the coupling power into each window can be designed in a deterministic way from the matching unit to that close to the T junction based on the power conservation [19]. When N coupling windows are cascaded, the coupling $C(n)$, the ratio of the divided power to the input power, in the nth window ($1 \leq n \leq N$) is given as

$$C(n) = \frac{A(n)^2}{\sum_{i=n}^{N} A(i)^2} \tag{1}$$

where $A(n)$ is a pure real value of the amplitude in the desired Taylor distribution. The coupling given in (1) can be controlled by the window width, while the reflection is minimized by the post location.

B. Design of Slot Pairs

The slot pairs on the parallel-plates are designed along the y-direction according to the following two steps.

1) The initial design is done similarly to the design for the coupling windows described in the previous subsection. The slot pair is analyzed by using an analysis model in Fig. 3(a), originally proposed for the design to get uniform distribution. In order to simulate the periodicity of the field in the parallel-plates, the internal region is replaced by a rectangular waveguide with the periodic boundary condition in the narrow walls. The external region is regarded as another rectangular waveguide with two sets of periodic boundary walls. Nonresonant slots are used for coupling control on the parallel-plate. In a slot pair, the coupling is controlled by the length of one slot and the reflection suppression is realized by optimizing the length and the distance of the other slot. In this reflection suppressing system, the design of Taylor distribution is straightforward based upon the power conservation, as is the case for the design of the coupling windows. Unfortunately, the amplitude taper after step 1) is different between the first half (toward $+y$) and the latter half (toward $-y$) of the array. The parameters of the two slots in a pair such as the length and the spacing will not be modified from that in the unit design.
2) The array with the parameters initially determined in 1) is not complete for realizing the desired Taylor distribution, mainly due to the mutual coupling of slots via exterior region. Then the full size of the 1-D slot pair array is analyzed as shown in Fig. 3(b). The mutual coupling from the pairs in the transverse (x) direction is approximated again by assuming that they are excited in equal complex amplitude. In the exterior region, the mutual coupling from the 2-D array is included discretely and sufficiently to get the convergence in the amplitude distribution. Numerical iteration is conducted until the desired Taylor distribution is predicted. Empirically, the slot parameters are modified only in the first half so that the coupling increases for weakly excited pairs. The parameters are unchanged in the pairs in the latter half.

IV. MODEL ANTENNAS

Three types model antennas are designed and fabricated. These have the sidelobes suppressed only in the *E*-plane (*E*), only in the *H*-plane (*H*), and in the both planes (B). The sidelobe

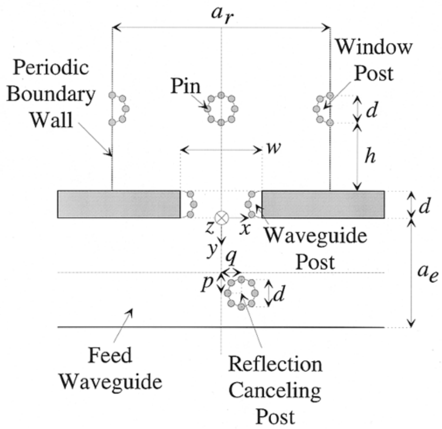
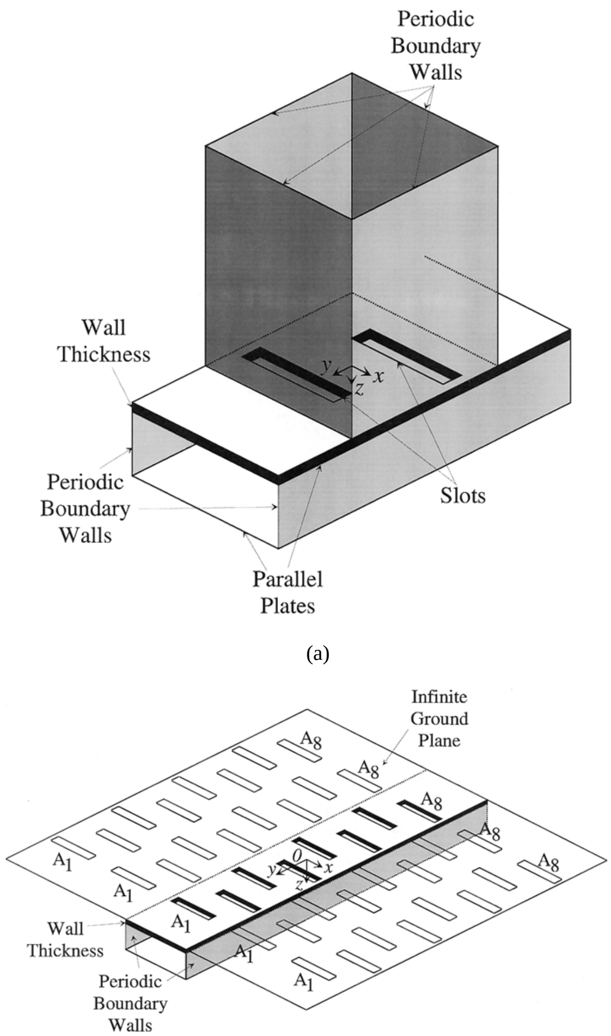


Fig. 2. Analysis model of the coupling window in the post-wall feed waveguide.



(a)

(b)

Fig. 3. Analysis models of the slot pair on the parallel-plates: (a) model for a unit pair and (b) model for a 1-D array.

level in the H-plane is associated with Taylor distribution in an array of the coupling windows in the feed waveguide. The

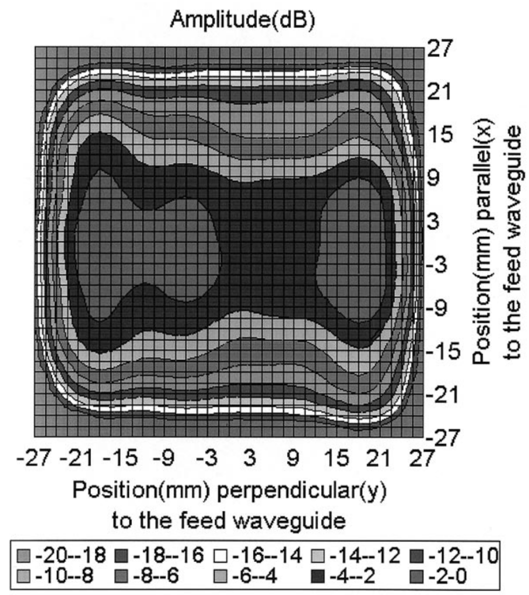


Fig. 4. Near-field amplitude distribution of antenna H (76.5 GHz).

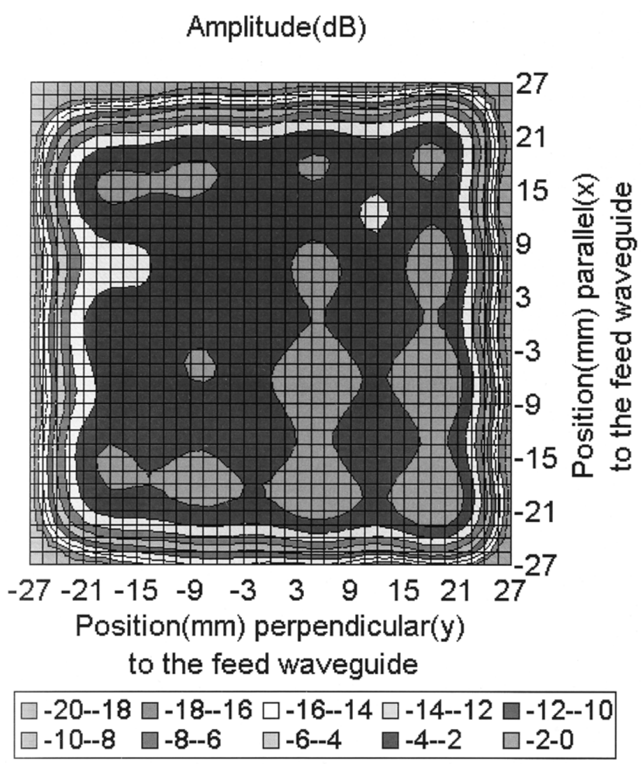


Fig. 5. Near-field amplitude distribution of antenna U (76.5 GHz).

E-plane sidelobes are suppressed by a Taylor distribution in an array of the radiating slot pairs on the parallel-plates. In (B), Taylor distribution is applied in both parallel and perpendicular directions of the feed waveguide. In the design for (H), the amplitude tapers in Taylor distribution are set to be −5.5 dB, −8.5 dB, and −12.0 dB to obtain sidelobe level of −20 dB, −25 dB, and −30 dB, respectively. Taylor distribution with −8.5 dB tapers are used for −25 dB sidelobe suppression in (E) and (B).

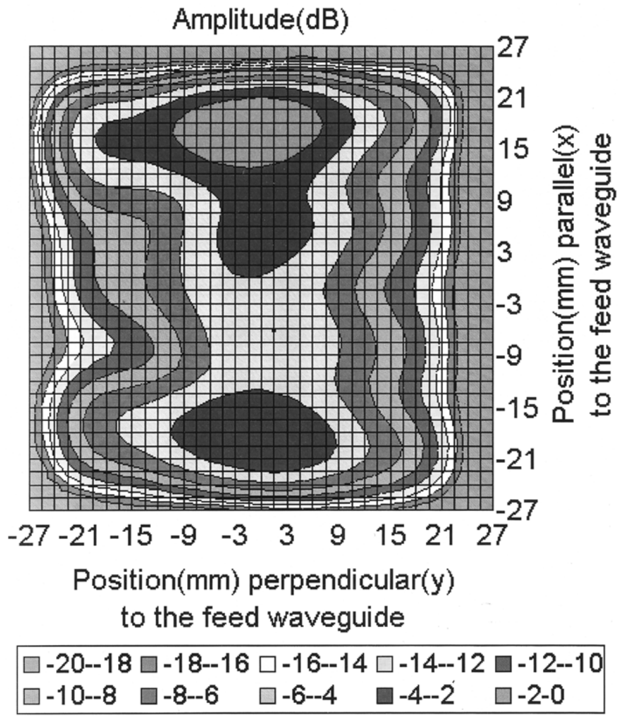


Fig. 6. Near-field amplitude distribution of antenna E (77.0 GHz).

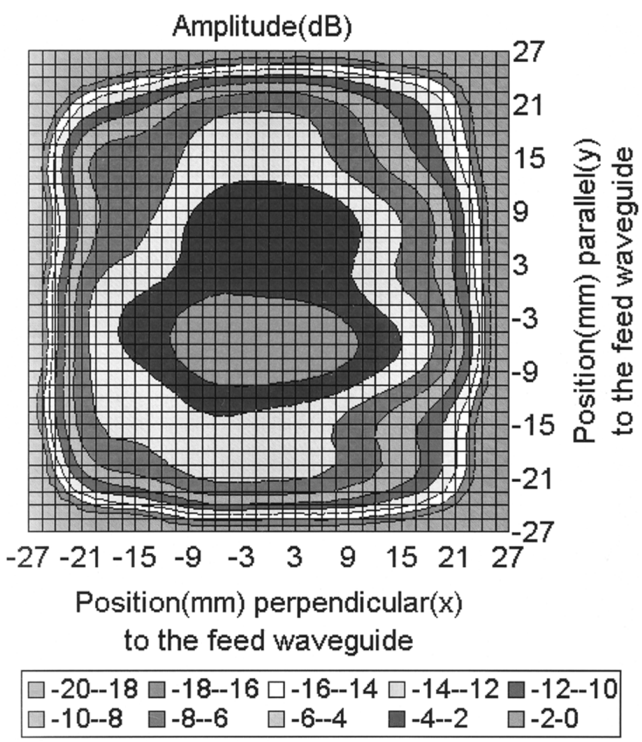


Fig. 7. Near-field amplitude distribution of antenna B (77.0 GHz).

The aperture size is 52 mm $\times$ 49 mm and is common for all the antennas. The design frequency is 76.5 GHz. A dielectric substrate of PTFE and glassfibers is used with 18-μm thickness rolled copper on the both surfaces. The use of rolled copper instead of plating copper is to reduce the conductor loss due to the roughness of the plate surfaces. The dielectric constant is 2.17 and the loss is $\tan\delta = 0.00085$ at 10 GHz. The height is 0.762 mm, 0.29 wavelengths at 76.5 GHz, which is much higher than that of a microstrip-type line. Many via-holes with 0.3 mm diameter are arrayed with a narrow spacing of 0.6 mm. The walls of the via-holes are metalized by plating copper. Slots with 0.2-mm width are etched on the upper plate.

V. Experimental Results

A. Near-Field Distribution

Fig. 4 shows the measured aperture amplitude distribution at 76.5 GHz of (*H*) for -12 dB taper in the design. Fig. 5 shows that of the antenna (U) designed for uniform distribution for the comparison. The shape of the amplitude taper realized by the array of the coupling windows is maintained well in the wave propagation in the parallel-plates. The amplitude around the ends of the feed waveguide in (*H*) is smaller by about 8 dB than that in (U). About 4 dB error in the illumination distribution is observed. It may be due to the analysis model assuming the uniform distribution. The amplitude perpendicular to the feed waveguide in (*H*) has 4 dB deviation as is also the case with that in (U).

Fig. 6 shows the amplitude distribution of (*E*) at 77.0 GHz, where the sidelobes are suppressed best in the radiation pattern as is explained later. This frequency is slightly higher than the design one, since the length in the radiating slots becomes 5–10-μm shorter in the fabrication. In Fig. 6, strong field is observed horizontally in the upper region. This comes from the strong excitation in the coupling window corresponding to this position. The measured amplitude taper in the direction perpendicular to the feed waveguide is about -8 dB, which is almost equal to the design taper.

Fig. 7 shows the amplitude distribution of (B) at 77.0 GHz. The strongest field is located around the center of the aperture. The amplitude taper is about -8 dB in both directions, parallel and perpendicularly to the feed. All these results suggest that the Taylor distribution can be realized in the parallel-plate slot array, though the analysis model with the mutual coupling taken into account must be used.

B. Radiation Patterns

Fig. 8 shows the measured radiation pattern of (*H*) for -30 dB sidelobe suppression in the design. The sidelobes in the *H*-plane are suppressed below -22.7 dB. The measured sidelobe level is slightly higher than the design one, reflecting that the amplitude taper in the near field distribution in the measurements is smaller than the design as shown in Fig. 4. The sidelobes in the *E*-plane is suppressed to -11.6 dB. The 3-dB beamwidth in the *H*-plane is 5.0°, which is wider than 4.1° in the *E*-plane. Fig. 9 shows the actual sidelobe level and the 3-dB beamwidth as functions of the design sidelobe level. The values for the uniform design are also included in this figure for the comparison. For lower design sidelobe level, the actual sidelobe level decreases and the 3-dB beamwidth becomes wider. In all the cases, the actual sidelobes are a bit less suppressed than the design one. In other words, the design should include this discrepancy in advance in order to get the desired sidelobe level.

Fig. 10 shows the radiation pattern of (*E*) at 77.0 GHz. The sidelobe suppression is achieved to the level of -22.0 dB and

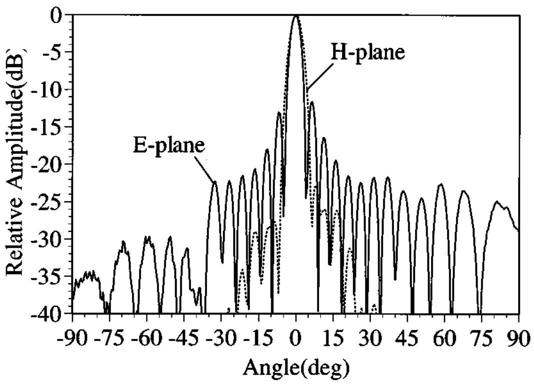


Fig. 8. Radiation pattern of antenna H (76.5 GHz) (solid line: E-plane pattern; dotted line: H-plane pattern).

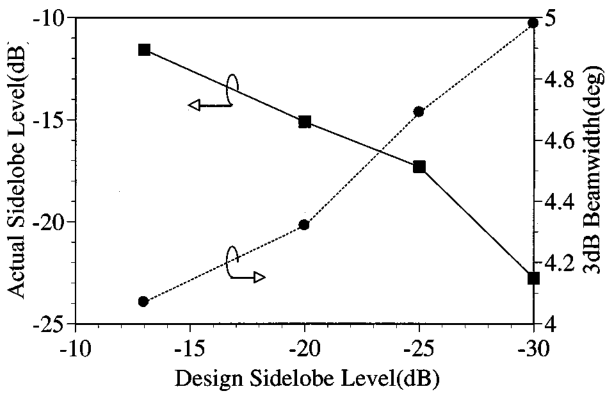


Fig. 9. Actual sidelobe level and 3-dB beamwidth of antenna H as functions of design sidelobe level (76.5 GHz).

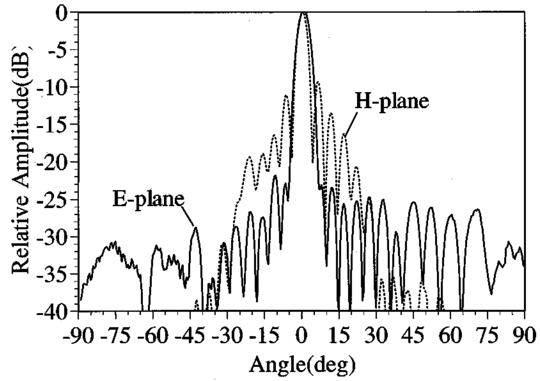


Fig. 10. Radiation pattern of antenna E (77.0 GHz) (solid line: E-plane pattern; dotted line: H-plane pattern).

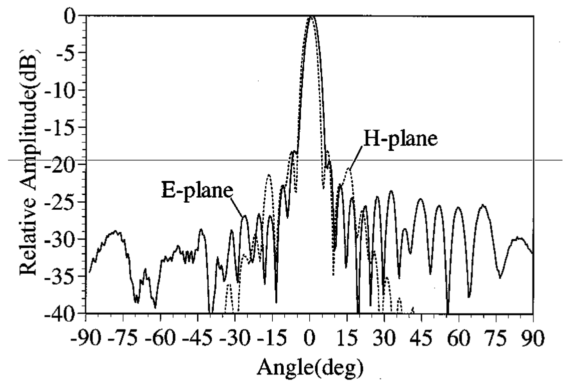


Fig. 11. Radiation pattern of antenna B (77.0 GHz) (solid line: E-plane pattern; dotted line: H-plane pattern).

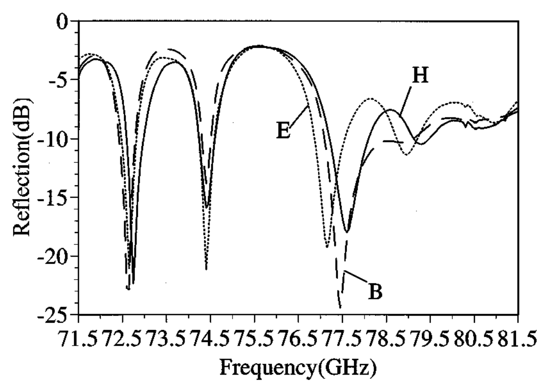


Fig. 12. Frequency dependence of reflection.

the 3 dB beamwidth is 4.9° in the E-plane. The analysis model of a rectangular waveguide with the periodic boundaries in the narrow walls is effective in the design for the sidelobe suppression in an array of the radiating slot pairs on the parallel-plates. The sidelobe level of -9.4 dB in the H-plane is slightly higher than that for uniform aperture field because of the asymmetrical aperture field along the feed waveguide as shown in Fig. 6.

Fig. 11 shows the radiation pattern of (B) at 77.0 GHz. The sidelobe suppression in both planes is successful. The sidelobe level is -18.1 dB in the E-plane and -18.0 dB in the H-plane. The 3-dB beamwidth is 4.8° in the E-plane and 4.6° in the H-plane.

When Taylor distribution is adopted either in the perpendicular or the parallel direction to the feed waveguide, the sidelobe level in the radiation pattern can be estimated by the amplitude level in the near-field distribution since the aperture field is almost uniform in the opposite direction. However, this is not correct when Taylor distribution is applied to the both directions.

C. Reflection

Fig. 12 shows the frequency dependence of the reflection. All the antennas have almost the similar tendency. The reflection is around -4 dB (40%) at 76.5 GHz. This reflection loss for the gain is estimated to be about -2.2 dB (100–40% = 60%). It is revealed after measurement that the input aperture itself has -11 dB reflection due to its position error of 0.2 mm in all the antennas. The frequency dependence has the minimums at some period. This may come from the interference of the reflection at the input port and that of the match junction at the ends of the feed post-wall waveguide.

D. Gain

Fig. 13 shows the frequency dependence of the gain of the sidelobe-suppressed antennas. The result of the antenna for the uniform aperture field is included for the comparison. The thick

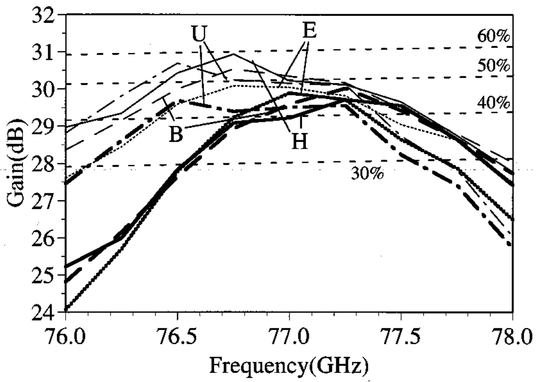


Fig. 13. Frequency dependence of gain (thick lines: measured; thin lines: eliminating the reflection).

lines are the measured gain. The thin lines indicate the gain eliminating the reflection loss in order to evaluate the gain reduction due to the sidelobe suppression. The gain reduction by the sidelobe suppression is less than 1 dB both in the measurement. The peak of the measured gain is 29.9 dBi at 77.0 GHz in (*E*). The efficiency is 46.3% for the aperture size. The bandwidth in the gain eliminating the reflection is almost the same among all the antennas.

VI. CONCLUSION

We have designed and fabricated three types of the 76-GHz antennas. The shape of the amplitude taper has been maintained well in the wave propagation in the parallel-plates. We have measured low sidelobes below -22 dB for *E*- or *H*-plane suppression. For the antenna with sidelobe suppression in the both (E and H) planes, slightly larger sidelobe of -18 dB was realized. The serious gain reduction by the sidelobe suppression has not been observed.

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