An E-Band Partially-Corporate Feed Slot Array with Laminated Quasi Double-Layer Waveguide Structure and PMC Terminations

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1. Introduction

Authors have developed various types of single-layer slotted waveguide arrays with simple structure and high mass-productivity. Those arrays have been successfully applied to relatively narrowband commercial services for satellite broadcast reception in 12 GHz band and wireless IP access at home in 26 GHz band etc. However, one weak point of that antenna is that the bandwidth of the antenna gain is restricted due to the long line effect resulting from the series-fed structure. For larger bandwidth, partially-corporate and corporate waveguide feeding circuit in the same layer with the radiating elements [1] have been developed by keeping the simple antenna construction at the expenses of enlarging the element spacing and the degradation in sidelobe. A double-layer antenna with a feeding circuit installed underneath the radiating waveguides deserves more expectations. A suitable fabrication technique for the realization of double-layer antenna in millimeter-wave band is also an essential issue.

In this paper, a double-layer partially-corporate feeding structure [2, 3] to feed only two elements in series is introduced to enhance the bandwidth by reducing the long line effect in a series-fed array antenna. A 16×16-element array, which can be decomposed into 16 4×4-element sub-arrays, is to be realized demonstratively in the E-band. The fabrication technique called "diffusion bonding of laminated thin metal plates" [3, 4] is to be applied in the realization of double-layer antennas. The diffusion bonding is a process to realize stable surface bonding by applying plastic deformation and atom diffusion motion under the condition of high pressure and high temperature (~1000°C) in a protective atmosphere or vacuum. Etching of thin plates has the features of high precision around 20μm and low cost. The number of etching patterns is only five for the double-layer waveguide slot array [3]. Relatively long processing time of the diffusion bonding is not serious if a large number of antennas are processed simultaneously.

2. Array Configuration and Proposal of PMC Termination

Fig. 1 shows the configuration of the 16×16-element double-layer waveguide slot array in a perspective view. The whole antenna is fed by a standard waveguide from the bottom through an input aperture. The 16 sub-arrays are fed in-phase and in parallel with no frequency dependence, via an input aperture and a series of H-plane T-junctions in order. Since an in-phase fed array with regular slot arrangement has an advantage of suppressing the second-order beam [3, 5], all the radiating waveguides in the top layer are to be fed in-phase through center-inclined slot couplers [6] in the bottom layer. The 16×16-element array with uniform excitation is to be realized for maximizing the directivity.

As shown in Fig. 2 (a), the right-and-left two 4×4-element sub-arrays are fed in same amplitude and phase according to the partially-corporate feed structure. Generally, the last slot coupler terminated by a perfect electric conductor (PEC) wall has a termination distance of half guided wavelength from a short circuit. A large slot-free region existing in between the adjacent sub-arrays results in the degradation of sidelobe levels (SLLs) [1]. In Fig. 2, the arrowed circles indicate the magnetic field inside the feeding waveguides. The centered two arrowed circles in solid lines being in the same direction indicate that the magnetic fields at the terminations of the left-and-right sub-arrays are also in same amplitude and phase.

The authors propose to remove the PEC walls and to join these two feeding waveguides as is illustrated by arrowed circles in Fig. 2 (b). Those two 4×4-element sub-arrays will be densely arrayed without any slot-free region while the inner field distribution as well as the operation of sub-arrays remains unchanged. In this open-connected structure, a virtual perfect magnetic conductor (PMC) wall is formed at the center according to the symmetrical arrangement of feeding waveguides, though the effects due to the asymmetrical arrangement of radiating slots are neglected here. Consequently, the PMC termination is newly introduced to the last slot coupler with a reduced termination distance of one quarter guided wavelength. The structures of the last slot couplers with PEC and PMC termination are illustrated in Fig. 3 (a) and (b), respectively. The key is that they are equivalent at the center frequency and will share the same structural parameters except for the terminations. Furthermore, as illustrated in Fig. 1 the feeding waveguides would intersect at a right angle according to the partially-corporate feed structure at four positions. Instead of introducing a triple-layer structure, the heights of the feeding waveguides are reduced to less than half locally to prevent this intersection. The total antenna thickness is kept unchanged compared to the standard double-layer antenna, even though the number of etching patterns is increased from five to seven for realizing this quasi double-layer antenna. The last slot coupler with PMC termination and a stair due to the crossover of feeding waveguide is also included in Fig. 3. In total, three types of the last slot couplers are to be realized.

3. Design of a 16×16-Element Array in the E-Band

The broadband design in reflection of the 4×4-element sub-array is the key to realizing the 16×16-element double-layer partially-corporate feed antenna. The standing-wave excitation is adopted in the array design of slot couplers and radiating slots with only two elements in series. To enhance the bandwidth, the widths of coupling slots and radiating slots are enlarged to some extent. The sub-arrays with different terminations in the last slot couplers are analyzed and designed by applying HFSS. The overall reflections are summarized in Fig. 4. Almost identical characteristics are achieved in the PMC terminated sub-arrays regardless of the stair. The bandwidth for reflection is enhanced largely by applying the stranding-wave excitation compared with the travelling-wave fed one. The characteristic of double resonance is achieved by tuning the resonances of the feeding and radiating parts toward a lower and higher frequency away from the center, respectively.

The 4×4-element arrays designed above with the standing-wave excitation are combined together into a 16×16-element partially-corporate fed array in the E-band (60~90GHz). The slot spacings in E- and H- planes are $d_E=0.78\lambda_0$, $d_H=0.84\lambda_0$, respectively. The array size is defined as $(d_E\times16) \times (d_H\times16) = 12.5\lambda_0 \times 13.4\lambda_0$. The full-structure analysis is conducted to the overall antenna by applying HFSS. The bandwidth of reflection for VSWR less than 1.5 is 5.7% as shown in Fig. 5. The frequency characteristic of the calculated directivity and gain are summarized in Fig. 6. The antenna gain of 32.55dB and the antenna efficiency of 85.9% are estimated by including the conductivity (58×10^6 S/m) of copper in HFSS. The calculated conductor loss is 0.27dB.

4. Antenna Fabrication and Evaluation

The antenna designed above is fabricated by the diffusion bonding of laminated thin copper plates in the E-band. Fig. 7 shows the picture of the test antenna. It is fed by a standard waveguide WR12 connected at the bottom. The array size is 44.8mm×48mm and the total antenna thickness is 8.9mm. The upper 2.9mm thickness is for the antenna part, while the lower 6mm thickness with the cross section of WR-12 is only needed in measurement for screw connection. The directivity calculated from the measured near-field distribution is also included in Fig. 6. The directivity of 32.8dB with the corresponding high aperture efficiency of 90.1% is realized at the center frequency, where a good uniformity in excitation is achieved. The antenna gain measured by comparing a standard gain horn in an anechoic chamber of 32.4dBi, and the antenna efficiency of 83.0% including all losses are achieved. There is no further loss resulting from the process of diffusion bonding, and good electric contact as well as stable surface bonding is also confirmed. The bandwidth for 1dB-down gain from the maximum is 9.0%, where a broadband characteristic is realized. Fig. 8 shows the radiation patterns at the center frequency. The SLLs in the E- and H-plane are -13.0dB and -12.0dB, respectively. The half-power beam widths in the E- and H-planes are 3.8 degrees and 4.2 degrees, respectively. The experimental results are in good agreement with the simulated ones in both cut planes. High cross polarization discrimination of -37dB at the neighborhood of boresight is experimentally confirmed, even though wide radiating slots with the width-to-length ratio at almost 1/2 are adopted.

5. Conclusion

A double-layer partially-corporate feed structure with only two elements in series is introduced to the waveguide slot array to enhance the bandwidth of antenna gain. A PMC termination originally realized by the symmetrical waveguide connection is proposed in the partially-corporate feed arrays. The 4×4-element sub-array with standing-wave excitation exhibits larger bandwidth of reflection than the travelling-wave fed one. The 16×16-element array is fabricated by diffusion bonding of laminated thin copper plates in the E-band. As the experimental results, the antenna gain of 32.4dBi with the high antenna efficiency of 83.0% is achieved at the center frequency. The bandwidth of 1dB-down gain from the maximum is 9.0%, where a broadband characteristic is realized. High cross polarization discrimination of -37dB is also experimentally confirmed for wide radiating slots.

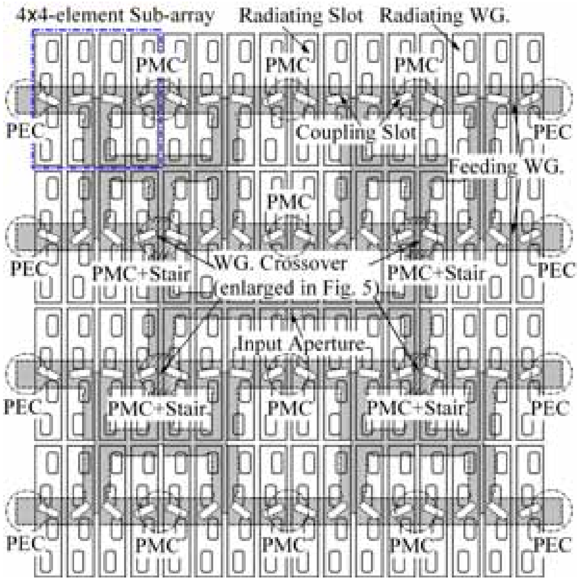


Figure 1: Configuration of a 16×16-element Array.

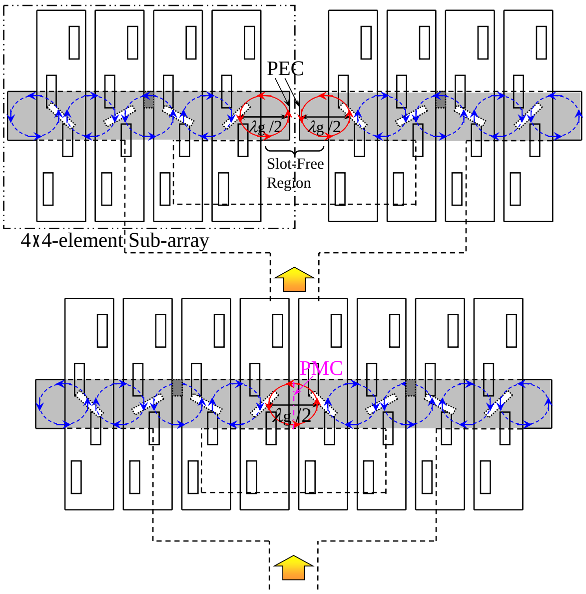


Figure 2: Proposal of PMC Termination.

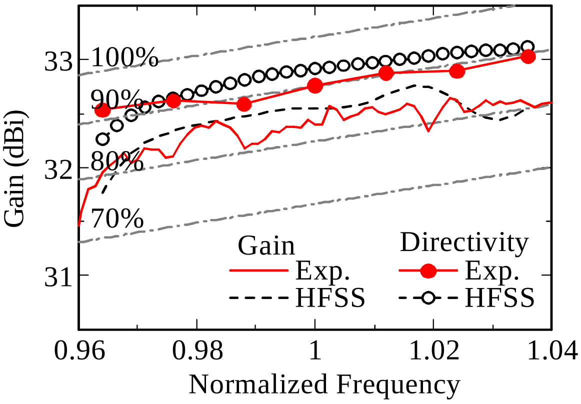


Figure 6: Gain and Directivity of a 16×16-Ele. Array.

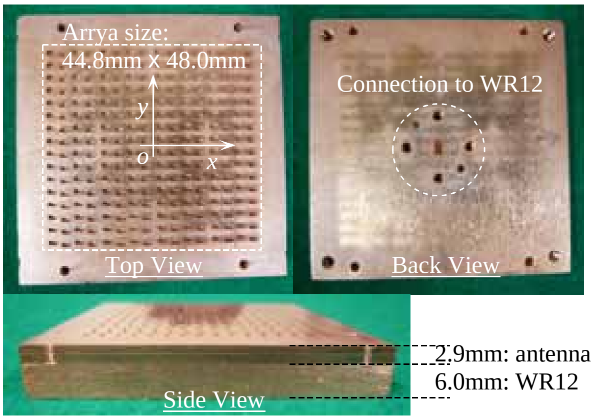
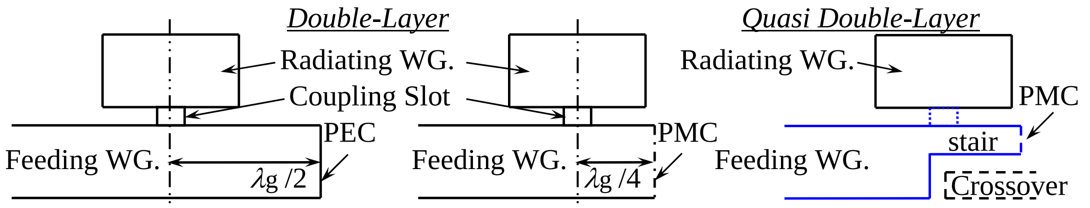
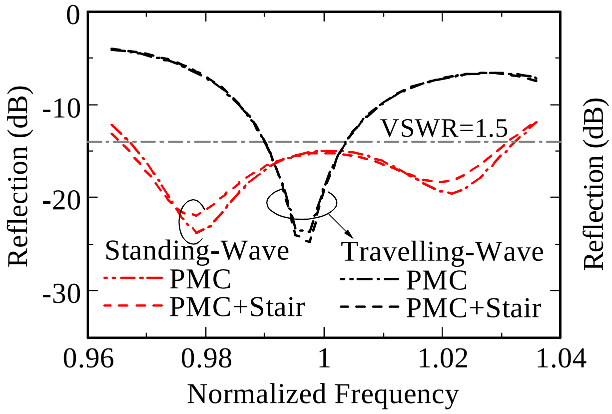


Figure 7: Test Antenna in the E-Band.



(*a*) PEC termination (*b*) PMC termination (*c*) PMC + Stair

Figure 3: Last Slot Couplers with PEC and PMC Terminations.



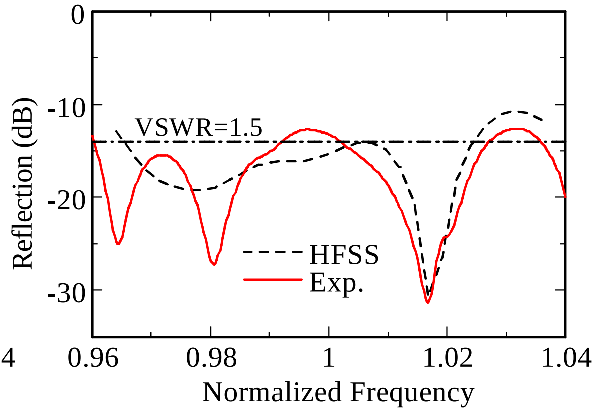
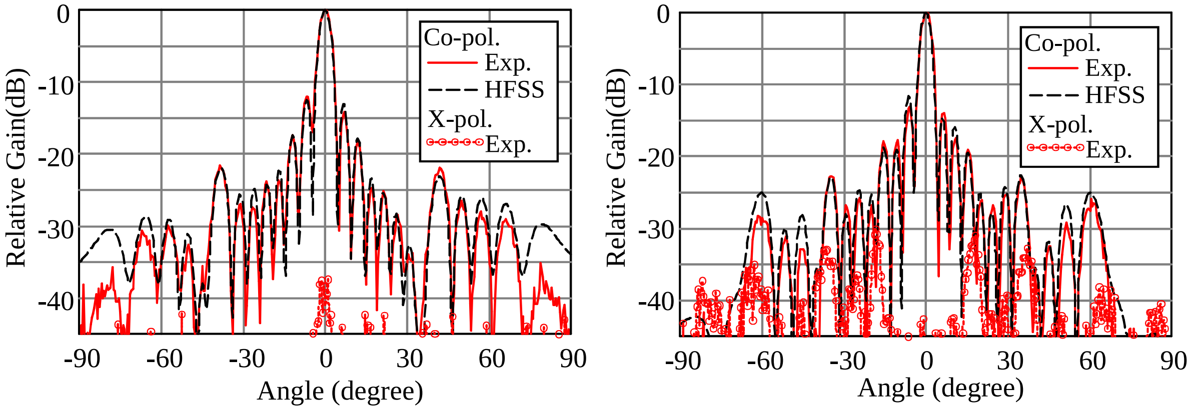


Figure 4: Reflection of a 4×4-Element Sub-Array. Figure 5: Reflection of a 16×16-Element Array.



(*a*) *E*-plane (*b*) *H*-plane

Figure 8: Radiation Patterns in Principle E- and H-plane at the Center Frequency.

References

[1] M. Ando, Y. Tsunemitsu, M. Zhang, J. Hirokawa and S. Fujii, “Reduction of long line effects in single-layer slotted waveguide arrays with an embedded partially corporate feed,” to be published in IEEE Trans. Antennas Propag., 2010.

[2] S.S. Oh, J.W. Lee, M.S. Song and Y.-S. Kim, “Two-layer slotted-waveguide antenna array with broad reflection/gain bandwidth at millimetre-wave frequencies,” IEE Proc.-Microw. Antennas Propag., Vol. 151, No. 5, pp. 393-398, Oct. 2004.

[3] M. Zhang, J. Hirokawa and M. Ando, “Design of a double-layer slotted waveguide array with a partially corporate feed circuit installed in the bottom layer and its fabrication by diffusion bonding of laminated thin plates in 38GHz band,” 2009 Intl. Symp. Antennas Propag., Session: TB2.2, Bangkok, Thailand, Oct. 2009.

[4] M. Zhang, J. Hirokawa and M. Ando, “Fabrication of a slotted waveguide array at 94GHz by diffusion bonding of laminated thin plates,” IEICE Tech. Rept., AP2008-35, 2008-6.

[5] L.A. Kurtz and J.S. Yee, “Second-order beams of two-dimensional slot arravs,” IRE Trans. Antennas Propag., Vol. 5, No. 4, pp. 356-362, Oct. 1957.

[6] S.R. Rengarajan, “Analysis of a center-inclined waveguide slot coupler,” IEEE Trans. Microwave Theory Tech., Vol. 37, No. 5, pp. 884-339, May 1989.