IEEE MICROWAVE AND GUIDED WAVE LETTERS, VOL. 4, NO. 7, JULY 1994

# Optimal Design of an Offset-Fed, Twin-Slot Antenna Element for Millimeter-Wave Imaging Arrays

Yongxi Qian, *Member, IEEE,* Shin-ichirou Iwata, and Eikichi Yamashita, *Fellow, IEEE*

*Abstract*—**The optimal design of an offset-fed, twin-slot antenna suitable for millimeter wave imaging arrays is reported. The dimensions of the antenna and the slot separation for realizing a desirable beam pattern are obtained by using the spectral domain method. The optimal position of the feeding microstrips for perfect impedance matching is determined through a full-wave analysis using the FD-TD method, which takes into consideration both the slot elements and the feeding networks. The input characteristics of an optimally designed antenna is evaluated with a network analyzer, where a reasonable agreement with theoretical predictions is obtained.**

## I. Introduction

MICROSTRIP-FED slot antennas in combination with Schottky diodes and other types of detectors have found applications in a number of quasi-optical systems, especially in far infrared and millimeter wave imaging arrays [1], [2]. A twin-slot structure with proper slot spacing and operating in the even mode gives a nearly symmetrical radiation pattern in the $E$- and $H$-plane and is superior to printed dipoles or patches in such properties as low cross-polarization and reduced TM-surface wave losses [3].

A center-fed slot on dielectric substrates such as RT/duroid has a typical radiation resistance of $500 \sim 600\ \Omega$ [4], which presents a serious obstacle in practical applications. One solution to this problem is to employ an offset feeding that is able to offer perfect impedance matching with proper choice of the feeding line position. Axelrod *et al.* presented a model for practical design of such offset-fed slot antennas [5], but it requires the previous knowledge of the radiation resistance of the center-fed slot, which has to be obtained by means of experimental measurement of the $S$-parameters at resonance.

The purpose of this work is to develop a rigorous, efficient approach for designing offset-fed, twin-slot antennas for imaging array applications. We use the spectral domain method to determine the dimensions and optimal slot spacing for realizing the desired symmetrical radiation pattern. Next, we investigate the return loss at the input reference plane by applying a full-wave analysis using the FD-TD method, which takes into consideration both the slots and their interaction as well as the whole feeding circuits. The optimal position of the feeding microstrip is the place where the return loss reaches a minimum. We have fabricated such an optimally designed antenna and tested its input characteristics in the $X$ band with the HP8510B network analyzer. The experimental results was found to be in reasonable agreement with theoretical predictions.

Manuscript received March 8, 1994.

The authors are with the Department of Electronic Engineering, University of Electro-Communications, Tokyo 182, Japan.

IEEE Log Number 9402616.

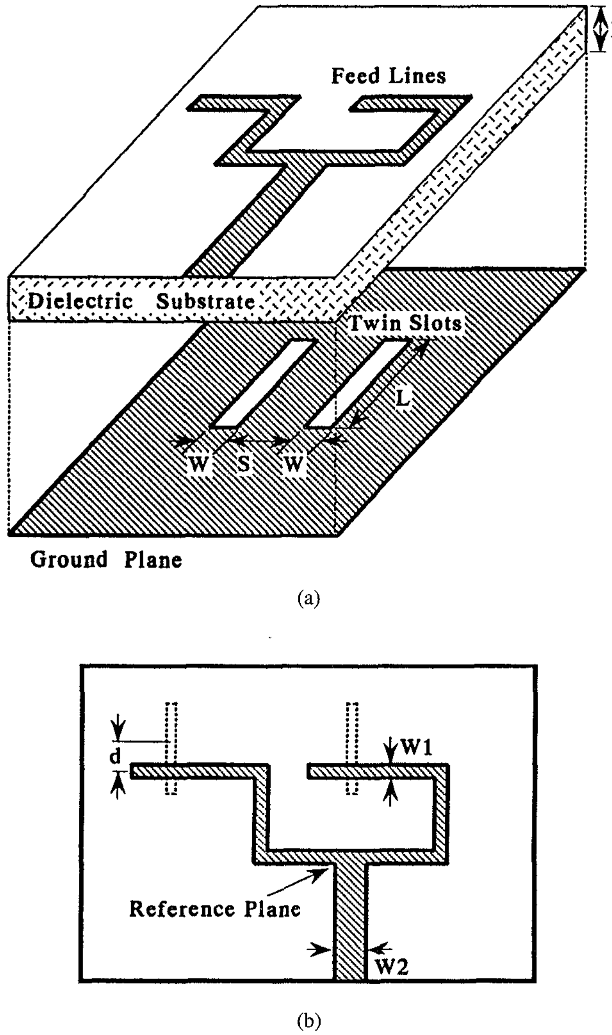


Fig. 1. Configuration of the microstrip-fed twin-slot antenna. (a) 3D view. (b) Top view.

## II. Antenna Configuration

Fig. 1 shows the configuration of the twin-slot antenna. The first step of designing is to determine the size and separation of the slots. For this purpose, we use the spectral domain method, which has been extensively applied to calculate the resonant frequency as well as radiation patterns of various planar antennas [6], [7]. The twin-slot antenna can operate in either even or odd mode, the former is the desired mode

1051-8207/94$04.00 © 1994 IEEE

for obtaining a broadside radiation pattern [7]. The separation of the two slots should be properly selected to obtain an approximately symmetrical beam pattern. Our calculation with a narrow slot approximation indicates that the optimal spacing is around $0.4\lambda_0 \sim 0.5\lambda_0$ for the case of low permittivity ($\epsilon_r = 2.2$) dielectric substrate. The resultant twin-slot antenna has an even-mode resonant frequency slightly higher than that of one single slot. As an example, we show the design of a twin-slot antenna operating at a center frequency of 10 GHz on a 1.52-mm–thick substrate with $\epsilon_r = 2.2$. Assuming a slot width $w = 0.5$ mm and a slot spacing $s = 15$ mm $(0.5\lambda_0)$, we determine the required slot length for resonance to be $L = 11.8$ mm.

Meanwhile, an efficient performance of the antenna requires a proper feeding structure, which here employs microstrip lines on the back side of the slot antenna. One merit of this configuration is a good isolation between the incident radiation and the feeding circuits. The two slots are fed in parallel in order to guarantee an even-mode operation. The width of the feeding microstrip is $w_1 = 1.5$ mm, corresponding to a characteristic impedance of 100 $\Omega$. The strip width at the antenna input is $w_2 = 5.0$ mm to realize a standard 50 $\Omega$ characteristic impedance at 10 GHz. Coupling between the microstrip and the slot is achieved with microstrip open stubs, where a maximum coupling of the RF signal is expected if the stub is designed to be one quarter-wave long with the fringing effect included [8].

## III. Input Characteristics

The input characteristics of the twin-slot antenna is investigated by using the FD-TD algorithm, a versatile method capable of solving various electromagnetics problems from circuit discontinuities to radiation structures. Mur's absorbing boundary conditions (ABC's) [9] have been applied to convert the open structure into a block with finite size for computation. Typical CPU time on a Hitachi S3800 super computer is 20 minutes for a structure with $60 \times 200 \times 200$ meshes.

Fig. 2 shows the calculated results of the return loss at reference plane of the offset-fed slot antenna described in the previous section. It can be seen that the return loss reaches a minimum value of about $-30$ dB at 10.04 GHz when the offset position is $d = 4.5$ mm. A nearly perfect matching of input impedance is realized at this point. Sliding the feeding microstrip to either side will decrease the peak value of the return loss.

Based on the theoretical results, we fabricated a twin-slot antenna with the above-mentioned dimensions and optimal feeding offset. The return loss at the reference plane is measured on a HP8510B network analyzer following a TRL calibration. The results are plotted in Fig. 3. The measured resonant frequency is 9.84 GHz, about 2 % lower than that of theoretical analysis. This discrepancy is acceptable if one considers the uncertainty of the dielectric constant (±2%) and thickness (±3%) of the substrate. The measured peak value of the return loss is $-25.7$ dB, which is 4.5 dB lower than predicted. One possible reason for this is that the present FD-TD analysis has neglected the thickness and loss of the strip conductor. Reflection of radiation power from the experimental environment may also have caused a slight increase in the return loss.

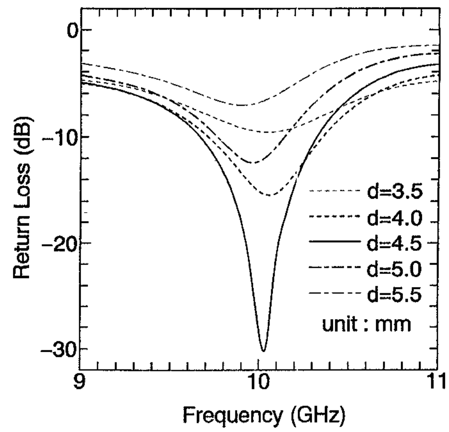


Fig. 2. Analytical results of the return loss at reference plane with different offset feeding positions.

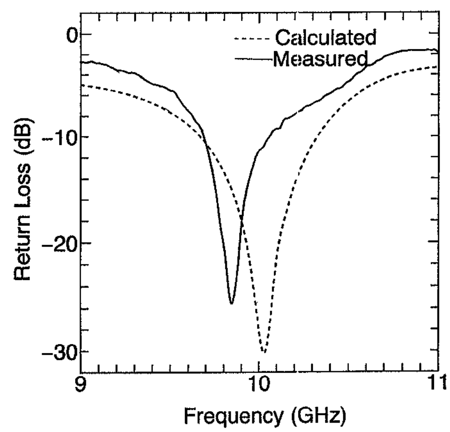


Fig. 3. Comparison of calculated and measured results of the return loss at reference plane for the fabricated twin-slot antenna.

## IV. Conclusion

An approach for optimal designing of twin-slot antennas suitable for far infrared and millimeter wave imaging arrays has been presented. By using the spectral domain method to obtain the antenna dimensions and the FD-TD algorithm to determine the offset feeding position, we are able to design an antenna element with a desirable beam pattern and nearly perfect impedance matching. Since the FD-TD method is a very powerful tool to analyze three dimensional structures, the present method can be readily extended to design antennas with hemispherical lenses or stratified structures. Furthermore, by updating the FD-TD algorithm, we can even analyze active and nonlinear regions included in the circuits [10], making possible a fully rigorous design of such quasi-optical systems.

## Acknowledgment

The authors would like to thank Mr. T. Adachi and Mr. H. Saito of Nissan Motor Co., Ltd. for their technical support.

## REFERENCES

[1] J. G. Heston, J. M. Lewis, S. M. Wentworth, and D. P. Neikirk, "Twin slot antenna structures integrated with microbolometer detectors for 94 GHz imaging," *Microwave and Optical Tech. Lett.*, vol. 4, pp. 15–19, Jan. 1991.

[2] J. Zmuidzinas and H. G. Leduc, "Quasi-optical slot antenna SIS mixers," *IEEE Trans. Microwave Theory Tech.*, vol. MMT-40, pp. 1797–1804, Sept. 1992.

[3] S. M. Wentworth, R. L. Rogers, J. G. Heston, D. P. Neitirk, and T. Itoh, "Millimeter wave twin slot antennas on layered substrates," *Int. J. Infrared Millimeter Waves*, vol. 11, no. 2, pp. 111–131, 1990.

[4] D. M. Pozar, "A reciprocity method of analysis for printed slot and slot-coupled microstrip antenna," *IEEE Trans. Antenn. Propagat.*, vol. AP-34, pp. 1439–1446, Dec. 1986.

[5] A. Axelrod, M. Kisliuk, and J. Maoz, "Broadband microstrip-fed slot radiators," *Microwave J.*, pp. 81–94, June 1989.

[6] S. Nam and T. Itoh, "Calculation of accurate complex resonant frequency of an open microstrip resonator using the spectral domain method," *J. Electromagnetic Waves and Appl.*, vol. 2, no. 7, pp. 635–651, 1988.

[7] T. H. Wang, T. Itoh, and H. Ling, "Spectral domain analysis of a coupled slot antennas," *IEEE Trans. Antenn. Propagat.*, vol. AP-36, pp. 1620–1624, Nov. 1988.

[8] K. C. Gupta, R. Garg, and I. J. Bahl, *Microstrip Lines and Slotlines*. Norwood, MA: Artech House, 1979.

[9] G. Mur, "Absorbing boundary conditions for the finite-difference approximation of the time-domain electromagnetic-field equations," *IEEE Trans. Electromagn. Compat.*, vol. EMC-23, pp. 377–382, Nov. 1981.

[10] B. Toland, J. Lin, B. Houshmand, and T. Itoh, "FDTD analysis of an active antenna," *IEEE Microwave and Guided Wave Lett.*, vol. 3, pp. 423–425, Nov. 1993.