94GHz Fabrication of a Slotted Waveguide Array Antenna by Diffusion Bonding of Laminated Thin Plates

Jiro Hirokawa, Miao Zhang, Makoto Ando
Department of Electrical and Electronic Engineering
Tokyo Institute of Technology
S3-20, 2-12-1 O-okayama, Meguro-ku, Tokyo, 152-8552, Japan
jiro@antenna.ee.titech.ac.jp

Abstract—We fabricate the single-layer slotted waveguide array antenna in 94GHz band by diffusion bonding of laminated thin metal plates. This new fabrication technique is a promising one of low cost, because of the high-precision etching in low price. Perfect electric connection can be realized between the slotted plate and the grooved waveguide base by diffusion bonding even at a high frequency such as 94GHz. A designed 18x18-element antenna is trial fabricated by using copper. The antenna efficiency is achieved at 60% for 31.4dBi gain at 93.7GHz in this copper antenna. The process of diffusion bonding using copper could result in over-etching of the slots by 50um, which degrades the aperture efficiency by 0.8dB.

I. INTRODUCTION

A single-layer slotted waveguide array [1][2] is fabricated in 94GHz band by diffusion bonding of laminated thin metal plates as shown in Fig.1. This new fabrication technique is a promising one of low cost, because of the high-precision etching in low price. One of the possible applications is for radar mounting in a small-size aircraft like a helicopter. High-frequency operation gives high resolution in radar system. Conventionally, this type of antenna was mass-produced in 25GHz band [3] by applying die-casting technique, where a die for the grooved waveguide base is crucial and expensive. The screwing between the grooved feed structure and the slotted plate near the feeding apertures has significant importance to realize stable operation, and will be difficult in 94GHz band due to too narrow walls of 0.5mm thickness. Perfect electric connection can be realized between the slotted plate and the grooved waveguide base by diffusion bonding of high temperature of about 1000 degrees even at a high frequency such as 94GHz. Therefore, both the choke structure and the antenna assembly using screws can be abbreviated together. The antenna has only three layers; slotted plate, waveguide and feed. A small number of etching pattern gives low cost. We do not need to use a die. Furthermore, this diffusion bonding technique can also be applied to the conventional slotted waveguide array [4] where the feed structure is placed below the radiating waveguides in different layers.

II. STRUCTURE AND DESIGN

The structure of the single-layer slotted waveguide array [3, 5] is illustrated in Fig.1. The feed waveguide is placed at the same layer with the radiating waveguides. Neighboring radiating waveguides fed in 180-degree out-of-phase are connected to a series of T-junctions through coupling windows spaced by a half guided wavelength. The coupling of the T-junctions is controlled by the width of the coupling window. On the other hand, the coupling of the slots is adjusted mainly by the slot offset from the waveguide center axis. An 18x18-element array is demonstratively designed for uniform excitation at 94.0GHz. The main beam is tilted at -4.7 degrees backwardly from the boresite. The dimensions of the feed and radiating waveguides are 2.05x1.00mm and 2.10x1.00mm, respectively. In order to realize stable process in diffusion bonding, we use 0.3mm for thickness of the slotted plate, which is three times the conventional electrical dimension in the 25GHz band antenna. And 1.0mm is also used for the thickness of the coupling window, which is twice the conventional electrical dimension. The thickness for the side walls in the grooved waveguide structure is 0.5mm, which is equal to the electrical dimension in the 25GHz band antenna.

The offset and the length of the slots are summarized in Fig. 2 for the thickness \( t \) of the slotted plate of 0.1mm and 0.3mm. The variation of the offset is identical between \( t=0.1 \)mm and 0.3mm because all the slots are resonant and the coupling can be controlled even for a thick slotted plate. The slot length to adjust resonance is slightly changed for the thickness. The frequency characteristics of reflection for
different thickness of the slotted plate are summarized in Fig. 3. It is easily observed that the reflection of the 18-slot array is less than -20dB over 90-98GHz for both \( d = 0.1 \text{mm} \) and \( 0.3 \text{mm} \).

Fig. 4 shows the window width and the wall height of the T-junctions. The width in each window becomes large for larger thickness to keep the required excitation because the field attenuates exponentially in the window region. The wall height for reflection cancellation also becomes large for thicker windows. Fig. 5 shows the division of a T-junction for the thickness \( d \) of the coupling window of 0.5mm and 1.0mm. The division for \( d = 1.0 \text{mm} \) has narrower bandwidth than that for \( d = 0.5 \text{mm} \), because the coupling windows narrower than the resonant width are cutoﬀ and the field in the window region is exponentially decayed for a large thickness. It is conﬁrmed that the nine-junction array for \( d = 1.0 \text{mm} \) has narrower bandwidth in terms of reflection below -20dB than that for \( d = 0.5 \text{mm} \). As a conclusion, all these effects of large thickness are precisely evaluated and taken into account during the antenna design.

III. FABRICATION AND MEASUREMENT

The antenna is fabricated by diffusion bonding of laminated plates using stainless and copper. The conductivity of stainless is \( 1.4 \times 10^6 \text{ S/m} \) and the conductor loss is \( 0.226 \text{ dB/cm} \) in a WR10 waveguide at 94GHz while the conductivity of copper is high (58.0x10^6 S/m) and the conductor loss is still small (0.035 dB/cm) at 94GHz. Figure 6 shows the simulated gain of various material and the measured gain and the directivity of the stainless antenna. The gain is affected by the conductor loss of the material. The diffusion bonding typically uses stainless because it is hard and it is tolerable for high temperature. In the stainless antenna, the measured efficiency is 44\% (-3.57dB) while the simulated one is 49\%. The gain is expected to be enhanced by small conductivity of copper. However copper is soft in comparison with stainless. The mechanical tolerance using copper after diffusion bonding could be small and the process of trial and error would be necessary.

Figure 7 shows the picture of the test antenna made of copper. The antenna size is 60mm in length and 55mm in width. The antenna is fed by a standard waveguide WR10 connected on the bottom through a feed aperture. As shown in Fig. 8, the total refection is -8.5dB at 94GHz in the copper antenna. This degradation from simulation result by HFSS may be due to over-etching slots as described below. The aperture field illuminations at 94.0GHz, measured in the near field measurement system are shown in Fig.9. The amplitude is strong around the ends of the radiating waveguides. The variation from the uniformity could result from over-etching of the slots by 50um. Figure 10 shows the simulated aperture field by adding 50um in all the slots. The agreement with the measurement supports the error of over-etching slots. The gain of the copper antenna is shown in Fig.11, where the directivity calculated from the aperture field illumination is also included. The solid line with triangular indicates the gain simulated by HFSS including the conductor loss. The peak gain is realized at 31.4dB with 60\% efficiency at 93.7GHz. Generally, the antenna efficiency can be expressed as the sum of reflection, aperture efficiency and conductor loss in dB. In the stainless antenna, the reflection loss is -0.31dB, the aperture efficiency is -1.14dB in Fig.6. Therefore the conductor loss of the stainless antenna becomes -2.12dB. On the other hand, the reflection is -0.27dB in Fig. 8. Therefore, the conductor loss is estimated at -0.33dB, which is low in comparison with the stainless antenna reflecting the difference in the conductivity. The aperture efficiency of -1.61dB dominates in the copper antenna. Its improvement would enhance the antenna efficiency largely.

IV. CONCLUSION

We fabricate the single-layer slotted waveguide array antenna in 94GHz band by diffusion bonding. According to the processing conditions, the thickness of slotted plate and that of coupling windows are increased to 0.3mm and 1.0mm, respectively. All these effects of large thickness are precisely evaluated and taken into account during the antenna design. The radiating characteristics of resonant slots are not degenerated much. On the other hand, the frequency characteristics of power dividing and reflection become narrow-band because non-resonant coupling windows are applied in the feed circuit. The designed 18x18 elements of the single-layer slotted waveguide array antenna is trial fabricated by diffusion bonding of laminated thin plates using copper. The antenna efficiency is achieved at 60\% for 31.4dBi gain at 93.7GHz in this copper antenna. The material of stainless will provide us with stable process in the tradeoff of large conductor loss. However, the low loss material of copper is indispensable in antenna fabrication. The process of diffusion bonding using copper could result in the misalignment of the thin metal plates, which degrades the aperture efficiency. As the future work, further fabrication is planned to be carried out to enhance the aperture efficiency as well as the antenna efficiency.

REFERENCES

Figure 1. Structure of the single-layer slotted waveguide array antenna

(a) overall view

(b) cross-section view

Figure 2. Frequency characteristics of reflection for the slot plate with different thicknesses

Figure 3. Slot parameters for the slot plate with different thicknesses

Figure 4. Window width and wall height of the T-junctions.

Figure 5. Frequency characteristics of reflection for coupling windows with different thicknesses
Figure 6. Simulated gain of various material and measured gain and directivity of the stainless antenna.

Figure 7. Picture of the test antenna by diffusion bonding of thin copper plates.

Figure 8. Frequency characteristics of reflection at antenna input.
Figure 9. Measured aperture field illumination for copper antenna at 94GHz

Figure 10. Simulated aperture field illumination adding 50um in all the slots for copper antenna at 94GHz

Figure 11. Antenna gain and directivity by measurements and HFSS in the copper antenna