Design of an alternating-phase fed single-layer slotted waveguide array with a latticed plate

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Abstract

This paper presents design of a slot array for an alternating-phase fed single-layer slotted waveguide array with a latticed plate. The latticed plate with a relatively large thickness is put on a slotted plate and they are tightly fixed by screws on a groove feed structure without electrical contact such as brazing. Slot coupling in a waveguide slot with a cavity, which is a radiation element of the slot array, is obtained by MoM with mutual coupling effects in the external region taken into account for the array design. The slot array with 25 elements is designed for uniform aperture distribution in 76 GHz. Validity of the design is confirmed by near field measurement of the prototype antenna.

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 and automotive radar systems in 76 GHz. A single-layer slotted waveguide array [1] is a promising candidate for these applications because of the following reasons. (i) Transmission loss of a hollow waveguide is extremely small even in millimeter wave. (ii) The simple structure consisting of only two components, a slotted plate and a groove feed structure, is suitable for mass-production. (iii) Operation of the array constructed with single mode waveguides is so stable that flexible design for aperture illumination control is possible.

Figure 1 presents a configuration of an alternating-phase fed single-layer slotted waveguide array with a wide choke. Resonant shunt slots are arrayed on the broad wall of radiating waveguides and a feed waveguide is connected at the end of the radiating waveguides in the same layer. The adjacent radiating waveguides are excited with 180 degree out-of-phase by a cascade of T-junctions placed at intervals of a half guided wavelength in the feed waveguide. In order to excite all the slots with in-phase, the staggered slot arrays on the adjacent radiating waveguides are arranged symmetrically. An outstanding feature of the alternating-phase fed array is that the electrical contact, such as brazing, between the slotted plate and the feed structure can be dispensed with because the currents on the both sides of the narrow wall between the radiating waveguides flow in the opposite directions and they do not cross the contacting surface, as shown in Fig. 1 (b) [2], [3]. Thus, the slotted plate is simply tacked on the feed structure and is fixed by screws at the periphery, since the choke surrounding the waveguides eliminates the leakage at the periphery without electrical contact [4].

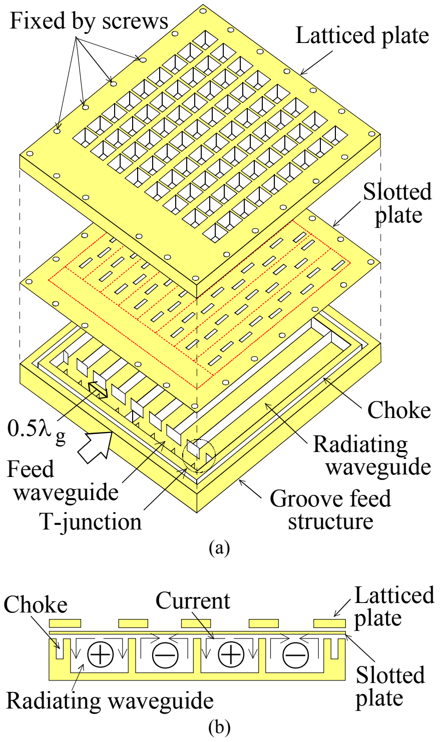


Fig. 1: Alternating-phase fed waveguide slot array with a latticed plate. (a) Bird's eye view. (b) Cross-sectional view of the radiating waveguides.

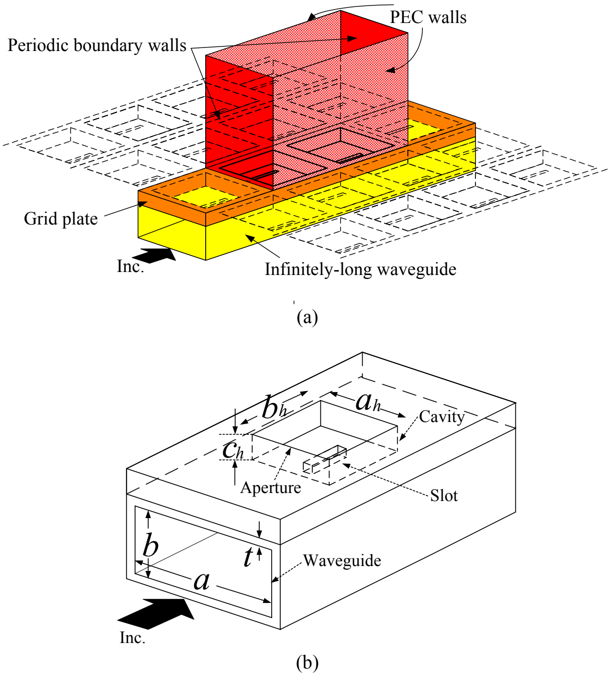
The alternating-phase fed array has already been mass-produced by die-casting technique at very low cost for the 26 GHz wireless IP access service (WIPAS) system [5]. 31.5 dBi gain with 65% efficiency is achieved by the prototype antenna fixed by screws. This array is also applied to 76 GHz and 34.8 dBi gain with 57% efficiency is achieved by the prototype fixed by screws with a thick metal frame at the periphery [6]. The high efficiency potential of the alternating-phase fed array in millimeter wave is confirmed, however, it is revealed that tight contact between the slotted plate and the groove feed structure is still indispensable to achieve the high efficiency performance in millimeter wave, nevertheless electrical contact such as brazing is not necessary.

In order to enhance the efficiency of the alternating-phase fed array for millimeter wave use, it is proposed that a latticed plate with a relatively large thickness is stacked on the slotted plate and that they are fixed by screws tightly on the feed structure, as shown in Fig. 1 [7]. Thickness of the latticed plate is not negligible in millimeter wave because, for examples, 1 mm is corresponding to a quarter wavelength in 76 GHz. This paper presents design of the slot array for the proposed antenna. The element of the array is regarded as a waveguide slot with a cavity. An analysis model to take effects of the cavity as well as mutual couplings in the external region into account is solved by MoM to obtain the slot coupling for the array design. The slot array with 25 elements is designed for uniform aperture distribution at 76.5 GHz. A prototype antenna is manufactured and validity of the design is confirmed by the near field measurement.

2. SLOT COUPLING ANALYSIS FOR ARRAY DESIGN

Fig. 2 (a) and (b) present an analysis model for slot coupling for design of the slot array and its structural parameters, respectively. The element of the slot array is regarded as a waveguide slot antenna with a rectangular cavity. It is important to take into account effects of the cavity and the mutual couplings via the external region for design of the planar array. In order to simulate the mutual couplings, PEC and periodic boundary conditions (PBC) are assumed in the external region [4]. This model is analyzed by the method of moments (MoM) [8], [9]. According to the field equivalent theorem, three apertures, the bottom and the top surfaces of the slot and the top surface of the cavity, are covered by PECs and equivalent magnetic currents are assumed on these three apertures, respectively. The whole structure is divided into four canonical regions; an infinitely-long rectangular waveguide, two rectangular cavities (inside the slot and inside the cavity), and a shorted rectangular waveguide surrounded by PEC and PBC walls. Each unknown magnetic current is expanded by only one sinusoidal basis function because of simplicity of the calculation. One sinusoidal basis function used to expand the unknown magnetic current of the top aperture of the cavity brings good approximation because a waveguide mode is created in the cavity due to the relatively large thickness of the latticed plate. This approximation is true in the range of the cavity width a_h less than a half wavelength and the cavity height c_h over a quarter wavelength [7]. TE_{10} mode propagating in the waveguide is assumed as an incident wave. Three integral equations derived from the continuity condition of the magnetic field on these apertures are solved by the Galerkin's method.

Figure 3 shows the relationship among resonant slot length, slot offset and the slot conductance obtained by the analysis mentioned above. The design frequency is 76.5 GHz. The dimensions of the waveguide are a = 2.53 mm × b = 1.47 mm. The thickness of the slotted plate t is 0.1 mm. The size of the cavity is $a_h = b_h$ =2.21 mm and c_h = 1.0 mm (approximately a quarter wavelength). The slot width w is 0.24 mm. From this figure, it is found that the slot length and the offset are increased as the slot conductance is increased. The variation of the slot length due to the change of the conductance is very small in comparison with the case without the cavity, because the mutual couplings between the slots are reduced by the cavity. This chart is used for design of the slot array.



(a)

(b)

Fig. 2: Slot coupling analysis for the array design. (a) Analysis model. (b) Structural paramteres.

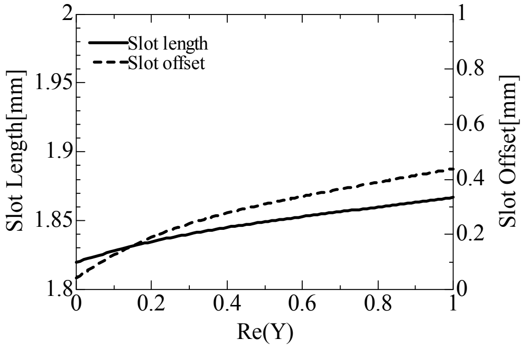


Fig. 3: Relationship among resonant slot length, slot offset, and the slot conductance. (a =2.53, b = 1.47, t = 0.1, w = 0.24, $a_h = b_h$ = 2.21, c_h = 1.0, unit:[mm], f_0 = 76.5 GHz)

3. ARRAY DESIGN

A slot array with a rectangular cavity is designed for uniform aperture distribution by using the results of slot coupling analysis mentioned above. The conventional design method for a resonant shunt slot array is available for this array because the radiation power can be controlled by the slot offset while the slot length is chosen to be a resonant slot [7]. The design procedure is summarized briefly as follows. (i) Conductance of each slot for uniform aperture distribution is calculated by using an equivalent circuit of the resonant slot array, which is represented by a series of shunt admittance. (ii) Length and offset of each slot are assigned for the conductance calculated in (i) as initial parameters with reference to Fig. 3. (iii) Finally, array analysis assuming finite number of slots is carried out with MoM for the initial parameters. The slot lengths and the offsets are revised iteratively until uniform aperture distribution is realized.

The number of slots in the array is set to be 25. The slot spacing is 3.36 mm, where forward beam tilting is adopted and the main beam is tilted by 2.5 degree from the boresight. The dimensions of the cavity (a_h = b_h =2.21 mm and c_h = 1.0 mm) are identical for all the slots. The other parameters are the same as presented in the previous section. The total array length is approximately 84 mm. Figure 4 presents the final parameters of the designed slot array. They are corresponding to the change of conductance for uniform distribution. Most of the slots except a few slots near the end have weak coupling that variation of the slot length and the offset are small. The final slot is specially designed together with the shorted wall to radiate all the residual power at the termination.

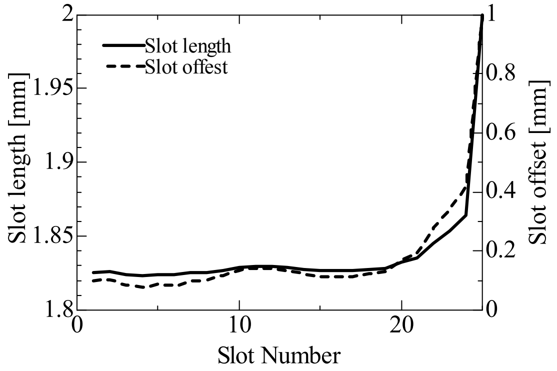


Fig. 4: Designed slot length and offset of the slot array.

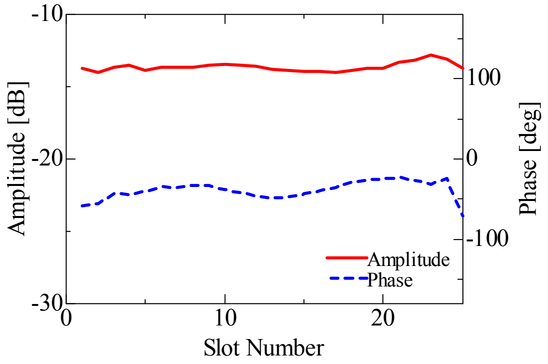


Fig. 5: Predicted aperture distribution of the slot array.

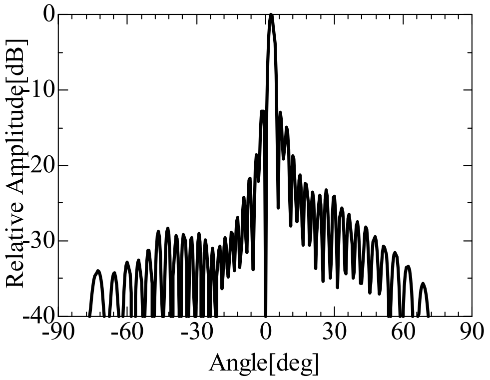


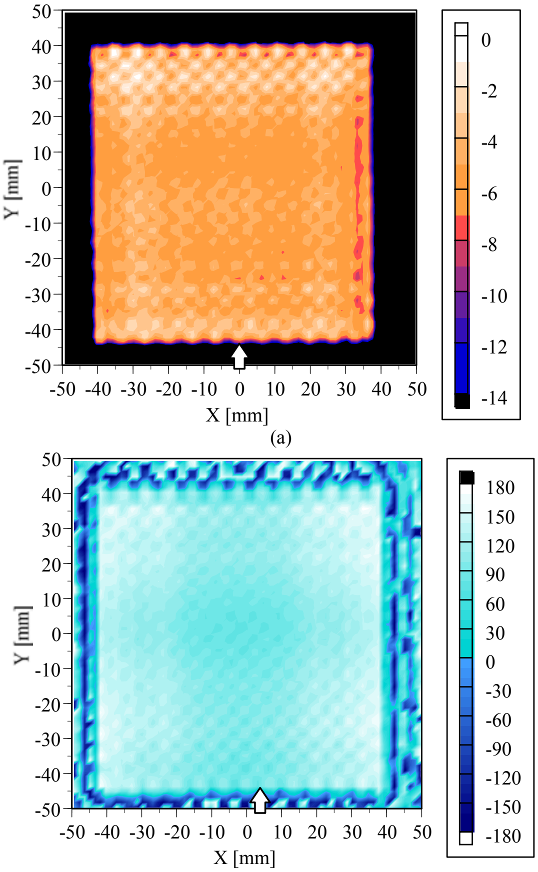
Fig. 6: Predicted radiation patter of the slot array.

Figure 5 presents the aperture field distribution predicted by the array analysis, where linear phase variation corresponding to the beam tilting angle is compensated. The deviations in the amplitude and phase distribution are within 2 dB and 40 degrees, respectively. Figure 6 presents the predicted radiation pattern of the array. From these results, it is found that uniform aperture distribution is achieved.

4. EXPERIMENTAL RESULTS

In order to verify the design of the slot array with the cavity, a prototype antenna with 24 waveguides and 25 slots on each waveguide is fabricated in 76 GHz. Uniform aperture distribution is synthesized by the slot array and by the T-junctions in the feed waveguide. The parameters of the slot array used for the prototype are presented in Fig. 4, while design of the T-junctions is presented in [6]. The aperture area occupied by the slots is approximately 84 mm (along the slot array) × 80 mm (along the feed waveguide). The slotted plate and the latticed plate are tacked and fixed by screws on the groove feed structure with a choke corrugated at the periphery.

Figure 7 (a) and (b) illustrate amplitude and phase distributions over the aperture at 76.5 GHz obtained by near field measurement. The feed waveguide is situated at the bottom (Y = –45 mm) in the figures i.e. the Y-axis is corresponding to the direction of the slot array. The linear variation of the phase due to the beam tilting angle is compensated. As shown in the figures, uniform distribution is confirmed for both the amplitude and the phase. Small ripples in the amplitude distribution are observed due to the alignment error of the slotted plate, which should be solved in the future. The phase distribution along the feed waveguide is slightly tapered by about 60 degrees from the center to the edge. The deviation of the amplitude and the phase along the slot array is approximately 4 dB and 40 degrees, respectively, which is in reasonable agreement with the prediction. The radiation pattern of the slot array calculated from the measured near field is plotted in Fig. 8. The predicted and measured patterns are in good agreement around the main beam, since the planar scanning is used for the near field measurement. Validity of the slot design is confirmed by the measurement.



(b)

Fig. 7: Measured aperture field distribution at 76.5 GHz. (a) Relative amplitude (in dB). (b) Phase (in degree).

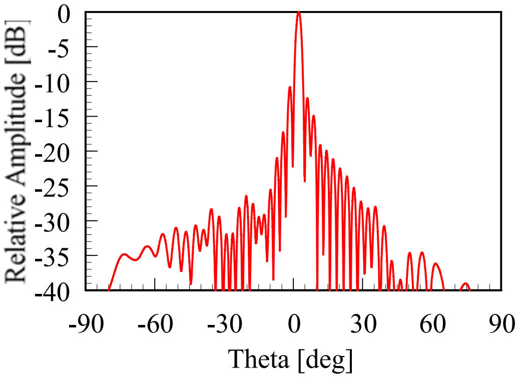


Fig. 8: Radiation pattern of the slot array calculated from the near field measurement.

5. CONCLUSION

Design of the slot array for the alternating-phase fed array with the latticed plate is presented. The analysis model with PEC and PBC walls in the external region is solved by MoM to obtain the slot coupling for the array design, where effects of the cavity as well as the mutual couplings are taken into account. The slot array with 25 elements is designed at 76.5 GHz and uniform aperture distribution within 2 dB deviations in amplitude and 40 degree in phase is predicted. The validity of the slot design is confirmed by the near field measurement for the prototype antenna. Gain and efficiency of this array should be evaluated in the future.

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