TITLE: Thin Film Antennas for Millimeter and Submillimeter Wave Radiation

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Thin Film Antennas for Millimeter and Submillimeter Wave Radiation

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Abstract – **Properties of the thin film submillimeter wave single slot antenna and slot antenna arrays on the dielectric substrate were theoretically and experimentally investigated. The thin film antennas were fabricated using microfabrication techniques, and the receiving experiments were carried out at 700 GHz. The experimental data agree with the theoretical predictions. The power gain of 13 dBi was obtained by the two-dimensional 8 x 3 slot antenna arrays.**

INTRODUCTION

The demand for millimeter and submillimeter wave systems consisting of planar antennas has recently increased in communication systems, remote sensing, radio astronomy and plasma diagnostics. Some planar antenna arrays fed by a waveguide structure for millimeter wave radiation have been reported [1], [2]. However, the waveguide structure is too complex to fabricate in the submillimeter wave region. On the other hand, a thin film antenna placed on the dielectric substrate is relatively easy to fabricate through recently developed microfabrication techniques. These techniques have encouraged the fabrication of thin film antennas, transmission lines, and detectors on the coplanar substrate. Also, new research has been done on thin film devices in the millimeter and submillimeter wave regions [3], [4].

As thin film antennas for millimeter and submillimeter wave systems, the dipole [5], slot [6], microstrip [7], spiral [8] and log periodic [9] antennas have been studied. Of these antennas, the slot antenna had a simple structure and directivity perpendicular to the substrate. These characteristics make the slot antenna a suitable antenna in the millimeter and submillimeter wave regions. The author and his group have been studying thin film slot antennas for millimeter and submillimeter wave radiation [10], [11].

In this paper, the fabrication and properties of a thin film slot antenna on a dielectric substrate and its arrays with parasitic slots, one-dimensional slot antenna arrays fed by coplanar waveguide (CPW), and two-dimensional slot antenna arrays fed by CPW at 700 GHz are discussed.

THEORETICAL ANALYSIS

Properties of thin film antennas cannot be discussed without taking into account the effects of a dielectric substrate, because the thin film antennas are always fabricated on the dielectric substrates. In the case of the slot antenna on the dielectric substrate, the power radiated from the antenna (P_0) is divided into three parts: the power radiated into the air (air side: P_a), the power radiated into the air through the substrate (substrate side: P_d) and the power loss (P_s) captured in the substrate as a surface wave.

The P_a, P_s and P_d are calculated using the theory based on the transmission lines model [12]. Figure 1 shows the variation of P_a/P_0, P_s/P_0 and P_d/P_0 of a single slot antenna on the dielectric substrate with substrate thickness (h). The power distribution in the region where the substrate is sufficiently thick converges to $P_a/P_0 = 0.11$, $P_d/P_0 = 0.17$ and $P_s/P_0 = 0.72$. This means that 72 % of the radiated power from the antenna is trapped in the substrate as a surface wave, and that the remaining 28 % is delivered to the power P_a (11 %) and P_d (17 %).

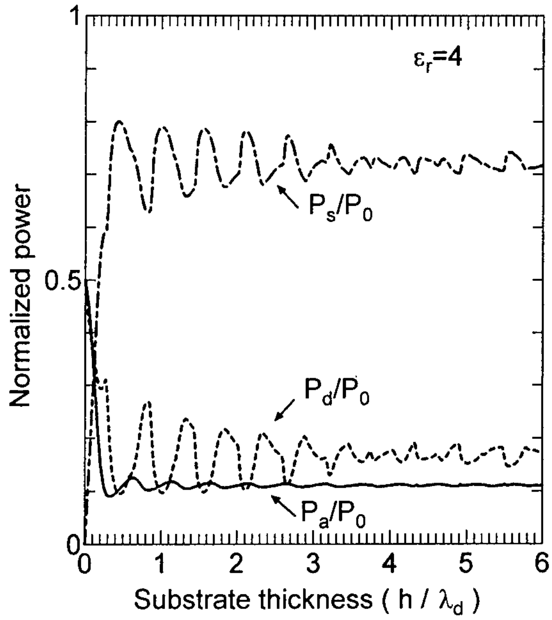

Fig.1 Power distribution of the slot antenna as a function of the substrate thickness.

The radiation pattern and the power gain of the antennas are also calculated. Here, the power gain is defined as the absolute gain in the direction normal to the substrate expressed in dBi, in comparison to a lossless isotropic point source in air. Figure 2 shows the power gain as a function of the substrate thickness. The dotted line indicates power gain on the air side while the solid line indicates power gain on the dielectric side. The gain on the air side decreases quickly until h = 0.3 λ_d and subsequently converged to –3.7 dBi. On the other hand, the gain on the dielectric side decreases quickly until h = 0.5 λ_d and exhibits a periodic variation with minima at even integer multiples of $\lambda_d/4$. Here, λ_d is the wavelength in the dielectric substrate given by $\lambda_d = \lambda_0/\varepsilon_r^{1/2}$ in terms of the free space wavelength λ_0.

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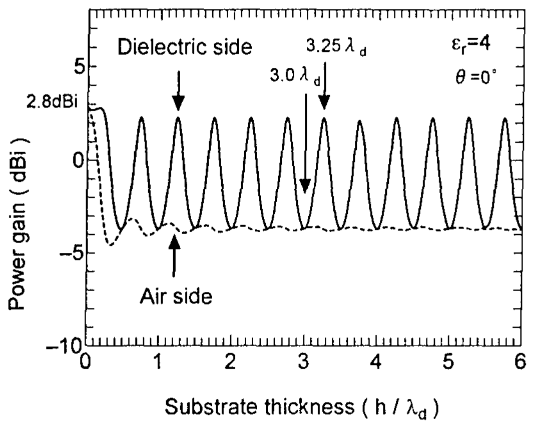
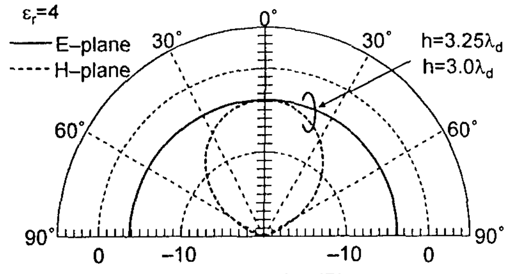
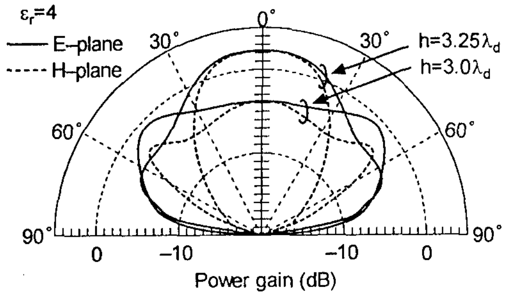


Fig.2 Power gain of the single slot antenna as a function of the substrate thickness.

Figure 3 shows the radiation patterns of the antenna on the dielectric substrate of h = 3.0 λ_d and 3.25 λ_d. Figure 3(a) shows the radiation pattern on the air side, and Fig. 3(b) depicts the ones on the dielectric side. The radiation pattern on the air side is independent of the substrate thickness. On the dielectric side, the radiation patterns for odd integer multiples of $\lambda_d/4$ (h = 3.25 λ_d) are sharper than those for even integer multiples of $\lambda_d/4$ (h = 3.0 λ_d). This sharper radiation pattern increases power gain on the dielectric side up to 2 dBi although the radiation power P_d/P_0 on the dielectric side is less than 0.2 in Fig.1.



(a) air side



(b) dielectric side

Fig.3 Calculated antenna patterns (h=3.0 λ_d and h=3.25 λ_d)

A method to reduce the surface wave is to use an antenna array. A double slot antenna fed by a coplanar waveguide decreases the surface wave loss, P_s, up to 50 %, and increases the P_d up to 30 % as shown in Fig.4. The P_s is further decreased to 36 % by using a four-slot antenna array with two parasitic slots, and power gain was improved by 5 dB over the single slot antenna at 700 GHz. It is considered that the coupling efficiency between two parasitic slots could still be improved by coupling the slots with CPW.

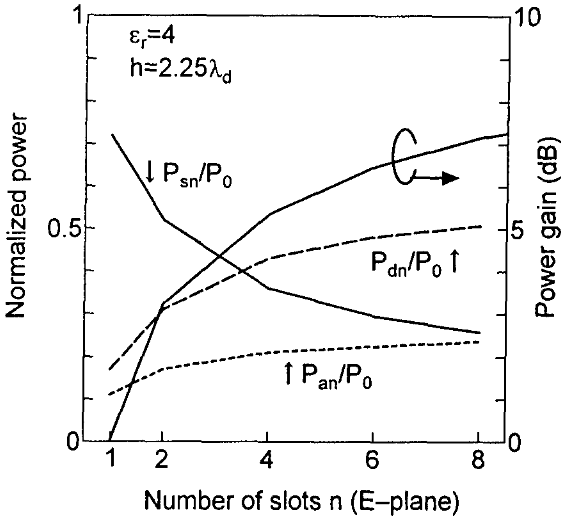
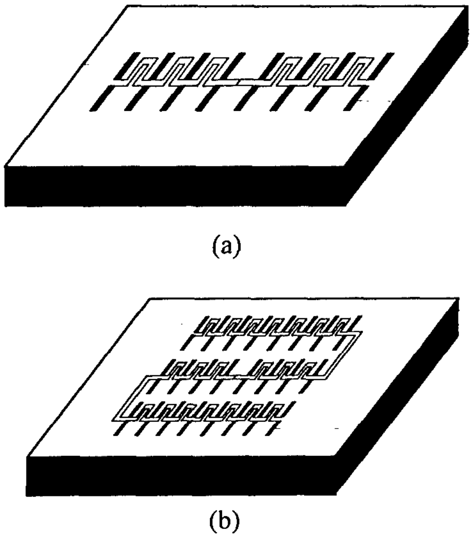


Fig.4 The relationship between the normalized power distribution and the number of slots. And the relationship between the power gain and the number of slots.

Figure 5 shows the configuration of the proposed array antennas fed by CPW. Figure 5(a) shows the one-dimensional eight-slot antenna array, and Fig. 5(b) shows the two-dimensional 8 x 3 slot antenna array. The length of the CPW between two slots is 1.0 λ_m in order that all the slots are excited with an equal phase, where λ_m is the mean wavelength shown by $\lambda_m = \lambda_0/[(1+\varepsilon_r)/2]^{1/2}$.


(a)

(b)

Fig.5 Configuration of the antenna arrays fed by CPW. (a) The one-dimensional eight-slot antenna array fed by CPW. (b) The two-dimensional 8x3 slot antenna array fed by CPW.

Figure 6 shows the relationship between the power gain and the number of slots in the one-dimensional n-slot antenna array and the two-dimensional n x m (E x H plane) slot antenna array. The power gain is calculated on the condition that the transmission efficiency of the CPW per λ_m is $\delta = 0.8/\lambda_m$ and that the rate of the radiated power

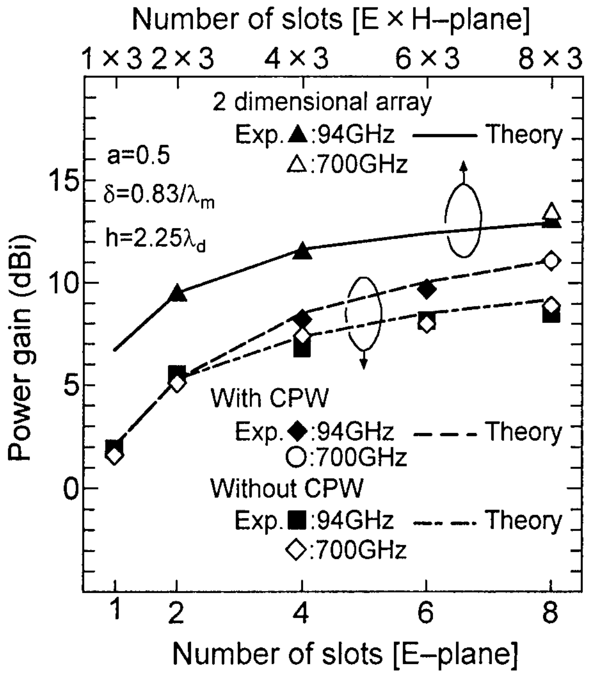


Fig.6 The relationship between the power gain and the number of slots.

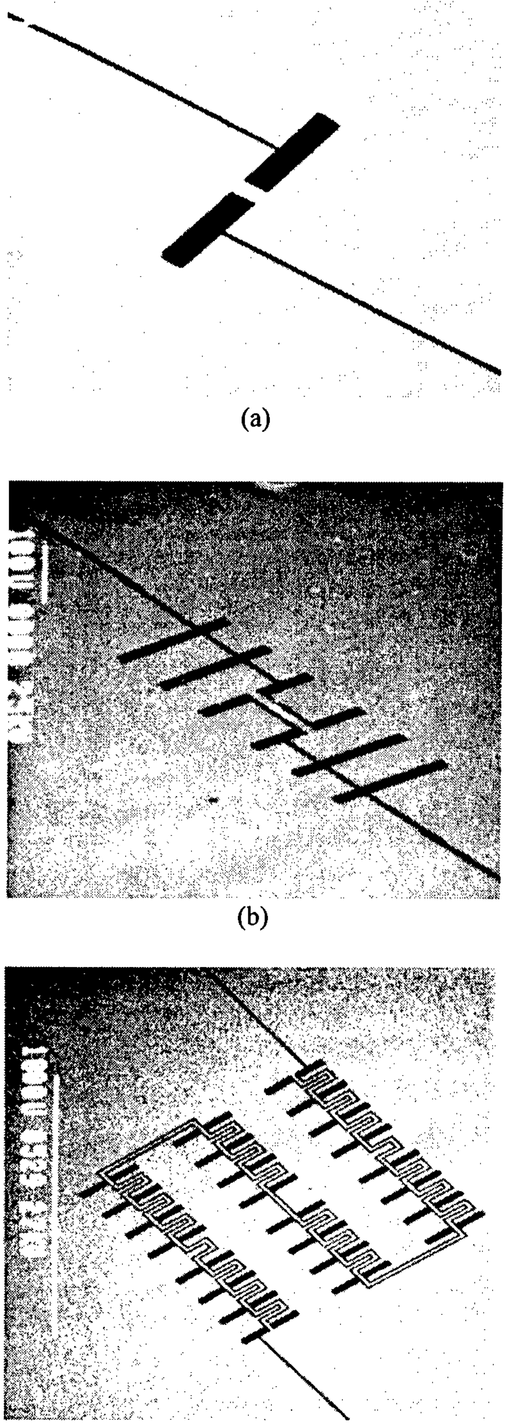
from the slot antenna is a = 0.5. In the figure the power gain of the parasitic slot antenna array is also shown for comparison. The two-dimensional 8 x 3 slot antenna array on the dielectric substrate, of which the thickness is odd integer multiples of $\lambda_d/4$, will have an improved power gain of 11 dB over the single slot antenna and a power gain of 13 dBi by irradiating the signal from the dielectric side.

EXPERIMENTS AND DISCUSSION

The receiving slot antennas for 700 GHz radiation were fabricated on the fused quartz substrate using a photolithographic method. Figure 7 shows the SEM photographs of the fabricated single slot antenna, six-slot antenna array with parasitic slots and two-dimensional 8 x 3 slot antenna array fed by CPW. The length and width of the antenna are 0.72 λ_m and 0.08 λ_m, respectively. Thickness of the substrate is 2.25 λ_d. A bismuth microbolometer is used as a detector and placed at the center of the CPW. To apply the bias current to the bolometer, DC cuts (narrow slits) are inserted.

In the experiments, an HCOOH laser pumped by a CO_2 laser was used for 700 GHz submillimeter wave source. The laser beam was chopped at 1 kHz and irradiated onto the slot antenna directly or through the substrate. The power gain of the slot antenna was calculated using the measured voltage and the sensitivity of the microbolometer.

Figure 6 shows the relationship between the power gain and the number of slots in the three kinds of antennas, when the 700 GHz submillimeter wave was irradiated through the substrate. In the figure, the data measured at 94 GHz is also shown. Symbols ▲, △, ◆, O, ■ and ◇ represent the measured power gain of the antennas. Experimental data agree with the theory based on the transmission line model [12]. It was confirmed from the figure that the two-dimensional 8 x 3 slot antenna array had a power gain of 13 dBi, which was 11 dB higher than that of the single slot antenna as theoretically expected.


(a)

(b)

(c)

Fig.7 SEM photographs of the fabricated slot antenna and its array. (a) The single slot antenna, (b) the six-slot antenna array with parasitic slots and (c) the two-dimensional 8x3 slot antenna array fed by CPW.

CONCLUSION

Properties of the thin film single slot antenna and the antenna arrays on the dielectric substrate were discussed using the theory based on the transmission line model, in order to obtain a thin film antenna with high power gain for millimeter and submillimeter wave radiation. Theory predicted the following things:

1. It is necessary to select the thickness of the substrate odd integer multiples of a quarter wavelength of the radiated signal.
2. The signal should be irradiated through the substrate. In this case, the power gain is 6 dB higher than that on the air side, and reach 2 dBi.
3. The one-dimensional eight-slot antenna array, consisting of six parasitic slots and a double slot antenna, improves the power gain by 7 dB compared to the single-slot antenna, and the power gain reaches 9 dBi.
4. The one-dimensional eight-slot antenna array fed by CPW has a power gain of 11 dBi.
5. The two-dimensional 8 x 3 slot antenna array fed by CPW has a power gain of 13 dBi, which is 11 dB higher than that of the single-slot antenna.

The single-slot antenna and its arrays were fabricated using microfabrication techniques and the receiving experiments were carried out at 700 GHz. The experimental data agree with theoretical predictions.

References

1. R. S. Tahim, G. M. Hayashibara, and K. Chang, "Design and performance of W-band broad-band integrated circuit mixers," IEEE Trans. Microwave Theory Tech., vol. MTT-31, pp.277-283, Mar.1983.
2. K. Sakakibara, J. Hirokawa, M. Ando, and N. Goto, "Single-layer slotted waveguide arrays for millimeter wave applications," IEICE Trans., vol. E-79B, pp.1765-1772, Dec. 1996.
3. S. S. Gearhart and G. M. Rebeiz, "A monolithic 250-GHz Schottky-diode receiver," IEEE Trans. Microwave Theory Tech., vol. MTT-42, pp.2504-2511, Dec. 1994.
4. M. C. Gaidis, H. G. LeDuc, M. Bin, D. Miller, J. A. Stern, and J. Zmudzinas, "Characterization of low-noise quasi-optical SIS mixers for the submillimeter band," IEEE Trans. Microwave Theory Tech., vol. MTT-44, pp.1130-1139, July 1996.
5. D. F. Filipovic, W. Y. Ali-Ahmad, and G. M. Rebeiz, "Millimeter-wave double dipole antennas for high-gain integrated reflector illumination," IEEE Trans. Microwave Theory Tech., vol. MTT-40, pp.962-967, May 1992.
6. B. K. Kormanyos, W. Harokopus, L. P. B. Katehi, and G. M. Rebeiz, "CPW-fed active slot antennas," IEEE Trans. Microwave Theory Tech.,vol. MTT-42, pp.541-545, Apr. 1994.
7. H. Legay, and L. Shafi, "A self-maching wide-band feed network for microstrip arrays," IEEE Trans. Antennas Propergat., vol. AP-45, pp.715-722, Apr. 1997.
8. T. Fukutomi, Y. Yasuoka, S. Kawasaki, and S. Ito, "A printed two-arm spiral antenna operating at the 90-GHz band," IEICE Trans., vol. J77-C1, pp.599-606, Nov. 1994.
9. B. K. Kormanyos, P. H. Ostdiek, W.L. Bishop, T. W. Crowe, and G. M. Rebeiz, "A plana wide-band 80-200-GHz subharmonic receiver," IEEE Trans. Microwave Theory Tech., vol. MTT-41, pp.1730-1737, Oct. 1993.
10. T. Shimizu, Y. Abe, and Y. Yasuoka, "Thin-film slot antennas for 700GHz submillimeter wave radiation," IEICE Trans., vol. E-78C, pp.1002-1006, Aug. 1995.
11. T. Shimizu, Y. Abe, and Y. Yasuoka, "Thin-film slot antennas for 2.5THz submillimeter wave radiation," Jpn. J. Appl. Phys., vol.35, pp. L266-L268, Feb. 1996.
12. H. Kobayashi, M. Yuki, and Y. Yasuoka, "Effects of substrate thickness on the gain of millimeter and submillimeter wave slot antennas," IEICE Trans., vol. J80-B, pp.54-62, Jan. 1997.