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An Alternating-Phase Fed Single-Layer Slotted Waveguide Array in 76 GHz Band and Its Sidelobe Suppression

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SUMMARY This paper presents designs and performances of 76 GHz band alternating-phase fed single-layer slotted waveguide arrays. Two kinds of design, that is, uniform aperture illumination for maximum gain and Taylor distribution for sidelobe suppression of −25 dB, are conducted. High gain and high efficiency performance of 34.8 dBi with 57% is achieved for the former, while satisfactory sidelobe suppression of −20 dB in the H-plane and −23 dB in the E-plane with high efficiency is confirmed for the latter. The simple structure dispensing with electrical contact between the slotted plate and the groove feed structure is the key advantage of alternating-phase fed arrays and the slotted plate is just tacked on the feed structure with screws at the periphery. High gain and high efficiency performances predicted theoretically as well as design flexibility of the alternating-phase fed array are demonstrated in the millimeter wave frequency.

key words: *alternating-phase, slotted waveguide array, planar antenna, millimeter wave, sidelobe suppression*

1. Introduction

High-gain and mass-producible planar antennas are strongly demanded in accordance with development of millimeter-wave applications such as fixed wireless access (FWA) systems in 20–40 GHz, high-speed wireless LANs or video transmission systems for indoor use in 60 GHz and automotive radar systems in 76 GHz. For most of these applications, in the automotive radar antennas operating in mechanical beam scanning for ITS systems, for example, not only high gain and narrow beam width but also low sidelobe level is strongly required.

A single-layer slotted waveguide array [1] is an attractive candidate for these millimeter applications because of the following reasons; (1) Transmission loss of a waveguide is extremely low even in millimeter-wave in principle, while the other types of planar arrays fed by microstrip or triplate lines inherently suffer from the serious transmission loss. (2) The simple structure consisting of only two parts, a slotted plate and a groove feed structure, is cost-effective and is suitable for mass-production, as shown in Fig. 1. (3) All the waveguides are operating in single-mode; mature design techniques such as sidelobe suppression are available.

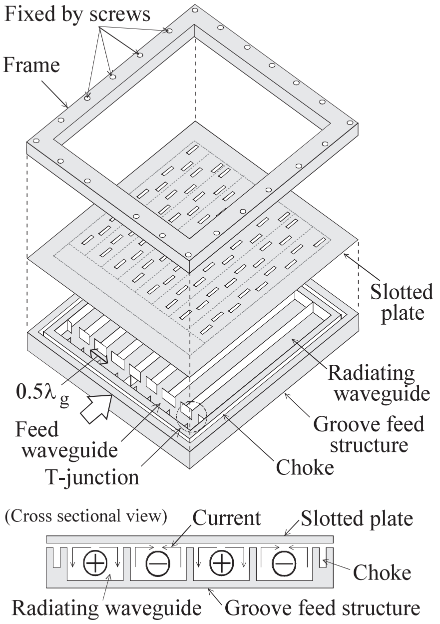

Fig. 1 Configuration of an alternating-phase fed single-layer slotted waveguide array.

Figure 1 presents the configuration of alternating-phase fed single-layer slotted waveguide arrays with wide chokes [2]–[7]. They consist of radiating waveguides with resonant shunt slots on the broad wall arrayed side by side and a feed waveguide attached in the same layer. The adjacent radiating waveguides are excited in 180 degree out of phase via windows spaced by half the guide wavelength of the feed waveguide. The unique advantage of the alternating-phase fed array is that the electrically tight contact between the slot plate and the narrow walls of the waveguides on the base plate is not required in principle because adjacent waveguides are excited in alternating phase and because electric currents on the narrow walls do not flow across the contacts shown in Fig. 1 [2]–[4]. Furthermore, a choke structure is introduced along the periphery of the aperture in order to eliminate the energy leakages at the periphery, where the above condition does not hold [5]. Therefore, the alternating-phase fed array can be mass-produced at low cost by just fixing the slotted plate tacked on the feed structure with screws at the periphery.

The alternating-phase fed array has already been mass-produced at very low cost by die-casting technique and is put

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into practical use for a user's terminal unit of 26 GHz wireless IP access service (WIPAS) system [6], [7]. The high gain of 31.5 dBi and efficiency of 65% has been achieved. In order to demonstrate the potential advantage of this waveguide array in the millimeter wave band, the alternating-phase fed array was also fabricated for 76 GHz radar application. However, the gain and efficiency of the test antenna, consisting of stainless steel, were low, only 32.6 dBi and 33%, respectively; the high potential of this unique arrays in millimeter wave frequency have not been fully confirmed [8], [9].

If we are not concerned about mass producability, excellent gain and efficiency of 35.5 dBi and 64% efficiency has already been realized by the prototype of the co-phase fed single layer slotted waveguide array in 76 GHz [10]. Sidelobe suppression for Taylor radiation pattern of −25 dB has also been reported. The serious disadvantage of the co-phase fed array where all the radiating waveguides are excited in-phase by π-junctions is that the electrically tight contact such as brazing between the slotted plate and the feed structure is indispensable [11]. Another example of a high-gain and high-efficiency planar antenna with more than 30 dBi gain in 76 GHz is the dielectric planar leaky-wave antenna developed by Anritsu, in which a dielectric slab waveguide of low-loss ceramic substrate is used as a feeder [12]; this is not so cost effective for mass production.

With the above background in mind, this paper solves two problems of the previous fabrication of alternating-phase fed arrays, that is, the choice of low loss conductor as well as grating lobe suppression. Influences of the materials of the antenna and the grating lobes in the diagonal planes due to the staggered slot arrangement on the gain and efficiency are discussed. The prototype antennas made of aluminum are designed in 76 GHz by techniques established for 26 GHz FWA systems [5]; it brings about 1 dB higher gain than the previous one of stainless steel while larger backward beam tilting is adopted to eliminate the grating lobes; 34.8 dBi gain and 57% efficiency is observed. In addition, the sidelobe suppression by adopting Taylor distribution is also conducted. The reasonable suppression of sidelobes, −20 dB in H-plane and −23 dB in E-plane, is achieved.

In Sect. 2, operation of the alternating-phase fed array is summarized briefly. In Sect. 3, key points of design of the slot array and the T-junctions associated with H-plane and E-plane radiation pattern synthesis are summarized, respectively. In Sect. 4, experimental results of the model antennas are described, where influences of loss in the conductor and grating lobes in the diagonal planes on the gain and efficiency are discussed. The performance of the model antennas with sidelobe suppression is also presented.

2. Alternating-Phase Fed Arrays

Figure 1 presents the structure of the alternating-phase array, which consists of two parts, that is, a slot plate as the broad wall and a corrugated base plate which accommodates radiating and feed waveguide in the same layer. The frame is used to reinforce screw mounting of the slot plate over the base plate. The feed waveguide consists of T-junctions and works as a multiple-way power divider to the radiating waveguides. The spacing between adjacent coupling windows is a half guide wavelength to excite the adjacent radiating waveguides with 180 degree out of phase. The width of the feed waveguide is set so that the wavelength is twice of the broad wall width of the radiating waveguides. Divided waves into the radiating waveguides are controlled by width and offset of the coupling windows in the T-junctions. The radiation pattern in the E-plane is associated with power diving distribution in the series of T-junctions in the feed waveguide into the radiating waveguides.

The radiating waveguides have a resonant shunt slot array on the broad wall [13]. Longitudinal slots with staggered offsets are arrayed at intervals of approximately a half of the guided wavelength so that the slots are excited in-phase. Thus, all the slots over the aperture are excited in-phase. The radiation pattern in the H-plane of the alternating-phase fed array reflects the excitation distribution of the slot array and length and offset of each slot in the array are varied to synthesize the aperture distribution. The coupling strength of each slot is mainly controlled by the slot offset, while the slot length is set to be a resonant slot. The slot spacing along the waveguide axis is constant as is usual the case with a resonant shunt slot array to realize uniform phase distribution [13].

3. Array Design

3.1 Slot Design

For accurate slot design, it is important to take the mutual couplings between slots in the external region into account since the slots on adjacent waveguides are arranged very closely in the alternating-phase fed array. The authors have established an approximate EM analysis model for slot coupling in the environment of uniform aperture illumination, where a combination of PEC walls and periodic boundary walls is placed in the external region to simulate the mutual couplings approximately [5]. The relationship among the slot offset, length and the coupling strength is analyzed by the method of moments for the model [14], [15] and is reserved as the design chart. In designing aperture distribution, the couplings are assigned for each slot by an equivalent circuit of the array first [16], [17]. Then offset and length of each slot required for the coupling are determined by using the design chart obtained in EM analysis. Finally, the slot offsets and lengths of the array are fine-tuned by taking the effects of finite size of the array into account. The detail of design of the slot array for uniform aperture illumination is described in the literature [5]. This design technique is extended to the aperture synthesis of Taylor distribution as well by simply changing the assignment of coupling strength of each slot in the equivalent circuit of the array. The details of the slot design for Taylor distribution is beyond the scope of this section.

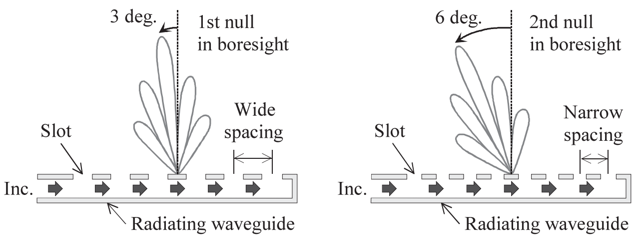


Fig. 2 Backward beam tilting with different slot spacing for grating lobe suppression.

Important design of the alternating-phase fed array is to suppress grating lobes in the diagonal planes, because the periodicity of the staggered slot arrangement in the diagonal directions becomes approximately 1 wavelength in the free space. This corresponds to the critical condition for the grating lobes to be visible or not. The gain and the aperture efficiency are degraded considerably by the grating lobes though their level seems not to be so high. Therefore, it is important to reduce the diagonal spacing. This is accomplished in this paper by introducing backward beam tilting, in which the main beam is slightly tilted toward the feed point from the boresight of the array as shown in Fig. 2. The beam tilting technique [18] is often used for suppressing the reflection from the slots at the feed point. The slot spacing s is perturbed from the half of the guide wavelength according to the tilting angle through the following condition [19],

$$s = \frac{\lambda_g}{2} + \frac{m}{N}\lambda_g \tag{1}$$

where the tilting angle is specified by m, that is, the m-th null of the radiation pattern of the array falls on the boresight as shown in Fig. 2; λ_g is the guide wavelength and N is the number of slots in the array. The negative number of m corresponds to the backward beam tilting and results in the smaller spacing than a half of the guided wavelength. The backward beam tilting reduces the slot periodicity in the diagonal directions and then the grating lobes, appearing in the diagonal plane, are suppressed. In this paper, gain of the alternating-phase fed arrays with different beam tilting angles ($m = -1$ and $m = -2$) is compared.

3.2 Design of the T-Junctions

Here the design of a unit T-junction as well as the feed waveguide for E-plane pattern synthesis is briefly summarized [9]. Figure 3 presents the analysis model for a unit T-junction. The structure is 2-dimensional because it is uniform in a perpendicular direction. The incident wave propagating in the feed waveguide couples to the coupling window and is divided into the radiation waveguide. Amplitude and phase of the divided wave are controlled by width w and offset d of the coupling window, respectively. The reflected wave from the window is canceled out by an inductive wall installed in the feed waveguide. The position of the inductive wall (p and q) is optimized so that the reflection is minimized. The reflection from each T-junction is negligibly small that traveling wave operation in the feed waveguide is expected.

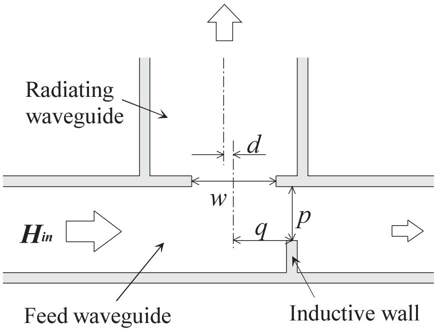
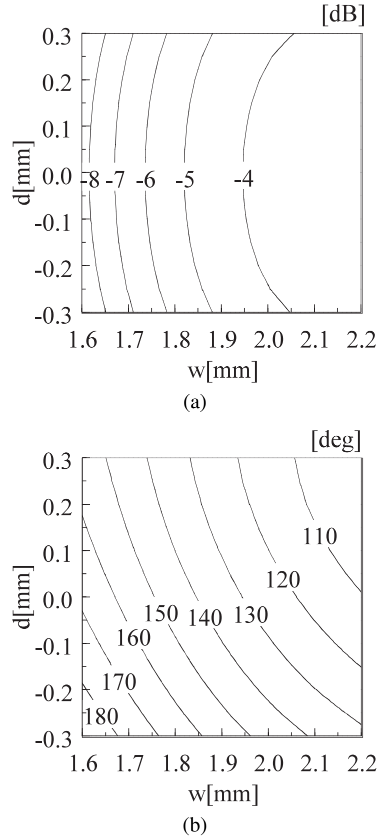


Fig. 3 Analysis model for a unit T-junction.



(a)

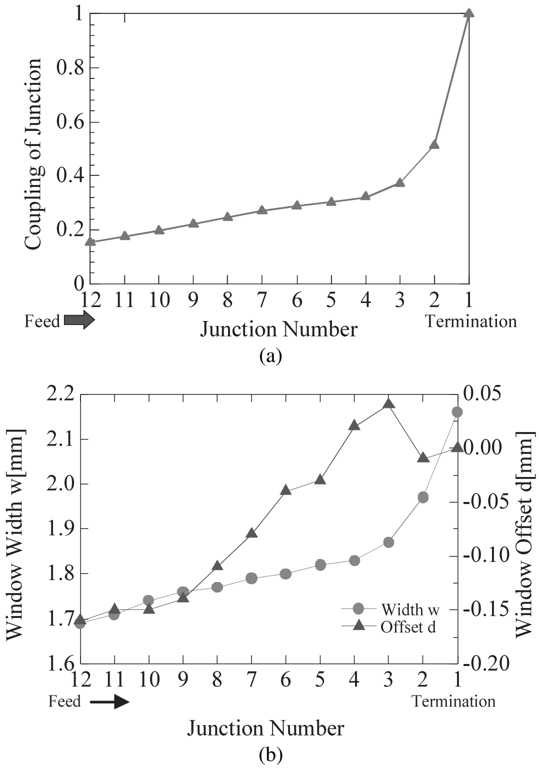
(b)

Fig. 4 Characteristics of a divided wave in a T-junction. (a) Amplitude. (b) Phase.

In design of the feed waveguide for desired power dividing distribution, it is necessary to control the window width w and the offset d of each T-junction. Figure 4(a) and (b) present amplitude and phase of the divided wave as a function of w and d, respectively, which is analyzed by the method of moments for a unit T-junction as shown in Fig. 3 [20], [21]. The frequency is set to be 76.5 GHz. The widths of the broad wall of the feed waveguide and the radiating one are 2.46 mm and 2.53 mm, respectively. Height and thickness of the narrow walls separating the waveguides are 1.47 mm and 0.78 mm, respectively. From these figures, *w* and *d* can be chosen so that the desired amplitude and phase of the divided wave are obtained for each T-junction. It is straight forward in that *w* is chosen for the specified amplitude in Fig. 4(a) first and then *d* is determined for the specified phase in Fig. 4(b).

Design of the T-junctions for Taylor distribution with −25 dB sidelobe level and $\bar{n}$= 5 is described [9]. Taylor distribution is widely used for high gain and low side lobe antennas. The radiation pattern of the Taylor distribution is a combination of patterns created by the Chebyshev distribution and the uniform distribution, that is, a few side lobes around the main lobe is constant level while the other side lobes are decaying rapidly toward the end-fire directions. The side lobe level of the Taylor distribution is associated with that of the Chebyshev distribution and $\bar{n}$ indicates the null point at which the both radiation patterns are changed.

The Taylor line source for the desired sidelobe level is synthesized by the Woodward-Lawson's method [22]. In this case, 8 dB amplitude taper with constant phase distribution is desired from the center to the termination of the feed waveguide. Figure 5(a) presents the specified coupling strength of each T-junction for the Taylor distribution, where 24 radiating waveguides are assumed. In this figure, the junction is numbered from the termination to the feed point and the results of 12 waveguides are presented since the T-junctions are arrayed symmetrically with respect to the center. The coupling strength is gradually increasing from the feed to the termination. Figure 5(b) presents variation of the window width *w* and the offset *d* of the T-junctions. The window width *w* varies corresponding to the coupling strength in Fig. 5(a) while the offset *d* is chosen so that the phase of the divided waves in the adjacent waveguides may be 180° out of phase.



(a)

(b)

Fig. 5 Design parameters of T-junctions for Taylor distribution with −25 dB sidelobes. (a) Coupling distribution. (b) Window width *w* and window offset *d*.

4. Measurements

4.1 Test Antennas

In order to evaluate the performance of the alternating-phase fed arrays in millimeter wave band, total of four test antennas with uniform or Taylor distribution (sidelobe level = −25 dB, $\bar{n}$= 5), each with 3° or 6° backward beam tilting, are designed and fabricated at 76.5 GHz [23]. The test antennas consist of 24 radiating waveguides with a slotted area of 80 mm in the feed waveguide direction by 84 mm in the radiating waveguide direction. Number of slots in a radiation waveguide depends upon the angle of backward beam tilting; 29 slots for 3 degree beam tilting ($m = -1$), while 31 slots for 6 degree beam tilting ($m = -2$). Common dimensions and parameters of the test antennas are summarized in Table 1.

Figure 6 presents a photograph of the test antenna. Material of the slotted plate and the groove feed structure is aluminum. The slotted plate with a thickness of 0.1 mm is processed by etching. The groove feed structure with a depth of 1.47 mm is manufactured by machining process. The manufacturing accuracy is specified within ±0.01 mm. The both

Table 1 Parameters of the test antennas.

Design frequency	76.5 GHz	
Number of waveguides	24	
Width of radiating waveguides	2.53 mm	
Width of feed waveguide	2.46 mm	
Height of waveguides	1.47 mm	
Thickness of narrow walls	0.78 mm	
Thickness of a slotted plate	0.1 mm	
Direction of beam tilting	Backward	
Beam tilting angle	3 deg.	6 deg.
Number of slots	29	31
Slot spacing	2.88 mm	2.69 mm
Aperture area	80 mm x 84 mm	

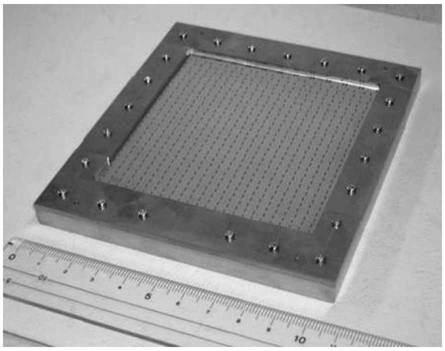


Fig. 6 Photograph of the test antenna.

parts are just tacked and screwed at the periphery of the antenna. A metal frame with a relatively large thickness is put on the slotted plate to realize close contact between the slotted plate and the feed structure around the choke, as shown in Fig. 1. A WR-15 standard waveguide is connected to the back of the feed structure as a feeder.

Gain and radiation patterns of the test antennas are measured in an anechoic chamber where a standard gain horn of 25 dBi is used as a reference antenna. Aperture field distributions are obtained by near field measurement. A truncated waveguide (WR-12) is used as a probe and is scanned at the height of 16 mm ($4\lambda_0$) over the aperture. The scanned area is 120 mm by 120 mm and the scanning step is 1.5 mm. The measured data is transformed from the scanning plane to the antenna aperture.

4.2 Performance of the Array with Uniform Aperture Distribution

Influences of loss due to the material of the antenna and the grating lobes due to the staggered slot arrangement on the gain and efficiency are discussed experimentally. Figure 7 presents frequency dependence of the measured gain and the corresponding efficiency of the test antennas designed for uniform aperture illumination. This figure also includes results of an antenna of stainless steel with the same design as that of 3 degree beam tilting ($m = -1$) [9]. Compared with the antennas of aluminum and stainless steel with 3 degree beam tilting, 34.2 dBi gain with 48% efficiency is obtained by the antenna of aluminum while 32.6 dBi gain with 33% efficiency by the antenna of stainless steel. The efficiency is increased by 15% by replacing the material to aluminum. The estimated losses of aluminum and stainless steel waveguide with the conductivities of 3.8×10^7 S/m and 1.4×10^6 S/m are −0.24 dB and −1.26 dB, respectively, where 60 mm is used for the effective length of the waveguides in the antenna. The excessive loss of about 1 dB reasonably accounts for the measured antenna efficiency degradation of 15%.

The highest gain of 34.8 dBi with 57% efficiency is obtained by the antenna of aluminum with 6 degree beam tilting. This efficiency is comparable to the co-phase fed waveguide array processed by brazing contact and is twice higher than conventional typical planar arrays in the range of high gain over 30 dBi and high frequencies. The efficiency is enhanced by around 10% in comparison with the antenna of the same material with 3 degree beam tilting. Figure 7 compares the calculated gain and efficiency of the antennas with the different beam tilting angles of 3 degrees and 6 degrees, where the waveguide loss is ignored. The discrepancy seems to be very small. It means that it is difficult to evaluate the small grating lobes accurately in the calculation, where the slots are approximated to small magnetic dipoles [24]. The influence of the grating lobes due to the staggered slots on gain and efficiency are compared quantitatively by the measurements.

Figure 8 presents the measured reflection at the feed point. It is around −15 dB at the design frequency for the both antennas. Figure 9(a) and (b) present the measured aperture field distribution at 76.5 GHz, where the feed waveguide is located between $Y = 40$ mm and $Y = 50$ mm. The reference plane of the phase distribution is set to be perpendicular to the tilted beam direction. Almost uniform aperture distributions are observed at the design frequency. The small ripples in the amplitude distribution are due to alignment error of the slotted plates.

The effects of misalignment of the slot plate in the single layer slotted waveguide arrays were discussed in [11]. Figure 10 presents predicted efficiency degradation due to the alignment error of the slotted plate in the X-direction. Taking 5% loss of the waveguides due to the conductivity of aluminum into account, the excessive loss of about 20% in measurement may be partly due to this alignment error of 0.06 mm or 1.5% of a wavelength in 76 GHz. Fine alignment accuracy is required in 76 GHz, as is usual the case with other millimeter-wave antennas, though the request for electrical contact is relaxed.

The phase distribution is slightly tapered along the feed

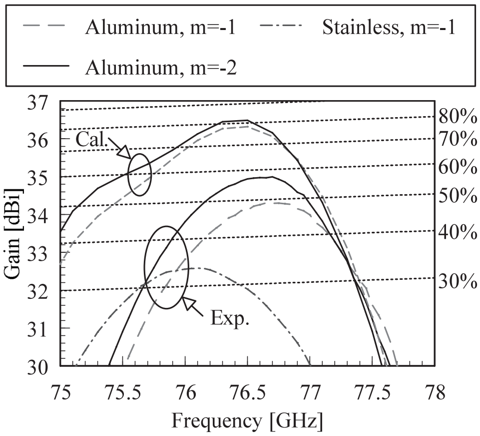


Fig. 7 Measured gain and efficiency of the test antennas for uniform aperture distribution with 3 deg. beam tilting ($m = -1$) and 6 deg. beam tilting ($m = -2$).

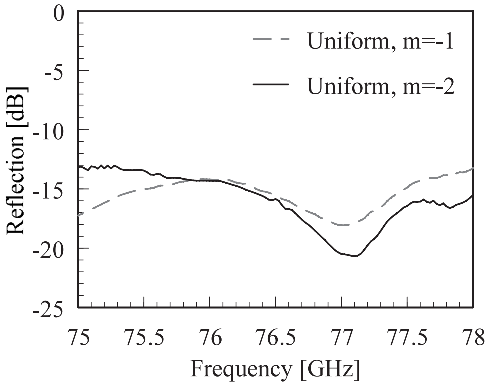


Fig. 8 Measured reflection at the feed point of the test antennas for uniform distribution with 3 deg. beam tilting ($m = -1$) and 6 deg. beam tilting ($m = -2$).

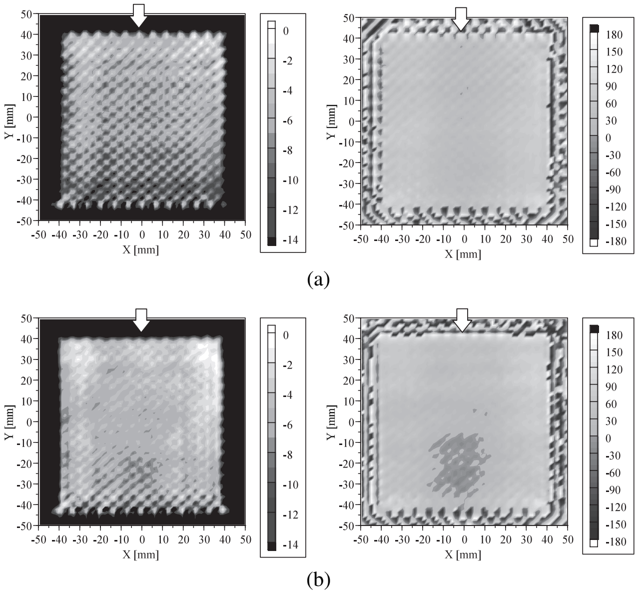


Fig. 9 Measured aperture illumination at 76.5 GHz. (Left; Relative amplitude in dB, Right; Phase in deg.) (a) Uniform antenna with 3 deg. beam tilting ($m = -1$). (b) Uniform antenna with 6 deg. beam tilting ($m = -2$).

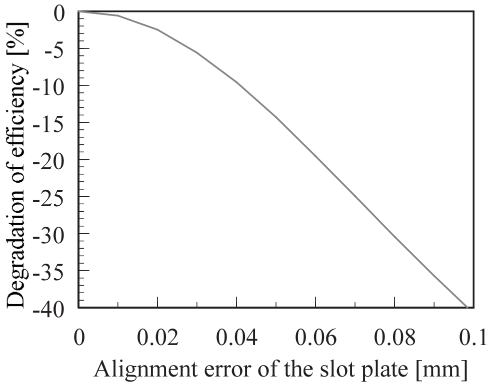


Fig. 10 Degradation of efficiency due to alignment error of the slotted plate.

waveguide (X-axis) in Fig. 9(a) and (b). The operating frequency of the T-junctions in the feed waveguide is shifted to 76.75 GHz. This is because the slotted plate just tacked and fixed by screws slightly affects operation of the T-junctions, while its effect is not taken into account in the design. This should be solved in the future.

Figure 11(a) and (b) present the radiation patterns of the uniform antenna with 6 degree beam tilting in the H-plane at 76.5 GHz and in the E-plane at 76.75 GHz, respectively. The measured patterns and the calculated ones are in good agreement. The first side lobe level is −13 dB in both H- and E-planes.

4.3 Performance of the Array with Taylor Distribution

Figure 12(a) and (b) present the measured aperture field distribution of the antennas designed for −25 dB Taylor patterns with 3 degree and 6 degree beam tilting at 76.5 GHz, respectively. 2-dimensional tapered amplitude distribution with uniform phase is observed for the both antennas, while the amplitude ripples due to the alignment error are observed similarly. Figure 13(a) and (b) present the radiation patterns

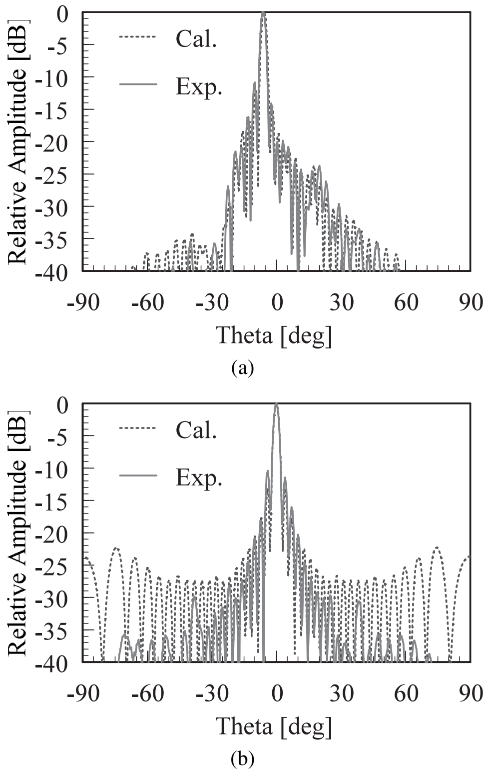


Fig. 11 Radiation patterns of the uniform antenna with 6 deg. beam tilting ($m = -2$). (a) H-plane. (b) E-plane.

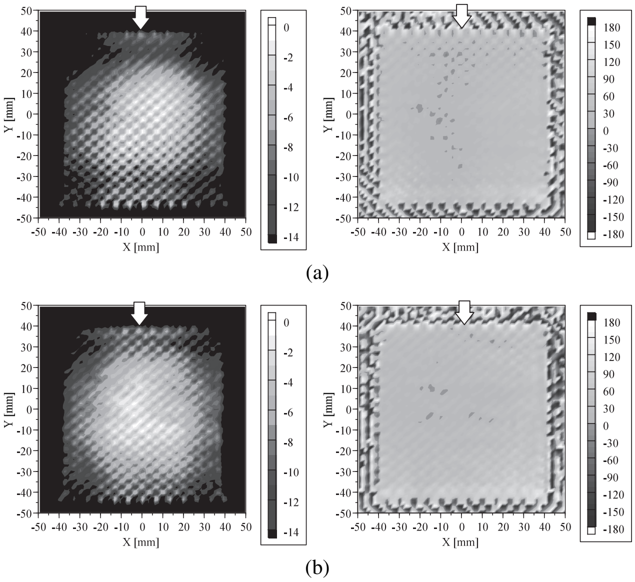
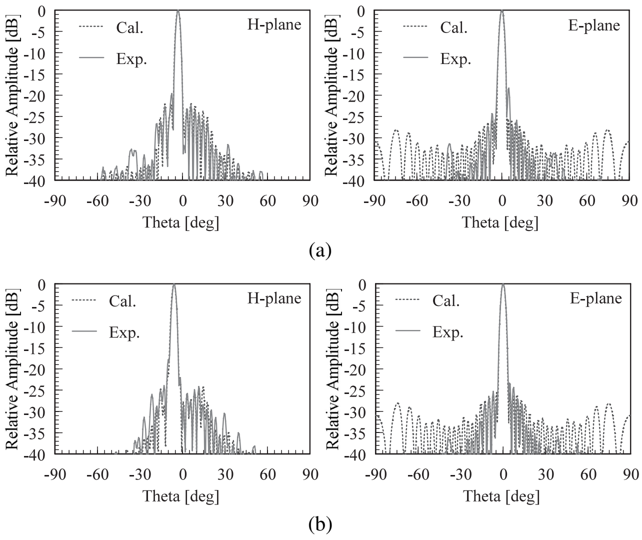


Fig. 12 Measured aperture illumination at 76.5 GHz. (Left; Relative amplitude in dB, Right; Phase in deg.) (a) Taylor antenna with 3 deg. beam tilting ($m = -1$). (b) Taylor antenna with 6 deg. beam tilting ($m = -2$).



(a)

(b)

Fig. 13 Radiation patterns of the test antennas with Taylor distribution. (Left; H-plane at 76.5 GHz, Right; E-plane at 76.75 GHz.) (a) Taylor antenna with 3 deg. beam tilting ($m = -1$). (b) Taylor antenna with 6 deg. beam tilting ($m = -2$).

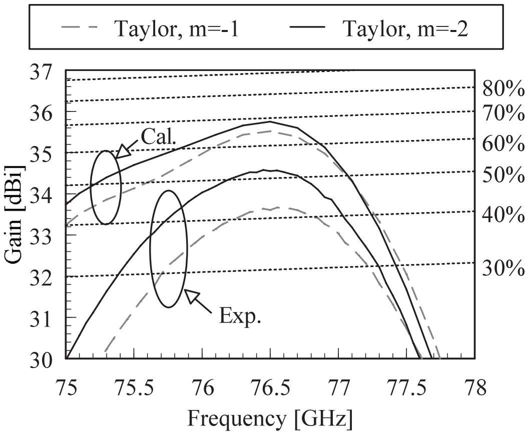


Fig. 14 Measured gain of the test antennas for Taylor distribution with 3 deg. beam tilting ($m = -1$) and 6 deg. beam tilting ($m = -2$).

of the Taylor antennas. The H- and E-plane patterns are measured at 76.5 GHz and 76.75 GHz, respectively. Good agreement between the measured patterns and the calculated ones is observed in the figures. Comparable sidelobe performances are obtained for the both beam tilting angles. The measured side lobe level is −23 dB in the E-plane of the antenna with 6 degree beam tilting, while it is −20 dB in the H-plane of the antenna with 3 degree beam tilting. Even for the calculated H-plane patterns, the sidelobe level exceeds the specified one of −25 dB by a few dB. This is because coupling strengths of slots near the both ends of the waveguides are not evaluated accurately, where the analysis model for slot coupling uses the periodic and PEC conditions to simulate the external mutual couplings as is described in Sect. 3.1. This problem should be solved in the future.

Figure 14 presents the measured gain and efficiency of the Taylor antennas. The reduction of gain and efficiency due to the tapered amplitude distribution is within 1 dB and 10%, respectively, in comparison with the uniform antennas. The difference of the efficiency due to the different beam tilting angles is 10% similarly as is explained in the previous section. Satisfactory performance of the sidelobe suppression as well as the high efficiency is confirmed by the test antennas for Taylor distribution.

5. Conclusion

The alternating-phase fed waveguide slot arrays with uniform aperture illumination for maximum gain and Taylor one for sidelobe suppression of −25 dB are designed and tested in 76 GHz. The structure of the test antennas dispensing with electrical contact is suitable for mass production in millimeter wave. The slotted plate is just tacked on the feed structure and is fixed by screws. High gain and high efficiency performance of 34.8 dBi with 57% is obtained by the antenna of aluminum with 6 degree backward beam tilting. The influences of the lossy material of stainless steel for waveguide antennas and the grating lobes due to the staggered slot arrangement on the gain and efficiency are evaluated experimentally. The suppressed sidelobes of −20 dB in the H-plane and −23 dB in the E-plane are obtained by the antennas with Taylor distribution. Satisfactory sidelobe suppression with high efficiency is confirmed. The high gain and high efficiency performance as well as design flexibility of the alternating-phase fed array is fully demonstrated.

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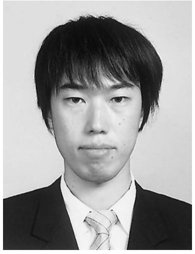

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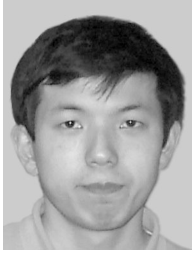

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