Chapter 3
Reflection characteristics due to mutual coupling among slots

3.1 Introductory remarks

Fixed Wireless Access (FWA) systems in the 26 GHz band have been commercialized in Japan for high-speed Internet connections between subscribers and base stations. Compact and low cost user terminals are realized by adopting alternating phase fed single-layer waveguide slot arrays [3-1]. This unique antenna consists of two parts, a slot plate and a base plate with corrugations screwed to each other, which dispenses with electrical contact in the strict sense. All the components in the array such as power dividers and slots are designed so that the reflection is suppressed in each component; the array works in traveling wave operation for widening the bandwidth of the array even in large size and high gain applications. A Time Division Duplex (TDD) technique is adopted, and the same frequency is used for transmission and reception. To double the frequency efficiency, we proposed the system which utilizes orthogonal polarization [3-2] [3-3] [3-4]. Challenges for full frequency reuse based upon high polarization purity, which is inherent to planar slotted waveguide arrays, are now underway. Fig. 1 shows an example of orthogonal arrangement of two arrays; the antenna in (a) is for transmitting while the antenna in (b) is for receiving or vice versa. An alternating phase fed array with a new feeding structure named center-feed single-layer waveguide arrays was developed for this system [3-5]. In this array, the feed waveguide is not at the end but is in the center of the array aperture; the bandwidth doubling of the array and the frequency-independent boresite beam without tilting are the two important design objectives of this array. The grating lobes due to blockage are remedied by adopting a tapered aperture illumination [3-6]. As is usual in the case of such an electrically-large structure, overall reflection can not be designed in strict sense and is assessed roughly by the simple sum of the reflections from components, which are electrically much smaller. Unfortunately, it turns out that the measured reflection is much higher than this primitive prediction and that the accumulation of reflection at the input port becomes notable as the size of the array increases.
In this chapter, we diagnose the reflection in large center-feed single-layer waveguide arrays. The FEM analysis using HFSS is conducted for the whole structure of this large array, which has more than 30 dBi of gain. Although the structure is very large in terms of the wavelength, the predicted reflection shows remarkable agreement with the experiments. The mechanism of reflection accumulation in the overall array is discussed. It is concluded that the external mutual coupling between slots in adjacent alternating phase radiation waveguides results in increased reflection at the design frequency. Amongst all, the dominant contributions are coming from strongly excited slots; for tapered illumination to produce low sidelobes, slots in the central part of the aperture cause considerable degradation.

3.2 Center-Feed Array Antenna [3-5] [3-7]

3.2.1 A center-feed single-layer waveguide array

Fig. 3-2 shows the structure of a center-feed single-layer waveguide array. The design frequency is 25.3 GHz. It has 32 (=16x2) radiation waveguides. The 32-way power divider at the center of the antenna aperture consists of 14 cross-junctions and 2 terminal-junctions; 7 cross junctions are arrayed in series on each side of the antenna input. Each cross-junction has 4 inductive posts and two ports coupling to radiation waveguides [3-8] [3-9] [3-10] [3-11] [3-12]. One radiation waveguide has 10 slots, each with a reflection canceling sidewall; the total number of slots in the array is 320 (10x32). Each part of the antenna is analyzed and designed by the method of moments [3-13] [3-14]. This antenna mechanically consists of a slotted plate and a waveguide base joined by a screw. The test antenna is fabricated for a FWA system at 25.3 GHz as shown in Fig. 3-1.

3.2.2 A multiple way power divider with a series of cross-junctions

Fig. 3-3 (a) shows the structure of a power divider consisting of cross-junctions and Fig. 3-3 (b) shows a photo of the actual structure. This structure can divide the
power equally to all radiation waveguides. Adjacent radiation waveguides are fed 180 degree out of phase (alternating-phase). All the windows that couple to radiation waveguides are designed to be reflection-free; the feed waveguide operates as a traveling wave waveguide.

### 3.2.3 A radiation waveguide - linear array of reflection canceling units consisting of a slot and a wall

Fig. 3-4 (a) shows the reflection canceling units where each unit consists of a slot and a wall. The reflection from the slot is canceled by the projection in the narrow wall; the units are regarded as reflection-free. This dispenses with the beam tilting technique widely adopted for reflection suppression and realizes a main beam in the normal direction of the slotted plate. Fig. 3-4 (b) shows the photo of a reflection canceling wall. The radiation waveguides also operate as a traveling wave waveguide.

One difficulty of this center feed array is that the grating lobes associated with the blocking area (width = 2.1 $\lambda$) above the feed waveguide. It results in grating lobes of about -10 dB in the direction of 5.5 degree from bore-site. In order to suppress these, the slot excitation distribution is synthesized and tapered toward the edge as in Fig. 3-5. Fig. 3-6 shows the H-plane radiation patterns for this tapered illumination as compared to that for uniform illumination. The grating lobes are suppressed down to about -15 dB. The gain degradation due to tapered illumination is 1 dB in theory but is less than 0.2 dB in measurements, where we can not account for slot mutual coupling effect in the design. [3-6].

Fig. 3-7 shows the measured gain of the prototype antenna. Antenna gain of 30.5 dBi, which meets the requirement from FWA system is obtained at 25.3 GHz. The size of this antenna is 205mm x 165mm and the aperture efficiency is 37%; this is not high enough in terms of the potential of this types of array and should be improved in the future.
3.3 Reflection Characteristics

3.3.1 Reflection from components

Reflection characteristics are evaluated by the commercial FEM software HFSS. Before analyzing the large scale array, the reflections from key components such as the antenna input aperture, the 16-way power divider and the linear slot array, assessed in the design, are reviewed. The antenna input aperture and the 16-way power divider are modeled as shown in Fig. 3-8. Structural symmetry is taken into account to simplify the model and reduce the computational load. Calculated reflection characteristics of each component are shown in Fig. 3-9. For each component, a return loss less than -20 dB is obtained at the objective frequency. Reflection from the linear array is small since the mutual coupling between slots along the radiation waveguide was taken into account in the design in this isolated environment. The overall reflection characteristic of the array is roughly predicted as the sum of the absolute value of reflections for these three components as in the same figure. A reasonable reflection of about -25 dB is predicted around 25.3 GHz upon the above assumption. At this stage, the slot mutual coupling between adjacent radiation waveguides in the external half-space is neglected.

3.3.2 Overall reflection from the array

The sum reflection given in 3.3.1 is a rough approximation in that the phase information as well as the mutual coupling between slots in adjacent waveguides are neglected. It may be called an “isolated waveguide model”. Generally, it is very difficult to simulate the reflection from electrically large, complicated structures, since not only the amplitude but also the relative phase of each component of reflection must be evaluated accurately. Modeling and meshing the entire antenna in the limited memories of personal computers is heavy and has not been discussed in the literature. But this challenging computation was conducted in spite of all these difficulties. The FEM analysis model is shown in Fig. 3-10 where due to the symmetry, only a quarter of the structure with a magnetic wall and an electric wall is considered. HFSS's adaptive mesh generation was adopted [3-15] and the mesh sizes for the Fig. 3-11 simulation models are 145,520 to 153,649 tetrahedra. It took from one to two hours and 1.7 GB
memory to simulate each model. When the difference of the magnitude of the S-parameters between two adaptive pass (Delta S less in HFSS) is smaller than 0.01, the calculation stops.

Fig. 3-11 shows the measured and calculated results of the reflection characteristics of the whole array. This experimental data is obtained using a network analyzer in an anechoic chamber. The reflection is defined and compared at the input waveguide, which is connected to the array via an input aperture. The reflection predicted for the “isolated waveguide model” is also included in the figure. The measured reflection is suppressed at a little bit higher frequency of 25.6 GHz and the reflection at the design frequency 25.3 GHz is as high as about –10 dB. The agreement of the full structure FEM analysis and the measurement is noteworthy for such an electrically large structure. The shift of frequency as well as the level of reflection about -10 dB are predicted accurately. It assures the high accuracy in fabrication and the stable operation with the simple contact by screws. At the same time, the “isolated waveguide model” is too rough and is not reliable.

3.4 Mechanism extraction of accumulated reflection in overall array

3.4.1 Slot mutual coupling between adjacent radiation waveguides.

In order to evaluate and understand the slot coupling in the array, the analysis model of the external half space is discussed carefully. In the design of the slots of the prototype array, a linear array model with infinite ground plane, called “isolated waveguide model”, was considered and the mutual coupling effects between slots in adjacent radiation waveguides were neglected. The full structure simulation adopts the more realistic model as shown in Fig. 3-12 (a), where the mutual coupling via the half space was considered. This alternating phase fed array, if it is large enough, is well approximated by the model with conducting metal walls between adjacent waveguides as shown in Fig. 3-12 (b). On the other hand, the isolated waveguide model used in the design approximately corresponds to the model in Fig. 3-12 (c) with absorbing walls between adjacent waveguides.
The FEM simulation is conducted for all three models in Fig. 3-12 (a), (b) and (c) and the reflection characteristics are shown in Fig. 3-11. As expected, the result (b) for the metal wall reasonably agrees with the full model in (a). On the other hand, the result (c) is quite different from these and is more close to the sum reflection used in the design.

Therefore, it is apparent that the mutual coupling greatly affects the reflection characteristics. It suggests that the slot design accuracy would be enhanced if the full model in (a) or its approximation in (b) is used in stead of the present “isolated waveguide model”.

### 3.4.2 Localization of mutual coupling in the aperture as functions of illumination distribution

In the previous section, the mutual coupling between adjacent waveguides is found to be the key factor for the accumulated reflection in alternating phase fed arrays. In this section, the slot with the dominant contribution in a linear array is localized. The overall reflection is calculated for the model with increasing number of slots in a radiation waveguide as shown in Fig. 13 (a). In every calculation, each radiation waveguide is matched or connected with an infinitely long waveguide which simulates the actual antenna operation. Fig. 14 shows overall reflection characteristics as the number of slots along the radiation waveguide is increased. The mesh sizes adopted for Fig. 14 are 96,193 to 272,317 tetrahedra. It took from one to twenty-two hours and 1.7 GB memory to simulate each model. If not for slots (zero), the reflection is similar to the sum reflection in Fig. 3-9 and 3-11. The return loss at the design frequency 25.3 GHz is considered. The reflection rapidly increases as the slot number increases; the degradation from “zero” to “first” and “first” to “fifth” is notable while that from “fifth” to “tenth” is not so clear. It seems as if the slots with lower numbers are more dominant that those with higher numbers. In order to support this observation, a complementary model was also analyzed which has the slots only from sixth to tenth slots array as is shown in Fig. 3-14. Here, the return loss is not increased drastically at the design frequency 25.3 GHz as shown in Fig. 3-14. Therefore it is confirmed that the mutual coupling of slots with lower numbers, those near the feed waveguide, greatly affects the reflection characteristics.
The above results are then viewed in terms of aperture illumination. This antenna adopts slot excitation tapered down as shown in Fig. 5 for suppressing side lobe levels due to blocking. Therefore, the comparison may depend upon the desired illumination; the overall reflection of an array with uniform slot excitation, though the side lobe level is high, was also conducted and is presented in Fig. 3-15. The mesh sizes for the Fig. 15 simulation models are 99,736 to 135,259 tetrahedra. As the number of slots increases, reflection gradually increases but it still remains as low as -20 dB at 25.3 GHz. Furthermore, all the slots are equally contributing to the degradation; the significant difference between the importances of slots is not observed in contrast with tapered illumination. By the way, when only the first row of slots exists, the reflection characteristics are different between the uniform amplitude array in Fig. 15 and the tapered amplitude model in Fig. 3-14. This difference is related to the fact that the slot coupling coefficients assigned for the first slots depend upon the distribution. For the tapered amplitude slot excitation model, the first row of slots radiates almost 20 % of the power. The first row of slots in the uniform amplitude model, on the other hand, only radiates about 10 %.

Finally, the conventional method of narrow band reflection suppression is referred to as well in Fig. 3-15. For a very narrow band system, we have only to modify the input structure, input aperture’s height in this specific example, so that the reflection cancels out at the desired frequency only. Measured reflection characteristics slightly moves into the desired frequency and return loss less than –17 dB is obtained at the desired frequency in the simulation. It is noted that the bandwidth is much narrower than the results of “tenth” in Fig. 3-15.

### 3.5 Conclusion remarks

We discussed the reflection characteristics of center-feed, alternating phase single-layer waveguide arrays. By increasing the number of slots in the radiation waveguides, the mutual coupling effects become serious. The slots near the feed waveguide, which are strongly excited, greatly affects the reflection characteristics. Our future study is to introduce the PEC wall model into the slot design of a linear array for accurate prediction of overall reflection from alternating phase fed arrays. Uniform illumination would be advantageous in view of mutual coupling and wideband reflection suppression.
References


Fig. 3-1 A terminal with orthogonal arrangement of arrays in dual polarization FWA systems.
Fig. 3-2 A center-feed alternating phase fed single-layer waveguide array.
Fig. 3-3 A multiple way power divider consisting of series of cross-junctions.
Reflection canceling unit with slot and wall.

(a) Unit consisting of slot and wall

(b) Picture

Fig. 3-4 Reflection canceling unit consisting of slot and wall.
Fig. 3-5 Synthesized aperture illumination for reduction of side lobes due to center feed waveguide blockage.
Fig. 3-6 H-plane radiation pattern. Tapered slot array excitation (Cal. and Exp.) and uniform slot array excitation (Cal.).
Fig. 3-7 Measured antenna gain.
Fig. 3-8 Various component models.

(a) antenna input aperture  (b) 16-way power divider  (c) slot array
Fig. 3-9 Reflection characteristics of each component.
Using symmetry

(a) Prototype        (b) Whole model        (c) A quarter model

Fig. 3-10 Whole analysis model. (center-feed single-layer waveguide arrays)
Fig. 3-11 Overall reflection characteristics.
Fig. 3-12 Model of external half-space above the array aperture. (In HFSS, metal wall is conductor with bulk conductivity of $1e+30$ Siemens/m. Absorber is expressed by the second-order radiation boundary condition).
(a) Number of slots increase  (b) Only sixth to tenth slots array

Fig. 3-13 Various models for external slot coupling simulation.
Fig. 3-14 Reflection as function of number of slots which are tapered amplitude slot excitation. (Cal.) The condition for convergence is Delta S less than 0.02
Fig. 3-15 Reflection as function of number of slots which have uniform amplitude of slot excitation. (Cal.) Narrow band matching (Exp.) is conducted for tapered illumination by changing the aperture height from 5.9 mm to 5.0 mm. Delta S less than 0.02.