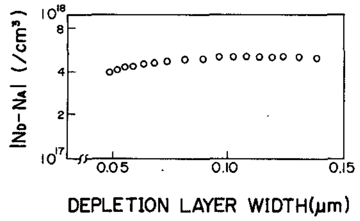

Fig. 1. Carrier density profile of the wafer.

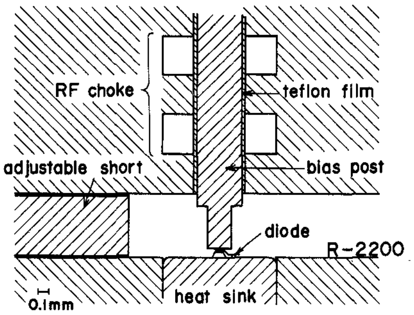

Fig. 2. Waveguide circuit with a tuning cap structure for 200-GHz-band operation.

breakdown voltage and depletion layer width at breakdown are 7.4 V and 0.14 μm, respectively. After annealing, the wafer was thinned to several microns, metallized by evaporating Ti–Au, separated into individual pellets by an air-brasive method, and bonded on a heat sink with a quartz stud. DC series resistance was 0.27 Ω for a diode of 23-μm diameter.

Oscillation Characteristics

Microwave measurements were made in the full-height waveguide (R-2200; 1.092 × 0.546 mm^2) with a tuning cap cavity shown in Fig. 2. Diode tuning was done by selecting the proper bias post and sliding the adjustable short. Sensibility of the power meter has been calibrated against a dry calorimeter. The oscillation frequency was measured by a two-dip-type frequency meter and by detecting a standing wave using a point contact diode mount with a movable short. High-pass filters were used to check the frequency measurements. Input–output characteristics for best performance are given in Fig. 3. CW output power of 50-mW at 202 GHz and 44 mW at 214 GHz were obtained, with conversion efficiencies of 1.3 and 1.2 percent, respectively. At 50-mW output power, the dc bias voltage and current were 9.2 V and 410 mA, respectively. When a high-pass filter with 230-GHz cutoff was inserted at the output port of the IMPATT diode mount, an oscillation in the 300-GHz band was observed. CW output power of 1.2 mW at 301 GHz was obtained for a diode with a diameter of 18 μm. When the high-pass filter was removed leaving the same tuning condition, a $\frac{1}{3}$ frequency of the 300-GHz band was observed. These facts imply that an oscillation of the fundamental frequency in the 100-GHz band would be excited. But the frequency is below the cutoff frequency of R-2200 waveguide used here.

In summary, Si IMPATT diodes have operated in the 200-GHz band with CW output powers as high as 50 mW. CW operation with practical power can be expected over a 300-GHz band.

Acknowledgment

The authors wish to thank M. Ino for useful discussions, H. Yamazaki for ion implantation of phosphorus, T. Makimura for diode assembly, and Y. Sato and K. Suzuki for encouragement.

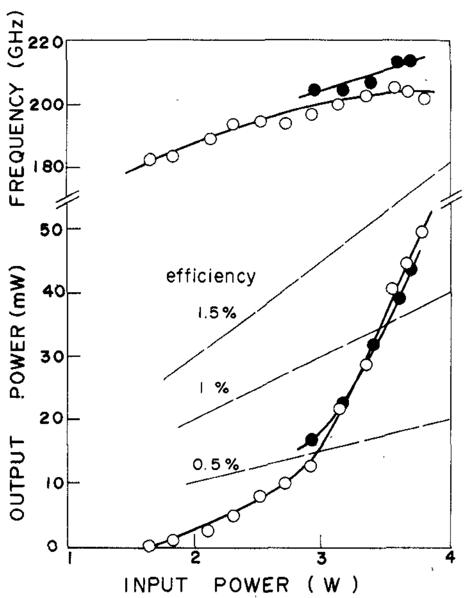

Fig. 3. 200-GHz-band output power and frequency versus input power for diode with a diameter of 23 μm and series resistance of 0.27 Ω. Open circles and solid circles represent the characteristics with two different caps.

References

[1] T. Ishibashi, T. Makimura, and K. Suzuki, "Si SDR IMPATT diodes for 150 GHz operation," Paper Tech. Group on Elec. Device, IECE, Jap., ED74-33, August 1974.

[2] D. H. Lee and R. S. Ying, "Ion-implanted complementary IMPATT diodes for *D*-band," *Proc. IEEE*, vol. 62, no. 9, pp. 1295–1296, Sept. 1974.

[3] M. Ino, T. Makimura, and H. Yamazaki, "High efficiency 80 GHz and 150 GHz band Si DDR IMPATT diodes," *Trans. IECE Japan*, vol. 58-C, no. 11, pp. 689–690, Nov. 1975.

[4] W. N. Grant, "Electron and hole ionization rates in epitaxial silicon at high electric field," *Solid State Elec.*, vol. 16, pp. 1189–1203, 1973.

[5] J. W. Gewartowski, "The effect of series resistance on avalanche diode (IMPATT) oscillator efficiency," *Proc. IEEE*, vol. 56, no. 6, pp. 1139–1140, June 1968.

A 230-GHz Radiometer System Employing a Second-Harmonic Mixer

PAUL F. GOLDSMITH AND RICHARD L. PLAMBECK

Abstract—**A radiometer system for use in the $\lambda \sim 1.3$ mm ($\nu \sim 230$ GHz) region has been constructed and used for radio astronomical observations. A second-harmonic mixer employing a single Schottky diode downconverts the incident power to an IF frequency of ~1400 MHz. The measured double-sideband system noise temperature is 6000 K (noise figure = 13 dB) and the double-sideband mixer conversion loss is calculated to be 10 dB. The mixer is tunable over a range of at least 15 GHz.**

Introduction

The development of microwave receivers for wavelengths shorter than 2 mm has been hampered by the lack of local oscillators to pump frequency downconverters. One approach to this problem has been to produce a local oscillator (LO) signal by multiplication of existing lower frequency sources. It has been

Manuscript received February 23, 1976; revised May 10, 1976. This work was supported in part by the National Aeronautics and Space Administration under Grant NGL 05-003-272, in part by the Office of Naval Research under Contract N00014-69-A-0200-1003, and in part by the National Science Foundation under Grants GP30424X and GP38585.

P. F. Goldsmith is with the Crawford Hill Laboratory, Bell Laboratories, Holmdel, NJ 07733.

R. L. Plambeck is with the Department of Physics, University of California, Berkeley, CA 94720.

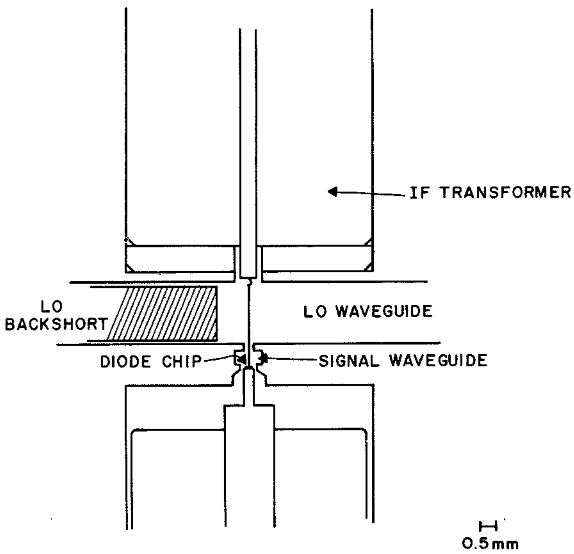

Fig. 1. A cutaway drawing of the harmonic mixer. The chip of gallium arsenide with the Schottky diodes on it (drawn in heavy black) is mounted on the end of a differential screw, shown in the lower portion of the figure. The diode chip is located in the lower wall of the signal waveguide (which runs perpendicular to the plane of the paper). The whisker contacting one of the diodes runs up through the signal waveguide, through the LO waveguide (lying in the plane of the paper), and is held by the center conductor of the IF transformer. The latter is designed to match a 200-Ω impedance to the 50-Ω input impedance of the IF amplifier. The IF transformer center frequency is 1400 MHz.

found, however, that at short millimeter wavelengths the low efficiency of the multiplication process, together with the limited output of the fundamental oscillator, limits the LO power available to less than that required for the optimum operation of the mixer [1], [2]. We have chosen to use the nonlinearity inherent in the Schottky diode to make a harmonic mixer in which the modulated component of the diode conductance at twice the LO frequency downconverts power (in the two sidebands at frequencies $\omega = 2\omega_{LO} \pm \omega_{IF}$) to the IF frequency ω_{IF}. This technique has been previously employed [3], [4] to make receiver systems for the $\lambda \sim$ 1-mm range, but reported system noise temperatures have been in excess of 100 000 K.

Harmonic Mixer Construction

The nature of a second-harmonic mixer requires the coupling of RF frequencies differing by a factor of 2 into the diode. The configuration adopted here is the crossed waveguide mount, shown in cross section in Fig. 1. The local oscillator wave propagates in the large waveguide (RG 138/U) in the plane of the paper, while the signal propagates in the small waveguide (RG 139/U) perpendicular to the plane of the paper; each waveguide is fitted with an adjustable backshort. Frequencies capable of being downconverted by fundamental mixing are below cutoff in the signal waveguide. Through holes located on the axis of each waveguide, a 1-mil (.001″) phosphor bronze whisker runs from the IF port on the top of the mixer to the diode on the bottom. The end of the whisker is pointed and contacts one of the matrices of the Schottky barrier diodes located on the top of the post in the lower wall of the small waveguide. The post is attached to the end of a differential screw which is advanced to bring the diode into contact with the whisker.

Mixer Diodes

The diodes used in this work are gallium arsenide Schottky barrier diodes. The reverse saturation current i_0 and the ideality factor η, defined by the relation

$$i(v) = i_0 \left[\exp\left(\frac{ev}{\eta kT}\right) - 1\right] \tag{1}$$

are 1.3×10^{-14} A and 1.2, respectively. The series resistance is 8 Ω and the zero bias barrier capacitance is 20 fF (1 fF = 10^{-15} F).

Receiver System

The harmonic mixer is incorporated into the spectral line receiver system shown in Fig. 2. The local oscillator is a 108–116-GHz klystron; the mixer itself should be usable with klystrons in the range of 95–150 GHz (signal frequencies of 190–300 GHz). The local oscillator frequency is controlled by phase locking the klystron to a harmonic of a stabilized 2–4 GHz oscillator. The IF parametric amplifier is a micromega unit with a bandwidth of 90 MHz; the IF system noise temperature is 75 K. After amplification at the first IF frequency of ~1400 MHz, the signal is further downconverted to 150 MHz, amplified, and sent to a set of narrow-band (0.25-MHz or 1.2-MHz-bandwidth) detectors for spectroscopic studies.

The large attenuation of the signal waveguide necessitates placing the feedhorn as close as possible to the mixer diode, thus precluding the use of waveguide devices for calibrating the radiometer. A quasi-optical calibration system with a rotating chopper wheel, whose blades are covered with Eccosorb AN-72 absorber (manufactured by Emerson and Cuming, Canton, MA), and a cold load is used. The cold load is a sheet of Eccosorb material immersed in liquid nitrogen. A 5-mm thickness of this material was measured to have a power transmission of less than 5 percent and a specular reflection of less than 10 percent. We assume, therefore, that these loads radiate as blackbodies.

In the course of calibrating the radiometer system, the relative gain of the two mixer sidebands was measured. This was accomplished with a tunable calibrated narrow-band signal made by placing a Fabry–Perot interferometer in front of the cold load. The mirrors of the interferometer were free-standing two-dimensional wire grids, as discussed by Ulrich *et al.* [5]. The relative gain was found to be sensitively dependent only upon the position of the backshort in the signal waveguide. Tuning the mixer for a minimum noise temperature always resulted in the sensitivities in the two sidebands being equal to within 35 percent.

Diode Noise

The effective temperature of the mixer at the IF frequency is defined by

$$T_E = \frac{P_N}{k\Delta\nu} \tag{2}$$

where P_N is the noise power delivered to the IF amplifier and $\Delta\nu$ is the bandwidth. For the dc bias alone, which is required for the lowest system noise temperature, T_E = 250 K. The diode noise is significantly increased by the application of local oscillator power. One source of this excess noise is the noise from the klystron itself. To reduce the level of klystron noise reaching the diode, a tunable TE_{011}-mode transmission filter with a loaded Q of approximately 1500 is installed in the LO waveguide near the mixer. With the filter in place, and the dc bias and LO power optimized for the lowest system noise temperature, we obtained T_E = 450 K.

Mixer Performance

Considering the receiver system as a cascade of lossy elements, we can write [7] that the system noise temperature T_N is given by

$$T_N = T_{AMB}(L_{INPUT} - 1) + T_E(L_M - 1)L_{INPUT} + T_{IF}L_{INPUT}L_M \tag{3}$$

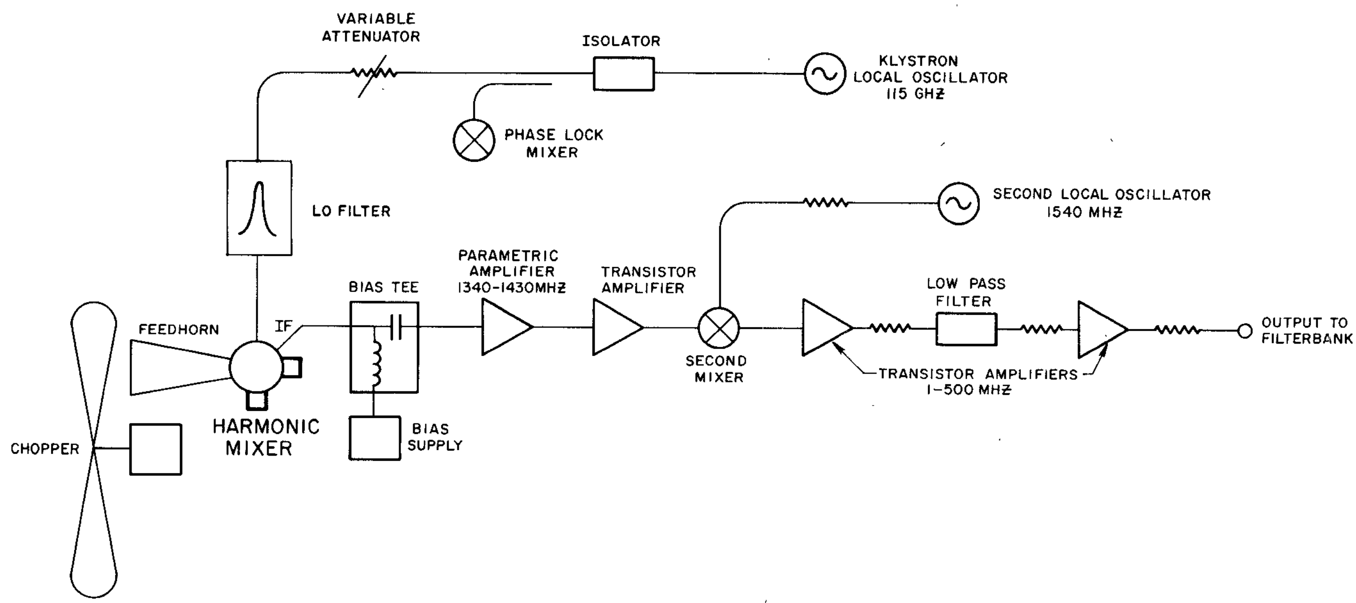

Fig. 2. Block diagram of a 230-GHz radiometer system.

where

T_{AMB}	ambient temperature of mixer = 294 K;
L_{INPUT}	loss of input waveguide (power input/power reaching mixer);
T_E	effective temperature of diode;
L_M	double-sideband conversion (RF to IF power) loss of the mixer;
T_{IF}	IF system temperature = 75 K.

The loss in the input waveguide L_{INPUT} is estimated to be 1.2 (0.8 dB). This waveguide includes the feedhorn, about 1 cm of standard waveguide, and a flange. We have measured a loss of 2.6 dB for a 2-cm section of RG 139/U waveguide and one flange; this number undoubtedly varies considerably from one specimen of this waveguide to another.

The measured system noise temperature is 6000 K. From (3) we calculate that the mixer conversion loss is 10.3 (10.1 dB).

Conclusion

The double-sideband system noise temperature of 6000 K reported here represents a considerable advance over previous systems at this frequency employing harmonic mixers [3], [4] and is comparable to the performance of a system utilizing a fundamental mixer [1], [2]. The improved mixer performance is primarily a result of the low values of the diode parasitics. The results reported in this paper support the theoretical conclusion of Meredith and Warner [6] that the frequency conversion efficiency of a second-harmonic mixer is not greatly inferior to that of a fundamental mixer.

Acknowledgment

The authors would like to thank M. V. Schneider and G. T. Wrixon for supplying the diodes used in this work and for helpful discussions about microwave mixers.

References

[1] M. V. Schneider and G. T. Wrixon, "Development and testing of a receiver at 230 GHz," in *1974 IEEE Int. Microwave Symp., Digest of Technical Papers*, pp. 120–122, June 1974.
[2] G. T. Wrixon, "Low-noise diodes and mixers for the 1–2-mm wavelength region," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 1159–1165, Dec. 1974.
[3] M. Cohn, F. L. Wentworth, and J. L. Wiltse, "High sensitivity 100- to 300-Gc radiometers," *Proc. IEEE*, vol. 51, pp. 1227–1232, Sept. 1963.
[4] W. A. Johnson, T. T. Mori, and F. I. Shimabukuro, "Design, development, and initial measurements of a 1.4-mm radiometric system," *IEEE Trans. Antennas Propagat.*, vol. AP-18, pp. 512–514, July 1970.
[5] R. Ulrich, K. F. Renk, and L. Genzel, "Tunable submillimeter interferometers of the Fabry–Perot type," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-11, pp. 363–371, Sept. 1963.
[6] R. Meredith and F. L. Warner, "Superheterodyne radiometers for use at 70 Gc and 140 Gc," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-11, pp. 397–411, Sept. 1963.
[7] W. W. Mumford and E. H. Scheibe, *Noise Performance Factors in Communication Systems*. Dedham: Horizon House-Microwave, 1968.

High-Efficiency Frequency Multiplication with GaAs Avalanche Diodes

B. M. KRAMER, MEMBER, IEEE,
A. C. DERYCKE, A. FARRAYRE, AND C. F. MASSE

Abstract—**GaAs avalanche diodes for frequency multiplication at millimeter wavelengths have been investigated. The GaAs diode design is described and compared with that of Si diodes. Experimental results obtained in the optimum circuit are presented. Frequency multiplication from 4 to 32 GHz with 6-dB conversion loss (400 to 100 mW) and 1.5-W dc bias power was achieved. A temperature dependence of the output power was measured to be less than 1 dB over the −40 to +60°C range.**

Introduction

Frequency multiplication using an avalanche diode enables millimeter-wave generation from a lower frequency signal, using a circuit similar to that of a varactor multiplier but with better overall performances principally in high-order multiplication (typically by a factor of 10). This device, first proposed in 1969 [1], uses a particular type of avalanche diode. After having extensively studied Si devices [2], [4] and having obtained very promising results, it became theoretically apparent that GaAs may have certain advantages. Thus we decided to study the possibilities of GaAs devices in the same area. With Si diodes the following performance was obtained at 35 GHz: 640-mW output power and 7-dB conversion loss with a multiplication factor of 10. It was also pointed out that frequency multiplication could have a

Manuscript received February 3, 1976; revised May 18, 1976.
B. M. Kramer, A. Farrayre, and C. F. Masse are with the Laboratory of Electronics and Applied Physics, 94450 Limeil-Brévannes, France.
A. C. Derycke is with the High Frequency and Semiconductor Center, University of Science and Technology, Lille, 59650 Villeneuve D'Ascq, France.