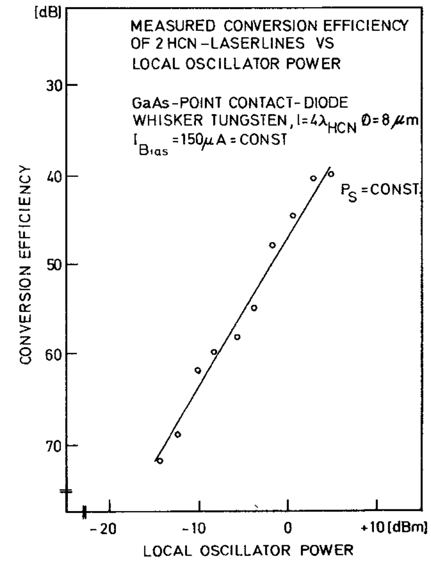

Fig. 4. Conversion efficiency versus LO power for a GaAs diode.

we are far away from the optimum driving point of our diode. It should be mentioned that with increasing frequency, the amount of LO power which is shunted by the barrier capacitance $C_j = 14 \times 10^{-15}$ F becomes more important. Fig. 4 shows a plot of the conversion efficiency versus LO power with constant signal power. It can be clearly seen that the LO power is not sufficient to drive the diode optimally. Hence the coupling efficiency has to be improved by a factor of 10, or the LO power has to be increased ten times.

To extend the heterodyning technique into the submillimeter region and to make it a successful tool for astronomical observations, certain improvements seem necessary. First, the coupling efficiency of submillimeter radiation to the mixer must be further improved. Secondly, more powerful LO generators must be developed. The second problem will likely be solved soon, since much progress had been achieved in the field of strong CO_2-pumped submillimeter lasers.

References

[1] W. Reinert, "Untersuchungen der Eigenschaften eines Heterodyne-Spectrometers für den Submm-bereich," Ph.D. dissertation, Univ. of Bonn, 1975; also *Space Sci. Rev.*, vol. 17, p. 703, 1975.

[2] H. C. Torrey and C. A. Whitmer, *Crystal Rectifiers* (M.I.T. Radiation Lab. Series), vol. 15. Lexington, MA: Boston Tech. Pub., 1964.

[3] C. M. Matarrese and K. M. Evenson, "Improved coupling to infrared whisker diodes by use of antenna theory," *Appl. Phys. Lett.*, vol. 17, p. 8, 1970.

[4] F. E. Terman, *Radio Engineers Handbook*. New York: McGraw-Hill, 1943.

[5] C. T. McCoy, "Present and future capabilities of microwave crystal receivers," *Proc. IRE*, vol. 46, pp. 61–66, 1958.

[6] R. V. Pound and E. Durand, *Microwave Mixers* (M.I.T. Radiation Lab. Series), vol. 16. Lexington, MA: Boston Tech. Pub., 1964.

Design of Printed Resonant Antennas for Monolithic-Diode Detectors

K. MIZUNO, SENIOR MEMBER, IEEE, Y. DAIKU, AND S. ONO, MEMBER, IEEE

***Abstract*—Model experiments at 10-GHz band have been performed to obtain optimum structures of printed resonant antennas for monolithic GaAs Schottky-diode detectors in the submillimeter-wave region. Design charts for antenna structures, which are also useful for a thin-film metal-to-metal diode structure on a dielectric substrate, are presented.**

I. Introduction

RECENTLY, Schottky-barrier diodes have received considerable attention as submillimeter detectors [1], [2], primarily because of their strong nonlinear behavior, fast response time, and mechanical stability. A thin metallic wire (cat whisker) is usually used to obtain the coupling of applied radiation field to the diode structure. It has been shown [3] that the whisker acts as a traveling-wave long-wire antenna. The whisker collects the radiation and applies it to the Schottky contact. The cutoff frequency of the Schottky diode is determined approximately by the contact diameter. The diameter below 1.5 μm is desirable for use in the submillimeter-wave range [4]. Reasonable submillimeter response, however, has been obtained [2] using a 2.5-μm Schottky diode with a high-gain long-wire antenna. In this configuration, the mechanical stability is good enough for laboratory use, but not sufficiently practicable for general use. Moreover, cryogenically cooling the diode to reduce the noise [5] is difficult with this configuration. In order to eliminate these undesirable factors, a planar-type configuration is employed here and the design of a printed resonant antenna on a dielectric substrate is described.

The schematic configuration of the detector is shown in Fig. 1. The directivity patterns of a half-wave dipole antenna printed on a substrate has the maximum in the

Manuscript received January 20, 1977.
K. Mizuno and S. Ono are with the Research Institute of Electrical Communication, Tohoku University, Sendai, 980 Japan.
Y. Daiku is with the Department of Electronic Engineering, Tohoku Institute of Technology, Sendai, 980 Japan.

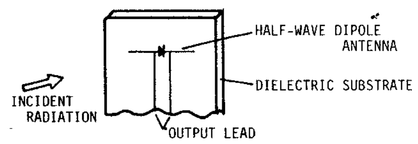

Fig. 1. Schematic configuration of the monolithic-diode detector.

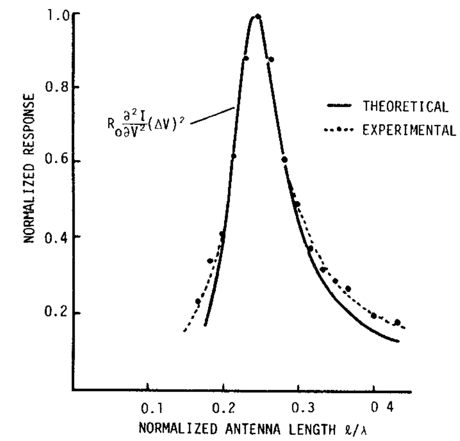

Fig. 2. Response of the detector as a function of the antenna length in the free space.

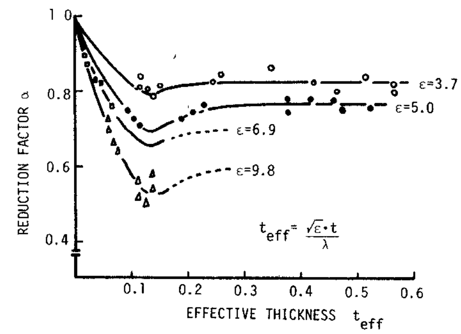

Fig. 3. Reduction factor of the antenna length as a function of the substrate thickness for several kinds of dielectric materials.

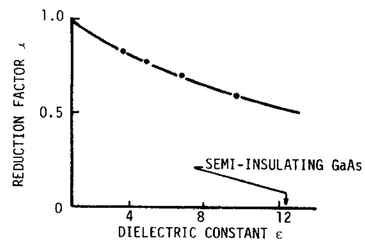

Fig. 4. Reduction factor of the antenna length versus dielectric constant of the substrate (for $t_{eff} > 0.2$).

direction perpendicular to the substrate surface, which would be favorable to beam-guide propagation systems of submillimeter waves. High-gain or two-dimensional information could be obtained with an arrangement of an array of antennas. For heterodyne mixing, two sets of antennas of different sizes on the substrate would be useful. A thin-film metal-to-metal diode detector with a similar structure has been studied [6] in the microwave, 300-μm, and 10-μm regions. However, so far the design of the antenna structure has not been given.

II. Design of the Antenna

A. Reduction Factor of the Antenna Length

The length of the resonant dipole antenna on a dielectric substrate should be determined according to the antenna loading and the substrate dielectric constant. In order to find the optimum antenna structure, we have performed model experiments at 10-GHz band. The results are expected to hold in the submillimeter-wave region by scaling down the dimensions.

As a preliminary process, we have determined the optimum antenna length in the free space for a known diode impedance. The diode used is a GaAs Schottky one, sealed in a ceramic sleeve 1.6 mm in diameter and 3.4 mm in length. Antenna wires 0.29 mm in diameter were soldered to the diode to form a dipole antenna of nearly half-wave in length. The diode impedance varies with the bias current. However, the optimum bias current is determined with no relation to the antenna impedance, because the response of the diode itself varies sensitively with the bias current. Fig. 2 shows the response of the detector as a function of the antenna length. The theoretical curve was calculated according to the impedance-matching condition between the diode and the antenna. The antenna impedance in the free space has been calculated and tabulated [7]. The change of antenna gain with the antenna length can be neglected in our experimental conditions. The experimental results are in good agreement with the theoretical ones. As the diode impedance is generally small, the maximum response is obtained usually for the resonant antenna of half-wave in length.

In order to design the optimum length of antennas on a dielectric substrate, we have introduced a reduction factor α of the antenna length as follows:

$$\alpha = \frac{\text{optimum length on a substrate}}{\text{optimum length in the free space}}.$$

A series of experiments have been performed to obtain the optimum length of the antenna for various dielectric materials. The results were compared with the optimum length in the free space to obtain the reduction factors.

Fig. 3 shows the experimentally obtained reduction factors as functions of an effective thickness t_{eff} of the substrate for various dielectric materials. The effective thickness is given as $t_{eff} = \sqrt{\varepsilon} \cdot t/\lambda$, where ε is the dielectric constant, t the real thickness of the substrate, and λ the free-space wavelength. For the effective thickness larger than 0.2, the reduction factor becomes constant with the thickness, and is determined approximately only by the dielectric constant, as shown in Fig. 4.

B. Polar Diagram

Fig. 5 shows a typical example of polar diagrams of the dipole antenna on a substrate. In the H-plane diagram, the effects by the dielectric substrate have been shown. When we printed a metal plate on the back of the substrate of a

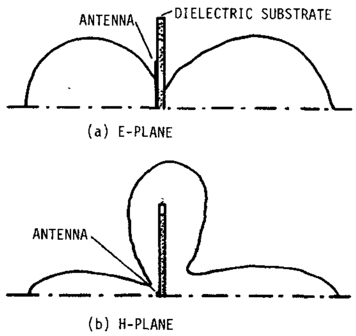

Fig. 5. Polar diagrams of a half-wave dipole antenna on a substrate.

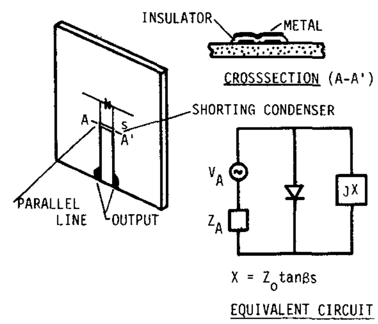

Fig. 6. Parallel-line output lead with an RF-shorting condensor and the equivalent circuit.

quarter of the operating wavelength in thickness, improvements in the gain and the directivity were observed.

C. Parallel-Line Lead

As shown in Fig. 6, a parallel line has been used as the output lead and the dc bias supply. The equivalent circuit of this configuration is also shown in Fig. 6, where Z_A is the antenna impedance, V_A the voltage induced in the antenna by the incident radiation, Z_0 the characteristic impedance, and β the propagation constant of the parallel line. Using this equivalent circuit, we can determine the optimum structure of the parallel line by the impedance-matching condition. Laplace's equation for the parallel line configuration has been solved by using the finite-difference method. Fig. 7 shows the calculated capacitance C per unit length of parallel lines. The phase-velocity v_p and the characteristic impedance Z is given by

$$v_p = v_{p0} \sqrt{\frac{C}{C_0}}$$

$$Z = \frac{1}{C \cdot v_p}$$

where v_{p0} and C_0 are the phase velocity and the capacitance for the parallel line in the free space, respectively.

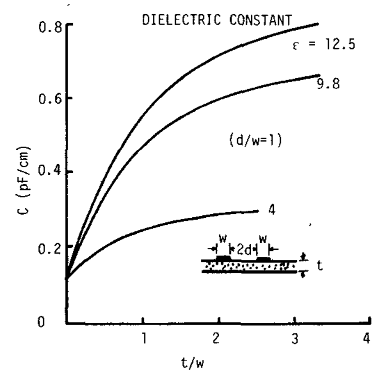

Fig. 7. Calculated capacitance of the parallel lines on dielectric substrates.

III. Conclusion

The optimum structure of a resonant dipole antenna on a dielectric substrate can be designed by the data previously given. At first, we determine a free-space antenna structure which is impedance matched to the given diode. Next, we can obtain the optimum structure of the antenna on the dielectric substrate by means of the reduction factor given in Fig. 4. The parallel-line output lead can be designed by using the equivalent circuit shown in Fig. 6 and the data given in Fig. 7.

Through combining the antenna structure described here with a planar Schottky diode, planar-type detectors for submillimeter waves can now be constructed.

Acknowledgment

The authors wish to thank the staff members of the Semiconductor Device Section, Musashino Electrical Communication Laboratory, NTT, for supplying the Schottky diodes used in the experiments.

References

[1] H. R. Fetterman *et al.*, "Submillimeter heterodyne detection and harmonic mixing using Schottky diodes," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 1013–1015, Dec. 1974.
[2] K. Mizuno, R. Kuwahara, and S. Ono, "Submillimeter detection using a Schottky diode with a long-wire antenna," *Appl. Phys. Lett.*, vol. 26, pp. 605–607, June 1975.
[3] L. M. Matarrese and K. M. Evenson, *Appl. Phys. Lett.*, vol. 17, pp. 8–10, July 1970.
[4] B. F. J. Zuidberg and A. Dymanus, "High-order submillimeter mixing in point-contact and Schottky diodes," *Appl. Phys. Lett.*, vol. 29, pp. 643–645, Nov. 1976.
[5] S. Weinreb and A. Kerr, "Cryogenic cooling of mixers for millimeter and centimeter wavelengths," *IEEE J. Solid-State Circuits*, vol. SC-8, pp. 58–63, Feb. 1973.
[6] J. G. Small *et al.*, "AC electron tunneling at infrared frequencies: Thin-film M-O-M diode structure with broad-band characteristics," *Appl. Phys. Lett.*, vol. 24, pp. 275–279, Mar. 1974.
[7] R. W. P. King, *The Theory of Linear Antennas.* Cambridge: Harvard Univ. Press, 1956, ch. 2.