Full-Model Analysis of a Large Number of Waveguide Slot Antenna Elements and its Design

#Miao ZHANG, Jiro HIROKAWA and Makoto ANDO
Dept. of Electrical and Electronic Eng., Tokyo Institute of Technology
2-12-1- S3-19, O-okayama, Meguro-ku, Tokyo, 152-8552, Japan, miao@antenna.ee.titech.ac.jp

Abstract

By applying the method of moments with dyadic Green's functions, the full-model analysis of a large-scale waveguide slot array is developed and presented in this paper. With comparison to the measured aperture distribution of a 302-element array, the external mutual couplings between all the slots are accurately evaluated. In addition, the computation time for a 300-element array is just one dozen seconds, so this analysis technique can be easily applied to the antenna design. As an initial approach, by iterating the slot offsets and lengths so as to improve the uniformity in excitation, the ripples in amplitude and phase of far field radiated from the slots are suppressed below 0.5dB and ± 5 degrees, respectively.

1. INTRODUCTION

A single-layer slotted waveguide array [1] is an attractive candidate for high-efficiency and high-gain planar antennas because of its negligible transmission loss and simple structure. To achieve higher mass productivity, an alternating phase-fed waveguide array [2], where neighbouring radiating waveguides are fed out of phase, is developed since close electrical contact between the radiating waveguides and the slotted plate is not needed in principal.

Conventionally, this type of the antenna is analyzed by the method of moments (MoM) with dyadic Green's functions. Both the inside and outside of the waveguides can be treated as canonical regions, where the dyadic Green's functions are already known. Therefore, the only unknowns in MoM are sources at discontinuities, as an analogy to the boundary element method. Here in particular, they are the expansion coefficients for the distribution of magnetic currents on the aperture of slots. On the other hand, the finite difference time domain (FDTD) method and the finite element method (FEM) require all the electromagnetic fields within the finely specified analysis cells and meshes to be calculated. Generally, MoM provides us with a smaller scale of the analysis matrix for a similar electric size of the analysis model in comparison with FDTD and FEM and so on.

In practical view of applying the analysis method to the actual antenna design, calculation time even for relatively large structure should be within a few minutes. An FEM-based simulator HFSS (High Frequency Structure Simulator) enable us to analyze a waveguide slot array of 304 elements [3] in nearly 89 minutes, where the actual simulated model is reduced to half due to the structural symmetry. The simulation environment is shown here: HFSS ver.10; 2 CPU: Xeon 3.60GHz; memory size: 16G bytes. However, it would be quite difficult at this stage to design the overall antenna by a large number of iterations of this HFSS analysis, due to its long calculation time.

Our objective is to develop full-model analysis of a large number of waveguide slot array elements by applying MoM together with dyadic Green's functions. As the first approach, all mutual couplings between the slots in the external region of the antenna will be precisely evaluated in this paper. Eventually the enhancement in the aperture efficiency is expected by realizing ideal distribution of excitation.

2. FULL-MODEL ANALYSIS

The basic concept for the method of moments using dyadic Green's functions is illustrated here. By applying the field equivalence theorem to the slot wall-thickness regions, both the internal and external apertures of the slots are covered by PECs (perfect electric conductor) together with unknown magnetic currents. Since the tangential components of the electric fields are zero on all the waveguide walls, the only unknowns due to the uniqueness theorem, are the tangential components of the magnetic current equivalent to the electric fields on the slot apertures. There is no requirement to determine the electric currents conducting on the walls of waveguide. Furthermore, by applying the dyadic Green's functions which have taken the boundary conditions on PECs into account for each region, only the condition for the continuity of magnetic fields on the slot apertures should be satisfied. From all these points of view, the scale of calculation can be reduced to a very low level.

A. Conventional Analysis

The conventional analysis model for the evaluation of mutual couplings between the slots in the external region of the antenna [4] is shown in Fig. 2(a). The number of the elements in the longitudinal (radiating waveguide) direction is N, finite; while in the transverse (feed waveguide) direction, L and R radiating waveguides with slots of equal excitation coefficients are assumed left-to-right, instead of the infinitely periodic array so as to reduce the scale and time of calculation. Additionally, an infinite ground plane is also introduced in the external region. It allows us to apply the dyadic Green's function for the half-space, which is inversely proportional to the distance between the source and observer points.

Unfortunately, the reactions between external magnetic currents in MoM converge slowly with respect to L and R. By considering the practical calculation time in design, the values of L and R are set to be 20 as the maximum.

B. Full-Model Analysis

In this paper, the real model as shown in Fig. 2(b), with M radiating waveguides and N slots cut in each waveguide, is analyzed. An infinite ground plane is also assumed here in the external region. The finite wall thickness is taken into account, where the reactions are calculated without taking mode summations due to the orthogonality of the eigenmode functions. Firstly, an incident wave to each waveguide with equal-amplitude and phase, which is called ideal feed condition, is assumed. Especially the amplitude of each incident wave is $M^{-1/2}$, so as to normalize the total input power to be 1. Secondly, because all M radiating waveguides are with same configurations at present, the design parameters for the N slots in identical waveguide are the slot offsets from the waveguide axis, the positions in the axial direction and the slot lengths, which account to only $3N$ in total number. The evaluation of reactions between the magnetic currents on the internal apertures of the slots in only one waveguide is enough. All of the external mutual couplings between the magnetic currents are taken into account. And the scale of the calculation can be reduced to half due to the reciprocity in reactions. As an example for calculation time, a 324-element antenna is analyzed in 12 seconds, where a personal computer with the spec of 1 CPU: 3.80GHz; memory size: 1G bytes is used. Thereafter, it is very possible to apply this full-model analysis to the design of slots.

3. Comparison with the Experiment

In this section, the measured aperture distribution for an antenna of 302 ($N \cdot M$=16 •19) elements at 25.3GHz is compared with the calculated excitation coefficients of the slots. Figure 3 shows the aperture distribution which is transformed from the measured near fields. Since the ground plane, which is adopted only in analysis, is not attached to the antenna during the experiment, fine ripples are clearly observed due to effects of diffraction. Figure 4 shows the excitation coefficients for the magnetic currents on the external apertures of the slots, plotted at corresponding positions. Figs 3 and 4 are showing the fields and the excitation coefficients respectively; these are a bit different data and can not be compared directly in strict sense. But both are showing the aperture distributions in approximate sense. For the amplitude in Figs. 3 and 4, a taper in the longitudinal direction and phenomenon of the excitation becoming weak on the outer sides of the array are well expressed. On the other hand, a phase taper corresponding to the beam tilt [5] away from the boresite is subtracted in those results. However, the main beam directs at -4 degrees in the analysis, but is modified as -4.5 degrees in the experiment due to the setting error of the antenna. The minus sign in degree means the beam direction shifted from the boresite toward the antenna input side. By comparison, it is also well observed that the phase progresses around the end and is disturbed around the periphery of the array. Consequently, the external mutual couplings between the slots are accurately evaluated by conducting the full-model analysis of a large-scale waveguide slot array.

4. Iterative Design for Uniformity Enhancement of Excitation

As mentioned above, a 300-element array is analyzed in just a dozen seconds. Therefore the iterative design for uniformity enhancement in both amplitudes and phases of the slot excitations would be feasible in reasonable time. As an initial approach, the waveguide located in the center of the antenna is focused upon and its uniformity in the excitation is improved by iteration method.

At first, the amplitude of far field radiated from each slot is mainly determined by the offset p, which is defined as the displacement from the waveguide axis. The modified offset can be expressed as following:

$$p' = p - sign\left(E^{amp} - E^{amp}_{ave}\right) \cdot \Delta p \quad (1)$$

$$\text{and, } sign(x) = \begin{cases} 1\,(x \geq 0) \\ -1\,(x < 0) \end{cases}$$

Here, averaged amplitude E^{amp}_{ave} is a target value. By iterating for about one dozen times, the deviation in amplitude of almost 4dB is suppressed to 0.5dB, as shown in Fig. 5.

Secondly, the resonant condition of each slot is investigated to improve the phase of far field. Instead of changing the slot position, the slot length is modified as following:

$$l' = l - sign\left(E^{pha} - E^{pha}_{ave}\right) \cdot \Delta l \quad (2)$$

So the transmission phase of S_{21} just beneath the slot approaches zero. Both the before- and after-iteration transmission phases are shown in Fig. 6. Similarly, the improvement in phase of far field, corresponding to the improved transmission phase, is also observed in Fig. 4.

Consequently, the ripples of amplitude and phase for the center-located waveguide are improved below 0.5dB and ± 5 degrees, respectively. The aperture efficiency also increases by 0.42%, though the improvement is not clear due to the change in the reflection in this specific example.

5. Conclusion

The full-model analysis applying the method of moments using dyadic Green's functions is developed for a large-scale waveguide slot array with a large number of array elements. The external mutual couplings between all the slots are precisely evaluated. By comparing with the measured aperture distribution for a 302-element array at 25.3GHz, the variation and disturbance in amplitude and phase of excitation coefficients are also accurately reflected by the proposed analysis. Furthermore, the calculation time for a 300-element array is just a dozen seconds, so iteration technique can be easily applied to the antenna design. As an initial approach, by iterating the slot offset and length so as to improve the uniformity in excitation, the ripples in amplitude and phase of far field radiated from slots are suppressed below 0.5dB and ± 5 degrees, respectively. As future work, the full-structure analysis including the feed circuit will be developed. Eventually, the establishment of antenna design technique with high-accuracy and high-efficiency, and the enhancement in the antenna efficiency including the defects from reflection are expected.

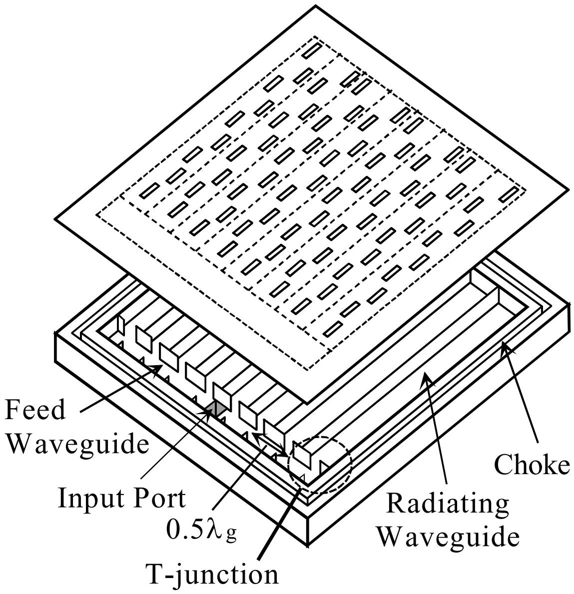
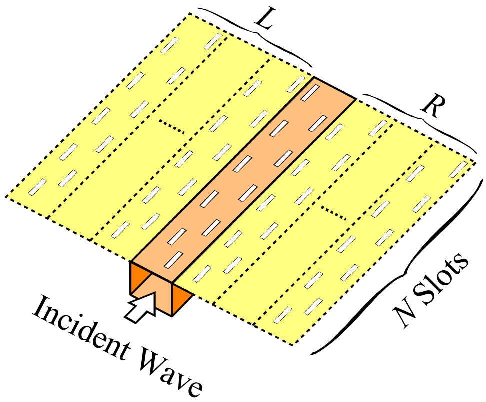
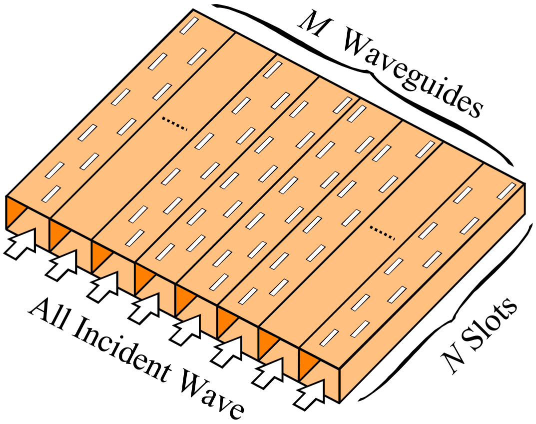


Fig. 1: Alternating Phase-Fed Single-Layer Slotted Waveguide Array



(a) conventional periodic model



(b) full-model analysis model

Fig. 2: Analysis Model for the Evaluation of External Mutual Coupling in a Slotted Waveguide Array

References

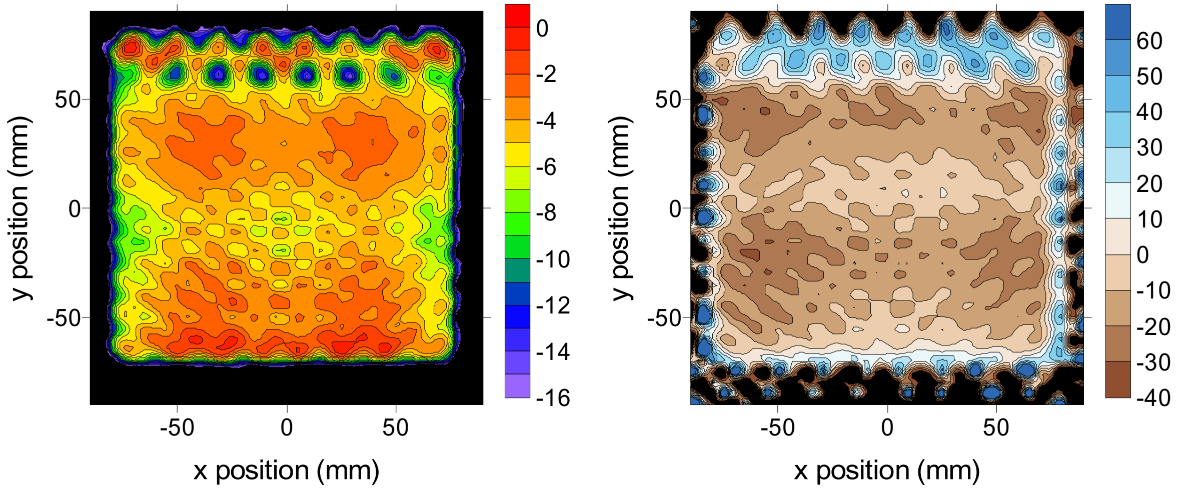
[1] N. Goto, "A planar waveguide slot antenna of single layer structure", *IEICE Technical Report*, P88-39, July 1988.

[2] 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.

[3] Y. Tsunemitsu, S. H. Park, J. Hirokawa, M. Ando, Y. Miura, Y. Kazama and N. Goto, "Reflection characteristics of center-Feed single-Layer waveguide arrays", *IEICE Trans. Commun.*, vol. E88-B, no.6, pp.2313-2319, June 2005.

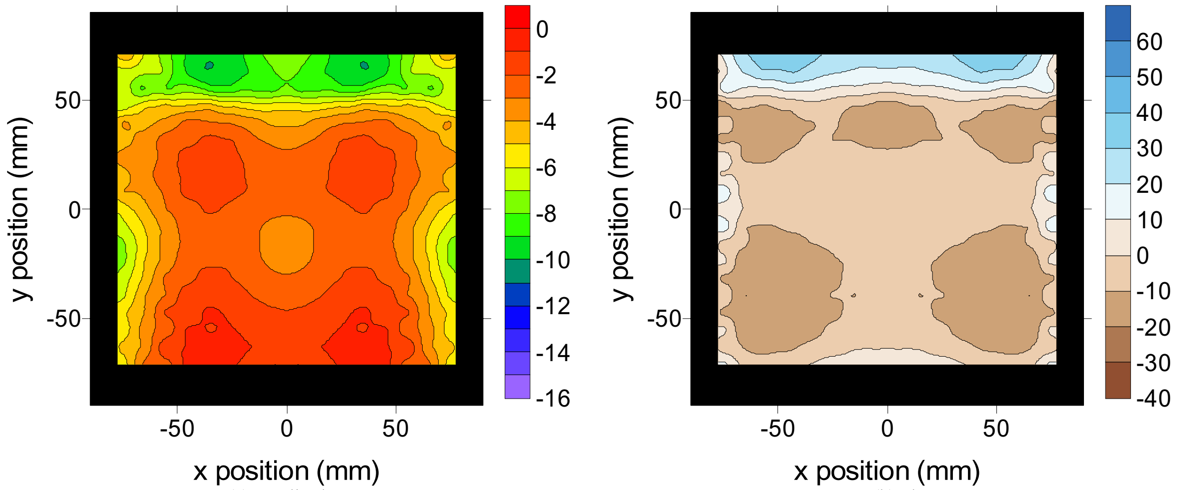
[4] K. Sakakibara, J. Hirokawa, M. Ando and N. Goto, "Periodic boundary condition for evaluation of external mutual couplings in a slotted waveguide array", *IEICE Trans. Commun.*, vol. E79-B, no.8, pp.1156-1164, Aug. 1996.

[5] R.E. Collin and F.J. Zucker, *Antenna Theory*, part 1, McGraw-Hill, New York, 1969, sec. 14.8, pp. 587.



(a) amplitude (b) phase

Fig. 3: Measured Aperture Distribution of Antenna



(a) amplitude (b) phase

Fig. 4: Calculated Excitation Coefficients for Each Slot

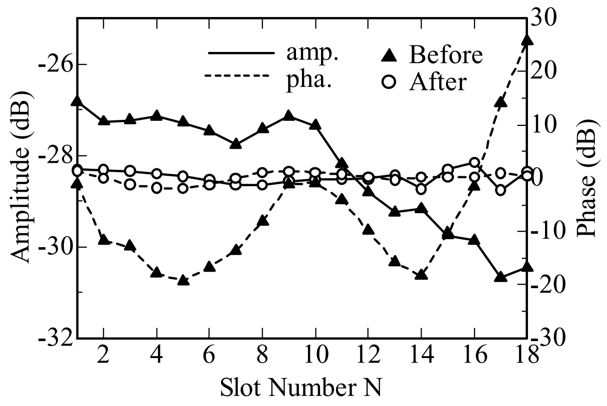


Fig. 5 Characteristics of Far Fields Radiated from Each Slot on the Center-Located Waveguide before and after Iteration

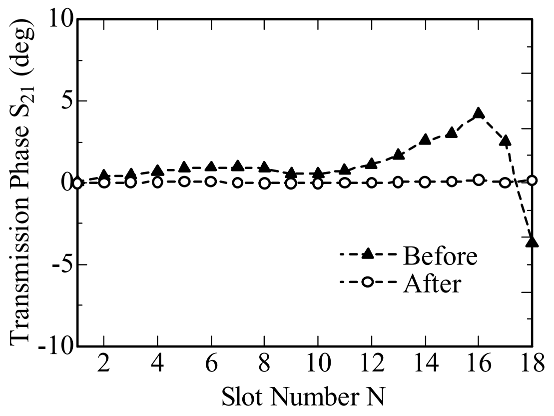


Fig. 6: Transmission Phase at Each Slot on the Center-Located Waveguide before and after Iteration