PAPER Special Section on Microwave and Millimeter-Wave Technology

An Alternating-Phase Fed Single-Layer Slotted Waveguide Array with a Sector Shaped Beam for Millimeter-Wave Radar Applications

Yuichi KIMURA[†a)], Atsuo SENGA[††], Masayoshi SAKAI[††], *Members*, *and* Misao HANEISHI[†], *Fellow*

SUMMARY This paper presents design of an alternating-phase fed single-layer slotted waveguide array for a sector shaped beam in the E-plane radiation pattern. A sector beam pattern is very effective for radar applications for detecting obstacles in a certain angular range without mechanical or electronic scanning. The sector shaped beam with 13 degree beam width is synthesized by a cascade of T-junctions in the feed waveguide which excite the radiating waveguides with a longitudinal shunt slot array. In order to realize the required excitation distribution of the radiating waveguides for the sector shaped beam, 30 T-junctions with symmetrical arrangement are designed by tuning a width of the coupling window, an offset of the window, and a width of the feed waveguide cascaded to the subsequent T-junction, respectively. Design and measurement are performed in 60 GHz band. The prototype antenna assembles easily; the slotted plate is just tacked on the groove feed structure and is fixed by screws at the periphery, which is the key advantage of the alternating-phase fed arrays. The measured sector pattern with low sidelobe level agrees well with the predicted one. Validity of the sector beam design as well as the performance of the alternating-phase fed array is confirmed by the measurement.

key words: *alternating-phase, slotted waveguide array, sector shaped beam, millimeter wave, planar antenna*

1. Introduction

Recently, millimeter wave applications such as fixed wireless access (FWA) systems in 20–40 GHz, wireless HDTV transmission systems for indoor use in 60 GHz, and automotive radar systems in 76 GHz, have been developed intensively and some of them are already commercialized. For these millimeter applications, high-gain and mass-producible planar antennas are strongly desired to obtain good system performance at low cost. In most of radar antennas, mechanical or electronic scanning systems are utilized, however the scanning systems lead to the increase in cost of manufacturing products.

A single-layer slotted waveguide array [1] is an attractive candidate for high gain millimeter wave applications due to the following reasons; (1) Transmission loss of a waveguide is extremely low even in millimeter wave, while the other planar circuits such as microstrip or triplate lines suffer from serious transmission loss, which results in degradation of the system performance. (2) The simple structure consisting of only two components, a slotted plate and a groove feed structure as shown in Fig. 1, is suited for mass production. (3) Flexible design of the aperture illumination control is possible, since the whole array is operated in stable single-mode waveguides.

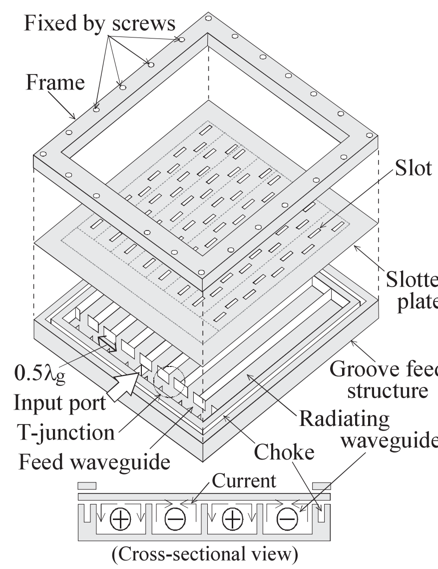

Fig. 1 Configuration of an alternating-phase fed single layer slotted waveguide array.

Figure 1 presents the configuration of an alternating-phase fed single-layer slotted waveguide array with a wide choke [2]–[7]. Radiating waveguides with a resonant shunt slot array on the broad wall [8] are arrayed side by side and one feed waveguide is situated at an end of the radiating waveguides to feed them. The whole structure is in a single layer. The feed waveguide with a cascade of T-junctions works as a multiple-way power divider to the radiating waveguides. The adjacent radiating waveguides are excited 180 degree out of phase with each other by coupling windows of the T-junctions, which is spaced by one half guided wavelength in the feed waveguide. Longitudinal slots in the radiating waveguides are arrayed at intervals of approximately a half of the guided wavelength to be excited in phase. The staggered slots in the adjacent waveguides are arranged symmetrically. Thus, all the slots over the aperture are excited in phase. The E-plane radiation pattern is associated with the divided waves into the radiating

Manuscript received February 5, 2007.
Manuscript revised April 13, 2007.
[†]The authors are with the Department of Electrical and Electronic Systems, Saitama University, Saitama-shi, 338-8570 Japan.
[††]The authors are with the Research and Development Center, The Nippon Signal Co., Ltd., Kuki-shi, 346-8524 Japan.
a) E-mail: ykimura@aplab.ees.saitama-u.ac.jp
DOI: 10.1093/ietele/e90–c.9.1801

waveguides, which are controlled by a width and an offset of the coupling window of the T-junctions. On the other hand, the H-plane pattern depends on slot excitations in the radiating waveguides; the coupling strength of each slot is mainly controlled by the slot offset, while the slot length is chosen to be a resonant slot.

The significant feature of the alternating-phase fed array is that the whole array can operate without electrically tight contact between the slotted plate and the groove feed structure in principle, since currents on the interior walls of the radiating waveguides do not pass the contacting surface, as shown in Fig. 1 [2]–[4]. Furthermore, a choke structure which surrounds the waveguides in the feed structure is introduced to eliminate the energy leakage at the periphery of the antenna [5]. Therefore, the alternating-phase fed array can be assembled by only fixing the slotted plate tacked on the feed structure with screws at the periphery. A metal frame with a relatively large thickness can be used to reinforce the screw mounting of the slotted plate over the feed structure.

The alternating-phase fed array is already mass-produced by the die-casting technique at very low cost for 26 GHz wireless IP access service (WIPAS) system [6]. High gain of 31.5 dBi and efficiency of 65% is achieved for this purpose. Furthermore, this antenna is tested in 76 GHz to demonstrate the potential advantage of this waveguide array in millimeter wave band as well as design flexibility for the aperture illumination control [7]. Highest gain of 34.8 dBi with 57% efficiency is obtained by the array designed for uniform aperture distribution. Side lobe suppression by the Taylor aperture distribution for both E- and H-planes is also presented [7]. Satisfactory suppressed side lobes of −23 dB in the E-plane and −20 dB in the H-plane are observed in the same frequency.

Taking advantage of this array mentioned above, this paper develops an alternating-phase fed array with a sector shaped beam for a millimeter wave sensing system in a railroad crossing. The sector beam is very effective for sensing or radar applications for detecting obstacles in a certain angular range without scanning systems. The coverage area required for this railroad crossing sensing system is 40 degrees and is covered by three antennas. Therefore, the sector shaped beam with 13 degree beam width is specified for each antenna. In this paper, the sector shaped beam with 13 degree beam width is synthesized for the E-plane radiation pattern of the alternating-phase fed array for the first time, while the Taylor pattern with a sharp main beam and suppressed side lobes of −30 dB is designed for the H-plane pattern by using the conventional design techniques [7] to obtain high gain and low side lobe performance. The E- and H-plane radiation patterns are associated with dividing characteristics of the T-junctions in the feed waveguide and of the slot array in the radiating waveguides, respectively. In Sect. 2, key points in design of the T-junctions for the sector shaped beam is described. A prototype antenna is designed and manufactured in 60 GHz. The experimental results and the performance of the antenna are presented in Sect. 3. Section 4 concludes this paper.

2. Design of T-Junctions for a Sector Shaped Beam

A sector shaped beam with 13 deg. beam width is synthesized for the E-plane radiation pattern of the alternating-phase fed array, which depends on the dividing characteristics of the T-junctions in the feed waveguide into the radiating waveguides. Figure 2 presents specified amplitude and phase distributions of the slots on the radiating waveguides for the sector shaped beam which is obtained by Woodward-Lawson sampling method [9], where the number of radiating waveguides is set to 30. The beam width of the sector shaped beam depends on the number of elements (waveguides) and excitation distribution of the elements. In this figure, five amplitude peaks with 0 or 180 degree phases are observed. Since the specified excitation distribution is symmetrical with respect to the center of the feed waveguide, the whole structure of the T-junctions becomes also symmetrical. Therefore, the structural parameters of 15 T-junctions are determined in this design. Figure 3 presents a right half of the feed waveguide. The T-junction and the connected radiating waveguide are numbered from the center (#1) to the end (#15), as shown in Fig. 3. In order to obtain 180 deg. phase required for the slot array in the radiating waveguides from #6 to #10 as shown in Fig. 2, arrangement of the staggered slot offset on these radiating waveguides are reversed with respect to the center of the broad wall as shown in Fig. 3. Therefore, the following task is to control amplitude

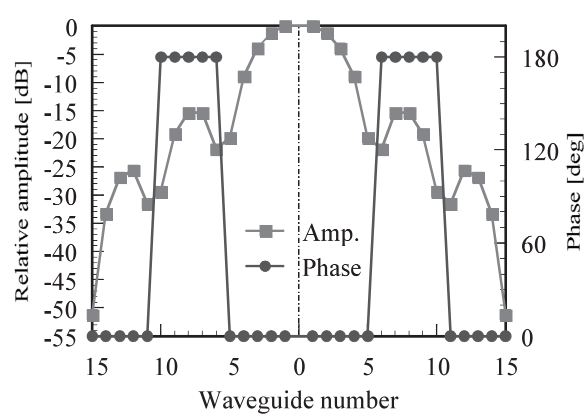

Fig. 2 Specified amplitude and phase distributions for 13 deg. sector shaped beam.

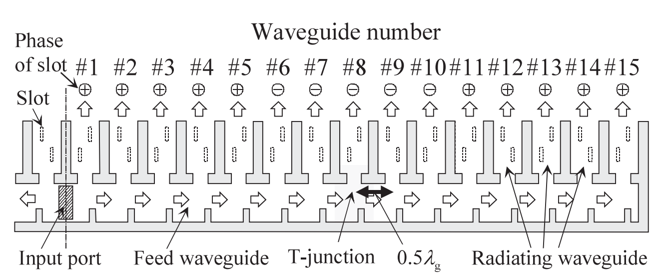

Fig. 3 Structure of the feed waveguide and the slot arrangement.

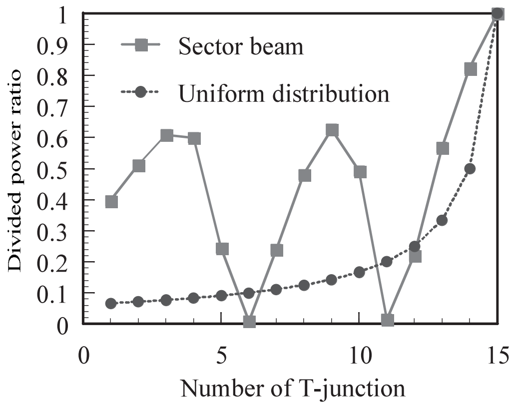

Fig. 4 Divided power ratio of T-junctions.

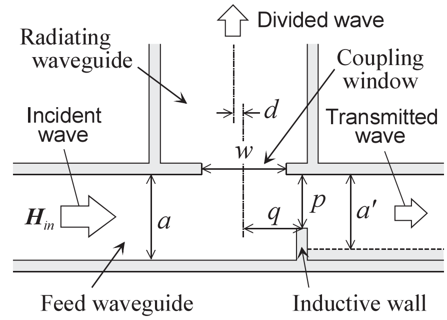

Fig. 5 Structure of a unit T-junction.

of the divided wave into the radiating waveguide in each T-junction and to adjust phase difference of the divided waves of the adjacent radiating waveguides to 180 degrees.

Figure 4 presents the divided power ratio of each T-junction, which is defined as a ratio of the divided power into the radiating waveguide to the incident power in the feed waveguide [10]. It is varied corresponding to the specified amplitude distribution in Fig. 2. For comparison, an example of the divided power ratio of the design for uniform aperture distribution is plotted in Fig. 4; it is given by $1/n$, where n represents the number of the T-junction countered from the end. Relatively strong couplings around 0.2 to 0.6 are required for the sector beam design in comparison with the case for uniform or Taylor distributions [7], while most of them are less than 0.2 except a few junctions close to the end for the uniform distribution. As is presented in the literature [7], the strong coupling brings about large phase delay in the divided wave into the radiating waveguide as well as the transmitted wave in the feed waveguide, while the phase delay is nearly zero for the weak coupling case. Therefore, in the T-junction design for uniform or Taylor distribution, the width of the feed waveguide remains constant and the phase delay is compensated by tuning the window offset in the T-junctions. However, it is no longer possible to maintain 180 degree phase deference of the divided waves into the adjacent radiating waveguides by tuning only the window offset for the sector beam design, since the variable range of the window offset has a limitation. In order to solve this problem, not only the window offset but also the width of the feed waveguide cascaded to the subsequent T-junction is optimized for the sector beam design. Another interesting fact in Fig. 4 is that the couplings in the T-junctions #6 and #11 is extremely weak that these waveguides can be removed and the areas are used for the screws to fix the slotted plate with the frame tightly.

Figure 5 presents an analysis model and structural parameters of a unit T-junction. The radiating waveguide is connected to the feed waveguide through a coupling window. An inductive wall is installed in front of the window in the feed waveguide to cancel out the reflection from the window. Because the reflection of the T-junction is negligibly small, each T-junction is designed independently by using the numerical analysis based on the method of moments, where the effects of wall thickness are taken into account [11]–[13]. The structural parameters are determined from the final T-junction (#15) to the center (#1), sequentially. The window width w is chosen so that the divided power ratio specified in Fig. 4 is obtained. The position of the inductive wall p and q are optimized to minimize the reflection from the window. In order to adjust the phase difference between the divided wave in the radiating waveguide and that in the adjacent one of the subsequent T-junction to 180 degrees, the window offset d and the width of the feed waveguide cascaded to the subsequent T-junction a' are tuned to compensate the phase delay, since the phase delay of the transmitted and the divided waves become large for strong coupling case.

Figure 6(a) presents the changes in phase of the transmitted wave (S_{21}) and the divided wave (S_{31}) in a T-junction when the divided wave ratio ($|S_{31}|^2$) is varied, where the width of the feed waveguide a (= a') is 3.16 mm, the width of the radiating waveguide is 3.2 mm, the height of the waveguides is 1.5 mm, the wall thickness separating waveguides is 1.0 mm, the window offset d is 0.0 mm, and the window width w is varied. The frequency in the analysis is 60.5 GHz. As shown in this figure, the phase of the transmission wave is increased when the divided wave ratio is increased, while the phase of the divide wave is drastically changed by more than 40 degrees. In this case, the variable range of the window offset d is from −0.3 mm to 0.3 mm, which provides the change in phase of the divided wave within approximately 26 degrees.

When the divided wave ratios in adjacent T-junctions differ significantly, it is necessary to change the width of the feed waveguide cascaded to the subsequent T-junction a' as well as the window offset d. Changing a' brings about another freedom to control phases of the divided waves in the adjacent T-junctions, since the guided wavelength in the feed waveguide between them is changed by a'. Figure 6(b) presents the phase difference between the divided waves in adjacent T-junctions when a' is varied, where the window width w is 2.54 mm and the other parameters are identical with those used in Fig. 6(a). In this figure, the phase difference is changed within 25 degrees. Figure 6(b) also includes the change of amplitude and phase of the divided wave in a

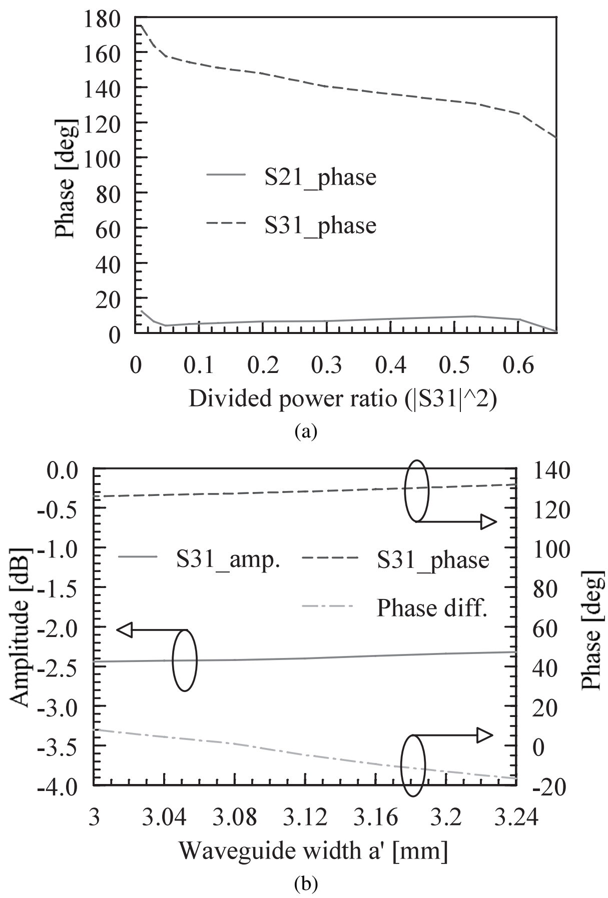

Fig. 6 (a) Phase of the transmitted wave (S_{21}) and the divided wave (S_{31}) in a T-junction when the divided wave radio ($|S_{31}|^2$) varies. (b) Phase difference of the divided waves in adjacent T-junctions and the change of amplitude and phase of the divided wave in a T-junction when a' varies.

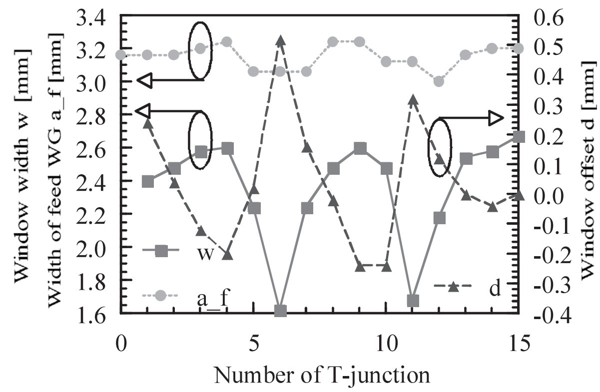

Fig. 7 Design parameters of T-junctions.

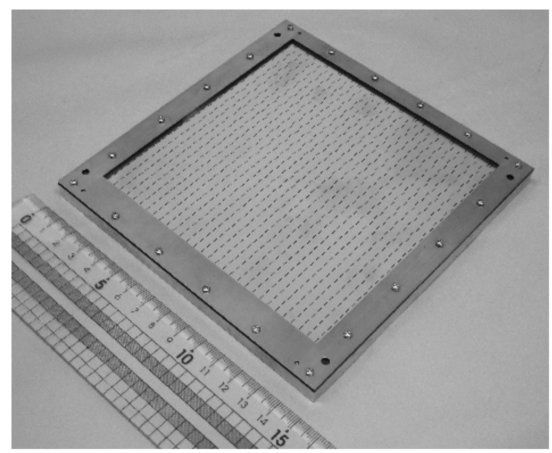

Fig. 8 Photograph of the prototype antenna.

T-junction when a' varies. The influence of a' upon the amplitude and phase of the divided wave is very small.

3. Experiments

According to the design guideline mentioned above, 30 T-junctions for a sector shaped beam with 13 degree beam width is designed. The design frequency is set to 60.5 GHz. The cross-sectional dimensions of the radiating waveguides are 3.2 mm in width and 1.5 mm in height. Thickness of the narrow wall separating the radiating waveguides is 1.0 mm. In the preliminary design of the feed waveguide, the width is set to 3.16 mm so that a half of the guided wavelength is identical with a distance between the adjacent radiating waveguides, which is revised in the design of T-junctions. Under these conditions, the T-junctions are designed. The determined parameters including the width of the coupling window, the window offset, and the revised width of the feed waveguide between the T-junctions, are presented in Fig. 7. The window width is corresponding to the required coupling and the width of the feed waveguide varies between 3.00 and 3.24 mm.

A slot array in the radiating waveguide is designed to radiate Taylor pattern with suppressed side lobes below −30 dB in the H-plane. The Taylor pattern is widely used for high gain, narrow beam width, and suppressed side lobe pattern [9]. The number of slots is set to 34. Backward beam tilting [14] is adopted to avoid gain reduction due to the grating lobes appeared in the diagonal planes; the main lobe is tilted by 2 degrees from the boresight. Details of design of the slot array and the choke are reported in [5], [7].

Figure 8 presents a photograph of the prototype antenna. All components are made from aluminum to reduce conductor losses. The groove feed structure is corrugated with a depth of 1.5 mm by machining process, while the slotted plate with a thickness of 0.1 mm is processed by etching. The both component are fixed with screws with a thick aluminum plate of 2 mm at the periphery of the antenna. The whole antenna size is 150 mm square and the effective aperture area which is occupied by the slots is approximately 125 mm square. A standard waveguide of V band is connected to the center of the feed waveguide from the back of the antenna as a feeder.

Figures 9 and 10 present the radiation patterns in the E- and H-planes measured at 60.0 GHz, respectively, where the lowest side lobe level is observed. The measured and predicted main lobes are in fine agreement for both the E- and H-planes. The measured side lobes in the E-plane are

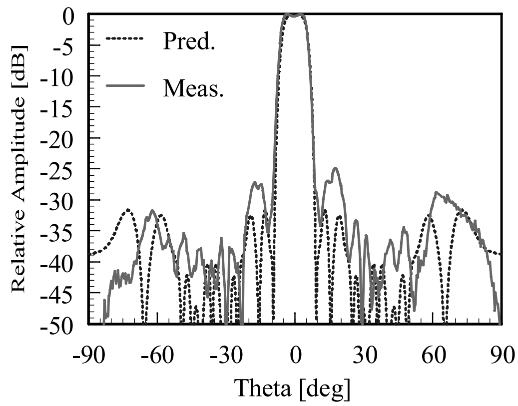

Fig. 9 Radiation patterns in the E-plane.

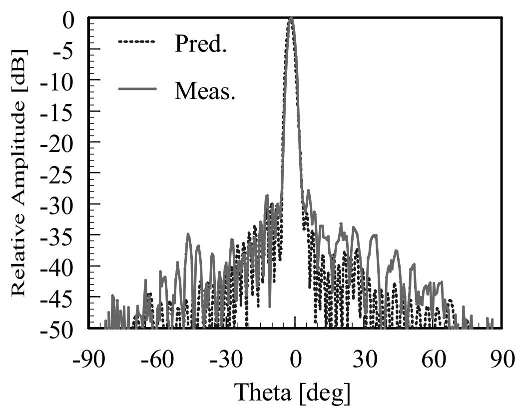

Fig. 10 Radiation patterns in the H-plane.

increased up to −25 dB, while those of the H-plane are well suppressed below −28 dB. The measured beam width in the E- and H-plane pattern is approximately 11.5 and 2.5 degrees, respectively. Excellent sector shaped beam in the E-plane as well as the side lobe suppression in the H-plane is achieved.

Figures 11(a) and (b) present the measured amplitude and phase of the aperture field distributions obtained by near field measurement at 60.0 GHz, where X- and Y-axes are corresponding to the feed waveguide and the radiating one, respectively. Linear variations of the phase along the Y-axis due to the beam tilting are compensated in Fig. 11(b). Five amplitude peaks with alternating phases are observed along the X-axis for the sector beam, as is shown in Fig. 2. Approximately −12 dB tapered amplitude distribution with 50 deg. phase deviations is created along the Y-axis for the Taylor pattern, while the desired one is −12 dB amplitude tapers with constant phase.

Figure 12 presents frequency dependence of the measured gain and reflection at the input port. The highest gain of 28 dBi is observed at 60.55 GHz because the aperture distribution along the radiating waveguide is close to uniform one at this frequency. The reflection is about −12 dB in the range of 60 to 61 GHz. The operating frequency is slightly shifted from the desired one; further iterative tuning of the parameters is necessary to adjust the frequency. Nevertheless, satisfactory design of the T-junctions for the sector beam with high gain performance of the alternating-phase fed array is confirmed.

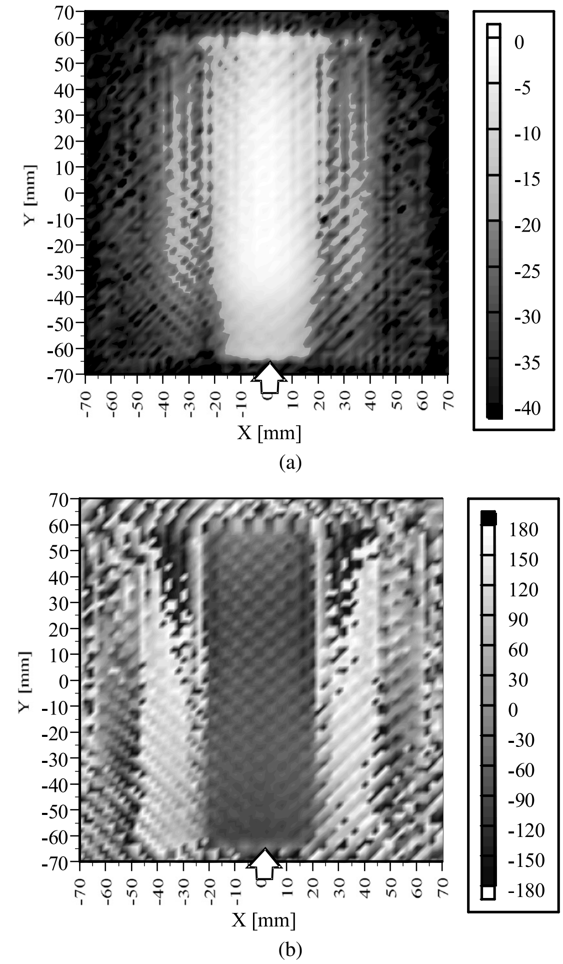

Fig. 11 Measured aperture field distribution. (a) Relative amplitude in dB. (b) Phase in degree.

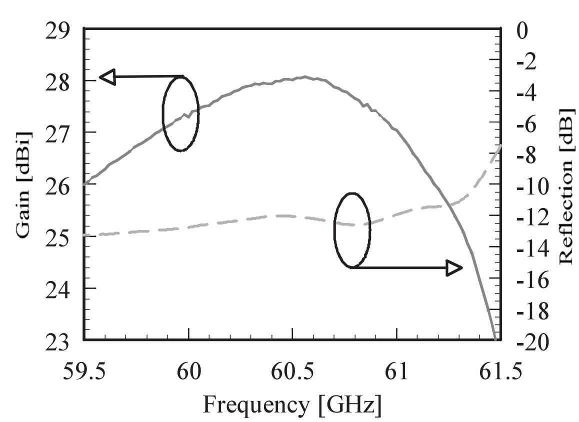

Fig. 12 Measured gain and reflection.

4. Conclusions

A sector shaped beam with 13 deg. beam width is synthesized for an alternating-phase fed slotted waveguide array in the E-plane. 30 T-junctions in the feed waveguides are designed to realize the required excitation distribution for the slot array in the radiating waveguides; 180 degree phase element of the slot array can be obtained by reversing the slot offset arrangement. The amplitude is controlled by the window width of each T-junction. In order to equalize the phases of the adjacent radiating waveguides, the window offset and the width of the feed waveguide between these T-junctions are tuned. A prototype antenna is designed and manufactured in 60 GHz band. The measured sector pattern agrees well with the predicted one. Validity of the sector beam design as well as the high gain performance of the alternating-phase fed array is demonstrated by the measurement.

Acknowledgments

The authors would like to thank Prof. Makoto Ando, Prof. Jiro Hirokawa, and Mr. Kimio Sakurai of Tokyo Institute of Technology for their cooperation in measurement.

References

[1] N. Goto, "A planar waveguide slot antenna of single layer structure," IEICE Technical Report, AP88-39, July 1988.

[2] N. Goto, "A waveguide-fed printed antenna," IEICE Technical Report, AP89-3, April 1989.

[3] R. Hirose, M. Ando, and N. Goto, "A design of a multiple-way power divider for a single layered slotted waveguide array," IEICE Technical Report, AP90-130, Feb. 1991.

[4] 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," IEE Proc., Microw. Antennas Propag., vol.144, no.6, pp.425–430, Dec. 1997.

[5] Y. Kimura, T. Hirano, J. Hirokawa, and M. Ando, "Alternating-phase fed single-layer slotted waveguide arrays with chokes dispensing with narrow wall contacts," IEE Proc., Microw. Antennas Propag., vol.148, no.5, pp.295–301, Oct. 2001.

[6] Y. Kimura, Y. Miura, T. Shirosaki, T. Taniguchi, Y. Kazama, J. Hirokawa, M. Ando, and T. Shirouzu, "A low-cost and very compact wireless terminal integrated on the back of a waveguide planar array for 26 GHz band fixed wireless access (FWA) systems," IEEE Trans. Antennas Propag., vol.53, no.8, pp.2456–2463, Aug. 2005.

[7] Y. Kimura, M. Takahashi, J. Hirokawa, M. Ando, and M. Haneishi, "An alternating-phase fed single-layer slotted waveguide array in 76 GHz band and its sidelobe suppression," IEICE Trans. Electron., vol.E88-C, no.10, pp.1952–1960, Oct. 2005.

[8] R.C. Johnson and H. Jasik, Antenna Engineering Handbook, Chap. 9, McGraw-Hill, NewYork, 1984.

[9] W.L. Stutzman and G.A. Thiele, Antenna Theory and Design, Chap. 10, John Wiley & Sons, 1981.

[10] R.C. Hansen, Phased Array Antennas, Chap. 6, John Wiley & Sons, 1997.

[11] J. Hirokawa, K. Sakurai, M. Ando, and N. Goto, "An analysis of a waveguide T junction with an inductive post," IEEE Trans. Microw. Theory Tech., vol.39, no.3, pp.563–566, March 1991.

[12] J. Hirokawa, M. Ando, and N. Goto, "Waveguide π-junction with an inductive post," IEICE Trans. Electron., vol.E75-C, no.3, pp.348–350, March 1992.

[13] T. Takahashi, J. Hirokawa, M. Ando, and N. Goto, "A single-layer power divider for a slotted waveguide array using π-junctions with an inductive wall," IEICE Trans. Commun., vol.E79-B, no.1, pp.57–62, Jan. 1996.

[14] R.E. Collin and F.J. Zucker, Antenna Theory, pt. 1, sec. 14.8, McGraw-Hill, 1969.

Yuichi Kimura was born in Saitama, Japan, on November 18, 1973. He received the B.S., M.S. and D.E. degrees in electrical and electronic engineering from Tokyo Institute of Technology, Tokyo, Japan in 1996, 1998 and 2001, respectively. He was a Research Associate from 2001 to 2006 and is currently an Associate Professor at Saitama University. His research interests include slotted waveguide array antennas and microstrip antennas. He received an IEEE AP-S Japan Chapter Young Engineer Award in 2006. He is a member of IEEE.

Atsuo Senga received B.E. and M.E. degrees in electrical engineering from The University of Electro-Communications, Tokyo, in 1998 and 2000, respectively. In 2000, he joined Nippon Signal Co., Ltd., where he has been engaged in the research of safety-related systems. His current interests are safety-related systems using radio technology.

Masayoshi Sakai received B.E. and M.E. degrees in electrical engineering from Keio University, Yokohama, in 1983 and 1985, respectively. In 1985, he joined Nippon Signal Co., Ltd., where he has been engaged in the research of safety-related systems. He received his Ph.D. degree from Meiji University, Kawasaki, in 1999. His current interests are safety-related systems using radio technology.

Misao Haneishi was born in Tokyo, Japan, on October 15, 1943. He received the B.S., M.S., and D.E. degrees in electrical engineering from Saitama University in 1967, Tokyo Metropolitan University in 1969, and Tokyo Institute of Technology in 1981, respectively. He was a Research Associate at Saitama University from 1969 to 1982, an Associate Professor from 1982 to 1990, and is currently a Professor. In 1997, he was with Department of Electrical and Computer Engineering, Manitoba University, Canada, as a Visiting Scholar on leave from Saitama University. His research interests include microstrip antennas and the relating sub systems. He is a co-author of 4 books on microstrip antennas. He received a Young Engineer Award from IEICE, Japan in 1977. He served as a Chairman of IEEE AP-S Tokyo Chapter from 1996 to 1997, a Councilor of IEICE Tokyo Branch from 1996 to 1998, a Planning Chair of ISAP2000 from 1997 to 2000, respectively. He is an Advisory Member of the Technical Group of Antennas and Propagation, IEICE since 1998. He is a member of IEEE and ITE Japan.