Loss Factors in Parallel-plate Slot-array Antennas on a Copper-clad Dielectric Substrate in the Millimeter-wave Band

#Yuanfeng She, Jiro Hirokawa, Makoto Ando
Department of Electrical and Electronic Engineering, Tokyo Institute of Technology
2-12-1, Ookayama, Meguro-ku, Tokyo 152-8552, Japan
yuanfeng@antenna.ee.titech.ac.jp, jiro@antenna.ee.titech.ac.jp, mando@antenna.ee.titech.ac.jp

1. Introduction

A post-wall waveguide-fed parallel-plate slot array antenna [1–3] has been proposed as a high-gain, high-efficiency and mass producible planar antenna in millimeter-wave applications. The authors are developing post-wall waveguide slot arrays using a copper-clad dielectric substrate which reduces the cost of waveguides structures by printed circuit board (PCB) fabrication technique.

The transmission loss reduces the antenna efficiency, particularly in millimeter-wave bands. In order to accurately estimate the antenna efficiency, loss in every part of the antenna should be carefully evaluated. The precise theoretical estimation of the losses including the effects of surface roughness is difficult [4,5]. The authors use the Whispering Gallery (WG) mode resonator method [6,7] to measure not only the complex permittivity of a dielectric substrate but also the effective conductivity considering the rough interface between the copper and the dielectric over a wide frequency range. A discussion [8] of the measured loss of microstrip lines has been shown to support the property of the effective conductivity obtained by this method.

In this paper, the authors investigate the efficiency of the post-wall waveguide-fed parallel plate slot arrays at 76.5GHz. Loss factors, such as the transmission loss (the dielectric loss and the conductor loss both in the feed and the parallel plate waveguides), the aperture illumination efficiency, the reflection and the insertion loss of the input transition have been taken into consideration. The transmission loss is evaluated in the sense of perturbation theory using the macroscopic model where the fields are decaying exponentially due to the presence of coupling windows in the feed and slots radiation in the parallel plate. The loss associated with the currents locally enhanced by slot radiation is also evaluated using a microscopic model with one slot pair.

2. Antenna Operation and Loss Factors

Figure 1 shows the structure of the post-wall waveguide-fed parallel-plate slot arrays [1]. The antenna operation is as follows: A power is fed through a stepped transition [9] from a standard waveguide at the middle of a feed waveguide. The power is uniformly divided through the coupling windows in the feed post-wall waveguide and a TEM wave is incident from one end of the parallel plate waveguide. A linear-polarized wave is radiated from an array of reflection-cancelling slot pairs on the parallel plate waveguide.

The loss factors in the antenna are as follows: The stepped transition results the reflection loss e_r and the insertion loss e_i. The overall transmission loss e_t is resulted from the dielectric loss and the conductor loss both in the feed and the parallel plate waveguides. In addition, a non-uniform distribution in radiation, in other word, the aperture efficiency e_a, makes the actual directivity less than that we expected. Moreover, we have additional loss e_l due to the local perturbation around the slot pairs with their radiation and so on. The antenna gain is measured by an anechoic chamber and it is compared with a standard-gain horn. The gain of the antenna can be expressed as $G = \eta D_0 = (e_r \times e_i \times e_t \times e_a \times e_l \cdots) D_0$. The theoretical limit directivity of the antenna is $D_0=4\pi S/\lambda_0^2$ where S is the array size and λ_0 is the wavelength in the free space. The radiation area S is defined as the element spacing times the number of the elements in each of the transverse and the longitudinal directions in the parallel plate waveguide. Figure 2 shows the measured gain ηD_0 and the estimated directivity e_aD_0 of five antennas with different sizes. The discrepancy between the theoretical limit directivity and the measured gain is affected by the above mentioned loss factors, while with the directivity obtained by the near-field measurement indicates the aperture efficiency.

3. Loss Evaluation of the Post-Wall waveguide-Fed Parallel-Plate Slot Arrays

3.1 Effective Conductivity and Complex Permittivity Confirmation

A procedure utilizing an open-type WG mode dielectric resonator was proposed to measure the complex permittivity of a dielectric substrate and the effective conductivity of a copper clad and posts in the millimeter wave bands [10]. Figures 3 shows the values of the effective conductivity of a PTFE substrate with copper clad on the surfaces. The effective conductivity is approximated by exponential function fitting for extrapolation from 10-100GHz [11]. The effective conductivity for the copper clad and for the posts are σ_{ci}=58×10^{6}e$^{-0.0192f}$ S/m and σ_{p}=58×10^{6}e$^{-0.0272f}$ S/m, where f is in gigahertz. We also get an approximate value of the complex permittivity by linear fitting in each frequency band; ε_r and $\tan\delta$ are 2.168 and 0.00065 respectively at 76.5GHz. The transmission loss evaluation of post-wall waveguides in a wide range of frequency bands has confirmed these electric properties as shown in Fig.4. The agreement between the estimated and the experiments confirms the effective conductivity and the complex permittivity using the WG mode resonator method and also provides the reliable prediction of transmission loss in post-wall waveguides.

3.2 Transmission Loss in Feed waveguide and Parallel Plate

We consider the losses in the slot arrays with uniform illumination of the aperture. Five sizes of the uniformly-excited antennas as shown in Fig. 5 are redesigned to reduce large reflection observed in [2]. Two improvements are introduced. One is the stepped transition at the input aperture, which is more tolerable against the fabrication error [9]. The other is the correction of the equivalent solid-walls in the analysis model for the coupling windows [12]. The sizes of the antennas are 30×30mm^2(A), 45×45mm^2(B), 60×60mm^2(C), 90×90mm^2(D) and 105×105mm^2(E), respectively. The effective conductivity and the complex permittivity in Sect.3.1 are used in loss estimation.

A power-attenuating model is analysed under the condition of a uniform coupling. The power is uniformly decaying from the windows in the feed waveguide or the slots in the parallel-plate waveguide linearly. Assuming the end-fed parallel-plate waveguide slot array antenna is shaped as length L_f and L_r along the feed waveguide and the parallel plate waveguide respectively. α_r and α_f stand for the transmission loss in the parallel plate waveguide where the TEM mode propagates and in the feed waveguide where the TE_{10} mode propagates respectively. They are obtained by the sum of losses from both the dielectric and the conductor respectively. Since the power is fed at the center and divided into two in the feed waveguide, we can double the integration of L_f /2 length [14]. For the 76.5GHz antennas A, B, C, D and E shown in Fig.5, L_f and L_r are both 30mm, 45mm, 60mm, 90mm and 105mm respectively and the estimated transmission losses are 0.17dB, 0.25dB, 0.33dB, 0.49dB and 0.58dB respectively in the feed waveguide and 0.19dB, 0.29dB 0.38dB, 0.56dB and 0.66dB respectively in the parallel plate waveguide.

3.3 Loss due to Local Perturbation of Currents by the Slot Radiation

Radiation from the slot pair gives the local perturbation from the propagating dominant TEM mode around the periphery because the electrical field is divergent at the edges along the length in a narrow slot. Thus, in additional to the loss in parallel-plate associated with the macroscopic model with exponential decay, additional loss results from the locally perturbed currents near the slot radiation. It is true that similar additional loss also occurs near the coupling windows in the feed waveguide. However the authors confirm that the level of this additional loss by the coupling windows in the feed waveguide is very small because the window structure of the coupling windows is parallel to the height or the currents uniform and their field is not divergent at the ends of the posts.

The authors use software HFSS to estimate the loss occurring near the slots. The effective conductivity and complex permittivity confirmed previously is used again in the simulation. The lossless model in Fig.6(a) which set the boundary condition of the upper and bottom metal as PEC and the loss tangent 0, is simulated to compare with the lossy model in Fig.6(b) which set the finite conductivity of copper and the loss tangent of the dielectric as described in Sect.3.1.

The unit radiating power is $S_{31lossless}^2 = |1-S_{11}^2-S_{21}^2|$ in the lossless case while in the lossy case $S_{31lossy}^2 = |1-S_{11}'^2-S_{21}'^2|$ includes not only the radiation power but also the losses. The discrepancy of $S_{31lossless}^2$ and $S_{31lossy}^2$ gives a loss including both the unperturbed transmission loss in the continuous model in Sect.3.2 and the additional loss due to the slot current perturbed by the slots. Thus the loss by the slot perturbation can be extracted from the HFSS simulated total loss as shown in the circle-cashed line in Fig.7. It is found that 7–9% of the radiating power will lose due to the slot perturbation, which will result 0.31–0.42dB loss for the antennas A–E in the parallel plate waveguide.

3.4 Reflection and Insertion Loss

It is found that the input aperture itself has a reflection less than -15dB at 76.5GHz. In other words, less then 0.1dB loss comes from the refection for this series of antennas. The insertion loss of the transition is about 0.13dB at 76.5GHz.

4. Loss Factors and Measured Antenna Efficiency

All the above loss factors influence onto the antenna efficiency. Figure 8 shows the overall antenna efficiency for various aperture sizes of the antennas. The solid line around 2dB with ±0.2dB error bars indicates the total loss obtained from the measured gain. Now we will discuss its breakdown. The hashing areas show the estimated loss including the overall transmission loss in the feed and the parallel plate waveguides, the loss due to the local perturbation with the slot perturbation, the aperture efficiency, the reflection and the insertion loss of the transition. These are accumulated and the overall loss estimation is given by dashed lines which are approaching to the measured results. Our estimation comprehensively considers the loss factors and gets a good agreement with the measurement. The theoretical design limit of the antenna efficiency can be predicted by using the loss factors. These results reveal that the efficiency of antenna may have the probability to be improved up after suppressing the losses associated with the transition, the aperture efficiency and decreasing the material loss using new structures.

5. Conclusion

The efficiency of the post-wall waveguide-fed parallel plate slot arrays due to various types of losses has been discussed at 76.5GHz. With the help of software HFSS, the loss due to each slot pair can be precisely analyzed by using the confirmed effective conductivity and complex permittivity. Therefore, the loss due to the slot perturbation can be extracted. The antenna efficiency can be quantitatively predicted due to the loss factors such as the overall transmission losses both in the feed and parallel plate waveguides, the loss by the slot perturbation, the aperture distribution, the reflection and the insertion loss of the transition. The limit and the potential of the antenna efficiency can be generally predicted in the millimeter-wave band.

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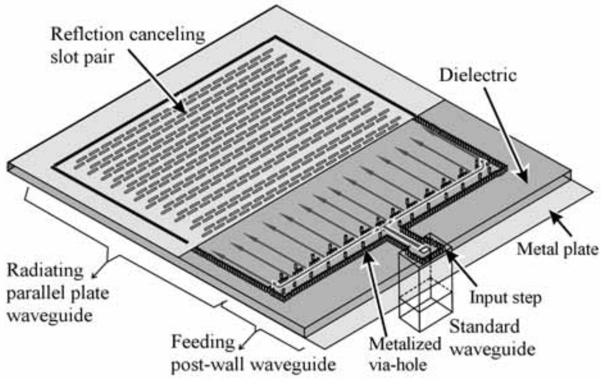


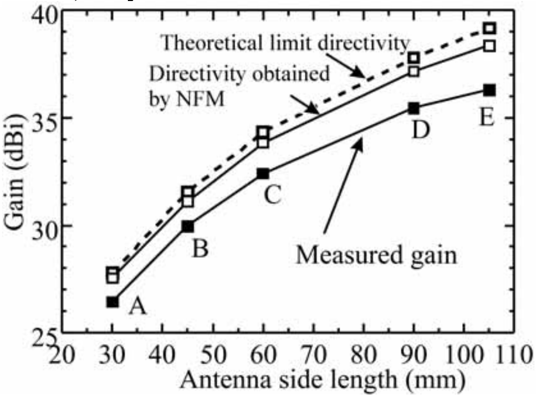
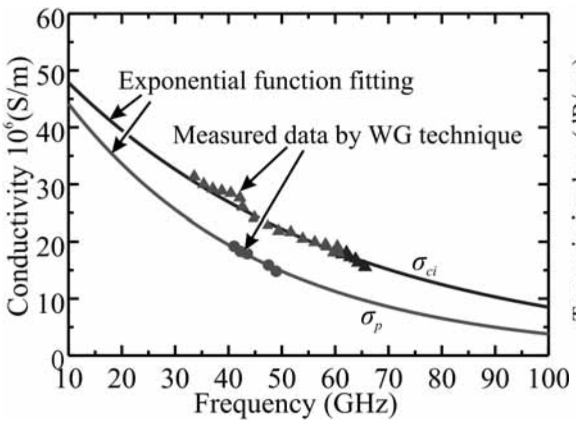


Figure 1 Post-wall waveguide parallel-plate slot arrays   Figure 2 Gain and directivity (76.5GHz)



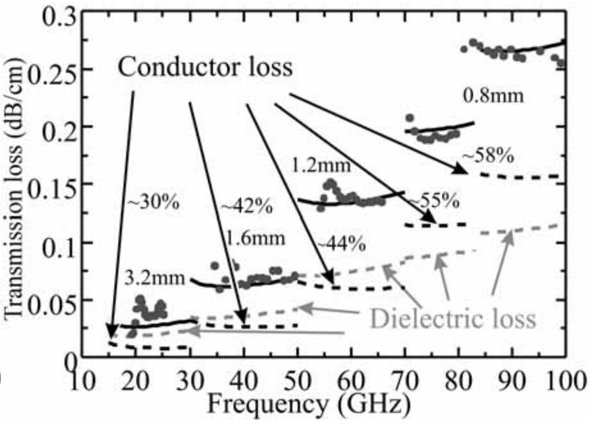
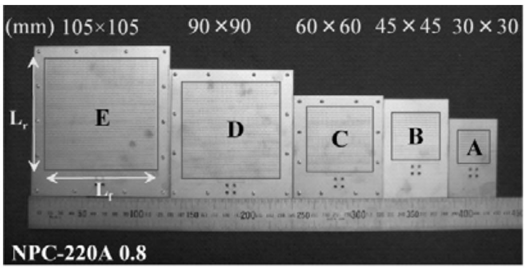


Figure 3 Effective conductivity   Figure 4 Transmission losses of post-wall waveguides



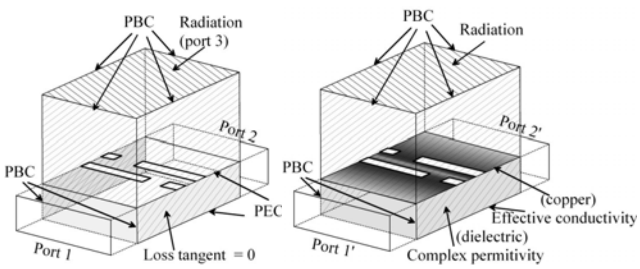
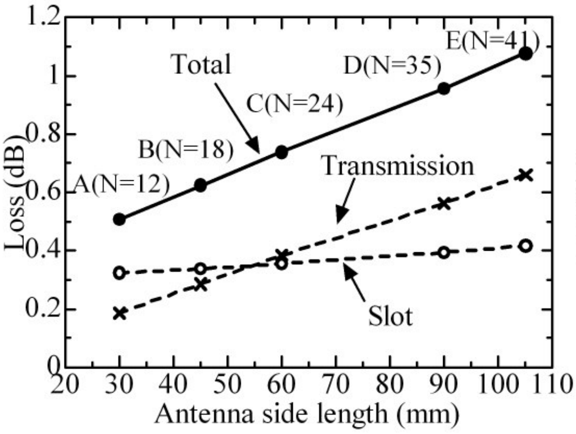


Figure 5 76.5GHz antennas with five sizes

(a) Lossless model   (b) Lossy model

Figure 6 Analysis model of the slot pair unit



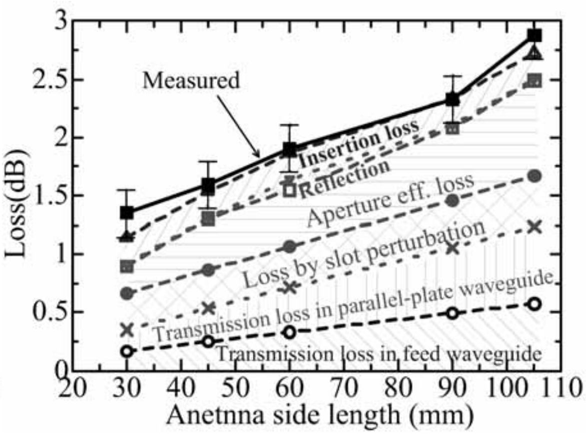


Figure 7 Loss by the slot perturbation   Figure 8 Antenna efficiency in different sizes