# Millimeter-Wave, Shot-Noise Limited, Fixed-Tuned Mixer

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*Abstract* —In a companion paper [1], two computer-controlled measurement systems for testing millimeter-wave Schottky-barrier diode mixers between 90 and 350 GHz have been presented. In this paper, a typical application of the measurement system to the testing and evaluation of a practical *W*-band, cryogenic, fixed-tuned Schottky diode mixer is used to demonstrate the performance of the instruments. The mixer is shown to have a single-sideband noise temperature of less than 140 K between 98 and 118 GHz and, at 110 GHz, achieves shot-noise limited performance, with a SSB noise temperature of only 81 K and corresponding conversion loss of 5.7 dB.

## I. Introduction

In a companion paper [1], a theoretical background to mixer measurements is presented and the design criteria and description of both the hardware and software of two computerized measurement systems are given. The instruments allow testing of millimeter-wave Schottky-barrier diode mixers in the frequency range from 90 to 350 GHz.

The computer-controlled instruments have provided a more accurate, reliable, versatile, and efficient means of mixer testing and evaluation than previously available and have been an essential and invaluable asset in development of millimeter-wave Schottky diode mixers, e.g., [2]–[4]. In this paper, a *W*-band, fixed-tuned, cryogenic, Schottky diode mixer is reported. Computer printouts that resulted from testing of the mixer are used in Section III to demonstrate the performance of the measurement system and to show the variety of data that can be obtained describing mixer performance. The ultra-low-noise performance of the mixer is discussed and compared to a shot-noise limit in Section IV of the paper.

## II. Mixer Development

The mixer, shown in Figs. 1 and 2, is a single-ended, fundamental frequency mount developed from an earlier design [4], [5]. That design featured a fixed tuning of the mixer which allowed the reduction of mixer conversion losses by lowering the ohmic losses and eliminating the reflection coefficient frequency dependence associated with the typical adjustable backshort structures.

The feed horn and waveguide structures of the mixer mount were all electroformed in copper on disposable aluminum mandrels. The feed horn incorporated in the mixer (see Fig. 1) is a corrugated scalar feed which provides the -11-dB, far-field *E*- and *H*-plane beam widths of the horn of 30° at 115 GHz. The mixer mount (Fig. 2) comprises a whisker-contacted, Schottky-barrier diode mounted in reduced-height waveguide. A five-section impedance transformer couples power from the full-height WR-8 input waveguide to the reduced-height waveguide. The reduction in waveguide height to 1/4 of the standard value in the vicinity of the diode lowers the impedance of the waveguide, thus making it easier to match the diode to its RF embedding network over a broad bandwidth. The IF output impedance is also reduced as a consequence of the lower RF impedance [6], making broader bandwidth IF matching feasible.

The Schottky-barrier diode, fabricated by R. Mattauch at the University of Virginia (designated type 2P9-300) is soldered to a microstrip RF choke which is epoxied in a channel in the diode block. The dimensions of the channel and the lengths of the choke sections were chosen to ensure that the choke presents a short circuit to the diode at 120 GHz, while appearing as a small capacitive reactance between 80–120 GHz and presenting a reactive termination to the device at higher frequencies (up to at least the third harmonic of the local oscillator), as is required for optimum mixer performance [7].

The mixer was optimized for low-noise, fixed-tuned operation in the frequency range from 98 to 118 GHz with a lowest possible noise temperature at 110 GHz. In order to obtain the desired performance of the mixer, the diode was contacted with a 330-$\mu$m-long whisker bent so that the end of the pin sat flush with the guide wall after contacting the diode. The fixed backshort was set 1.27 mm from the diode plane and was implemented with the aid of a section of short-circuited waveguide electroformed into a backing plate.

The mixer IF output is connected to an integral IF impedance matching transformer [5], bias tee, and dc block (see Fig. 1), which results in an IF output VSWR of less than 1.2:1 between 1.2 and 1.8 GHz when the mixer is operated at optimum LO and dc bias levels.

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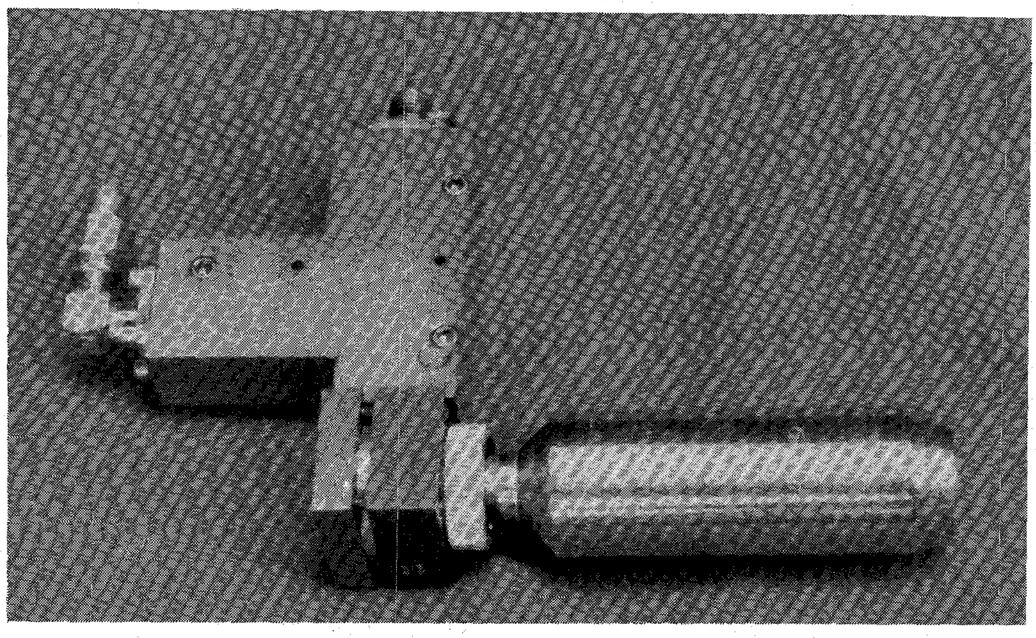

Fig. 1. A photograph of the mixer.

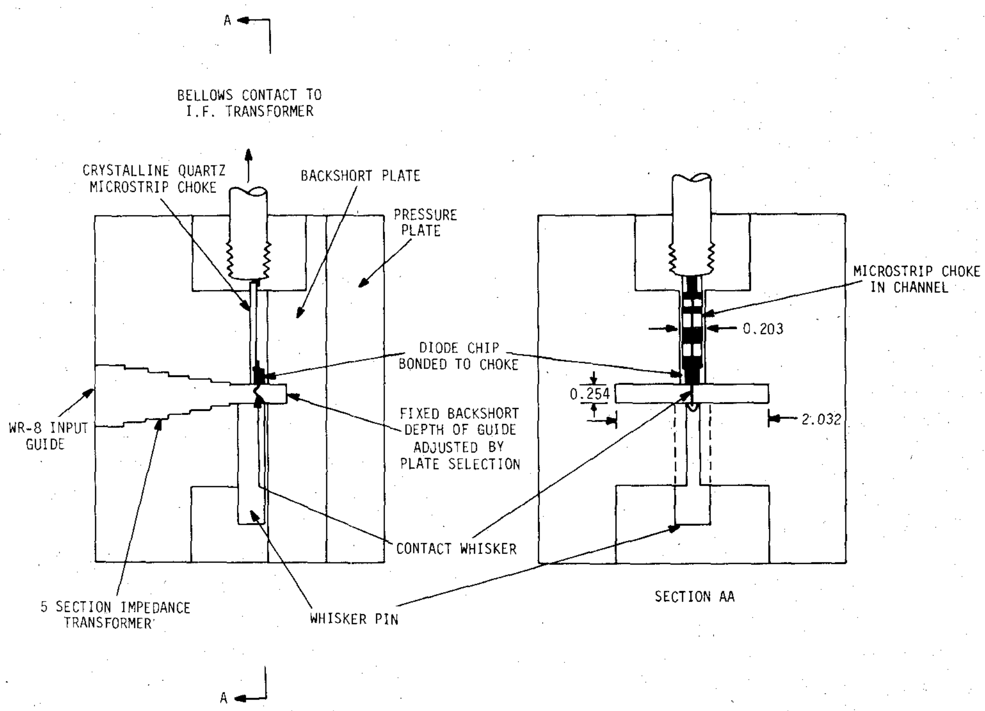


Fig. 2. A schematic diagram (not to scale) showing the details of the mixer design.

## III. Testing of the Mixer

The mixer was thoroughly tested using the computer-controlled measurement system reported in the companion paper [1]. The instrument employs a desktop computer not only for processing data but also for controlling the operation of the test apparatus, which enables one to carry out a much more extensive set of mixer performance tests, as well as to obtain data that could not be measured without the aid of high-speed real-time system control and data processing.

User-oriented "friendly" interactive software makes it very easy to use the system. The computer instructs the user of the system, checks for possible mistakes, and helps in presetting a test program. The computer supervises the calibration of the measurement system and stores the

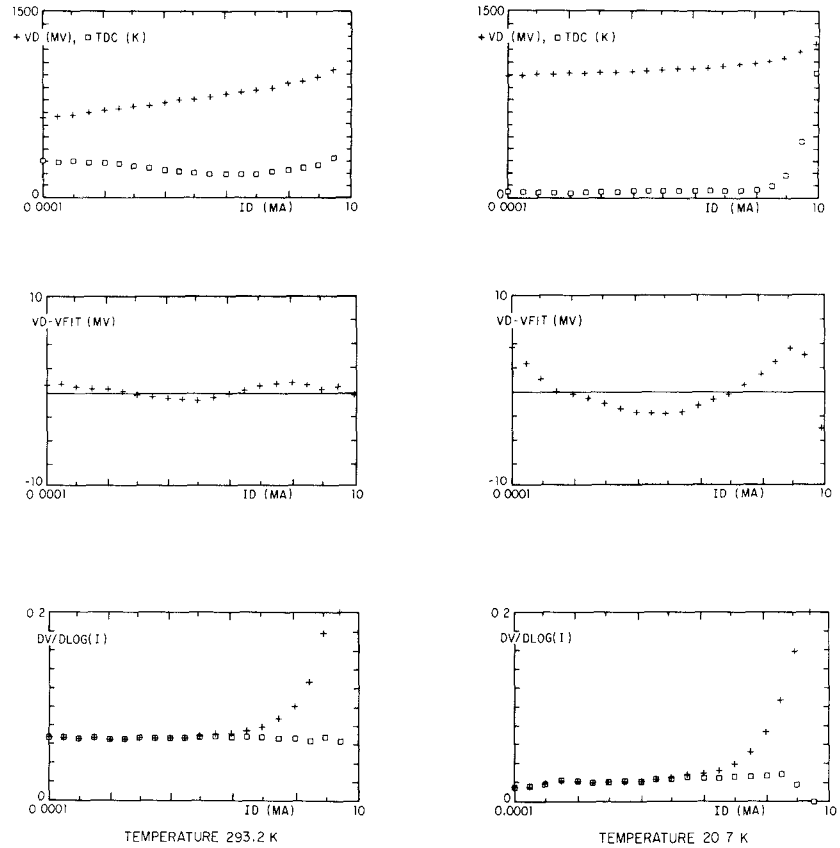


Fig. 3. Plots produced during cooling of the mixer. Only measurements at the first (room) temperature and the last (20.7 K) temperature are presented. Diode voltage $V_D$ and equivalent IF noise temperature $T_{dc}$ are measured and plotted versus dc bias current $I_D$. The computer fits measured $V_D$ to an exponential diode model response and plots residuals of the fit, $V_D - V_{FIT}$. It also computes and plots derivatives $dV_D(I_D)/d\log(I_D)$ and $d[V_D(I_D)-I_DR_S]/d\log(I_D)$. The latter is independent of $\log(I_D)$ for an ideal exponential diode.

calibration data. When the calibration is completed, the computer controls measurements according to the preset test program, collects data, and performs in real-time all calculations applying necessary corrections. It also displays and plots parameters of a mixer under test and, if desired, prints out plots and measured quantities.

### *A. Measurements During Cooling of the Mixer*

The measurements were made at room temperature and then at 20-K temperature intervals down to the lowest temperature of 20.7 K. The IF frequency was 1.45 GHz with 60-MHz measurement bandwidth.

At each temperature, the $I-V$ characteristic of the mixer diode and the equivalent IF noise temperature with dc bias only $T_{dc}$ were measured and the results of the measurements and real-time calculations were plotted versus bias current. When the measurements at a given temperature were completed, the computer fitted the data to a model response of an ideal exponential diode with a series resistor [6], [7] (i.e., $V_D = V_j + I_DR_s = V_j + R_sI_{sat}[\exp(qV_j/\eta kT)-1]$) using the least-squares method. It also computed residuals of the fit and derivatives $dV_D(I_D)/d\log(I_D)$ and $dV_j(I_D)/d\log(I_D)$.

The data was stored on the disk for further processing at a later time to produce plots of the measured diode parameters at specified temperatures or as a function of temperature.

The plots in Fig. 3 were produced during cooling of the mixer to illustrate operation of the measurement system. Plots presented in Fig. 4 are the result of processing data collected during cooldown and reflect the changes in diode properties upon cooling. At room temperature, the Schottky-barrier diode was characterized by a zero-bias capacitance $C_{j0} = 8.0$ fF, a series resistance $R_s = 11.7\ \Omega$, a saturation current $I_{sat} = 1.8\times10^{-17}$ A, $\Delta V = V_D(100\ \mu A) - V_D(10\ \mu A) = 67.6$ mV, and an ideality factor $\eta = 1.14$ ($V_0 = \eta kT/q = 28.7$ mV). The equivalent IF noise temperature $T_{dc}$ was 227 K and 200 K at dc bias currents of 10 $\mu$A and 300 $\mu$A, respectively. The measured $I-V$ characteristic fitted the expontial diode model very well (diode voltage within $\pm 1$ mV to the model). When the diode was cooled to 20.7 K, its series resistance rose by 3 $\Omega$ ($R_s = 14.7\ \Omega$), while

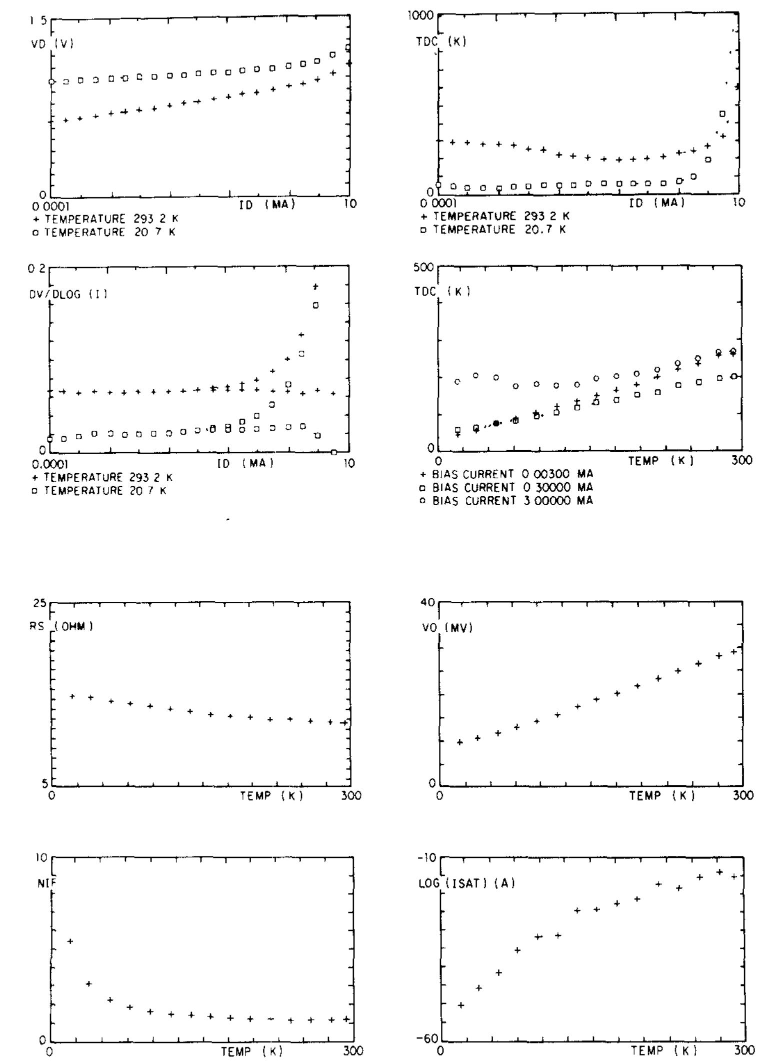


Fig. 4. Plots resulting from processing data collected during cooldown. Diode $I-V$ characteristics and $T_{dc}$ noise temperatures are compared at two temperatures. Measured $T_{dc}$ is also plotted versus temperature for three bias currents. Diode series resistance $R_s$, ideality factor $\eta$(NIF), $V_0 = \eta kT/q$, and saturation current $I_{sat}$ are plotted versus temperature.

the saturation current dropped to $1.9 \times 10^{-52}$ A. The ideality factor increased to 5.34 ($V_0 = 9.5$ mV), and $\Delta V$ was 24.1 mV. The exponential diode model did not describe the diode as well as at room temperature (up to 5 mV difference in diode voltage). The most significant effect observed in the diode upon cooling was the decrease of the equivalent IF noise temperature. $T_{dc}$ was reduced approximately by a factor of 4, being 50 K and 57 K at bias currents of 10 $\mu$A and 300 $\mu$A, respectively.

### *B. Measurements at Constant Temperature*

The measurement systems reported in [1] allow testing of a mixer at a constant temperature both without and with the LO signal applied. However, for clarity of the paper, only tests performed on the pumped mixer are presented here.

The RF performance of the mixer was measured at a temperature of 24 K for LO frequency varied from 96 to 120 GHz. All single-sideband (SSB) values quoted assume equal sideband losses and are based on double-sideband measurements. The sideband losses for the mixer reported here have been measured and found to be equal to within five percent. The accuracy of the reported results is estimated to be $\pm 3$ K and $\pm 0.1$ dB in the SSB mixer noise temperature and conversion loss, respectively.

The tuning of the mixer, once optimized, was fixed and only the quasi-optical diplexer was adjusted at each LO frequency using the mixer noise monitoring system implemented in the IF radiometer.

The mixer diode bias was kept constant at 0.94 V at each measurement frequency and the LO level was adjusted to result in a 0.36 mA dc component of the diode current. Using the radiometer monitoring system, these operating conditions were found to result in the lowest mixer noise temperature. This is confirmed in Fig. 5 in which the single-sideband mixer noise temperature and conversion

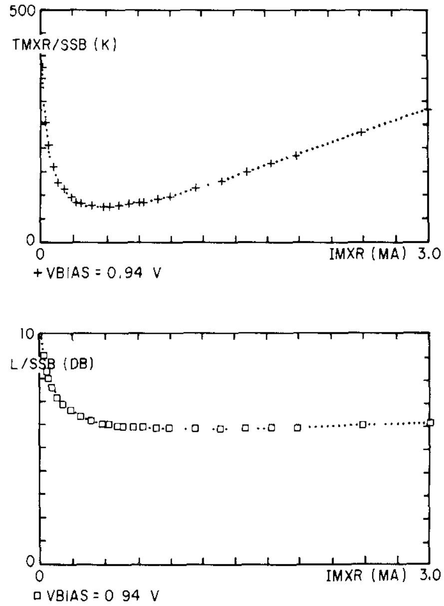


Fig. 5. Single-sideband mixer noise temperature $T_{MXR}$ and corresponding single-sideband conversion loss $L$ of the mixer as a function of LO level. The LO level is represented by the dc component $I_{MXR}$ of the diode current resulting from the applied LO signal. (Temp. = 24 K, $f_{LO}$ = 110 GHz, IF = 1.45 GHz, $\Delta f_{IF}$ = 60 MHz, equal sideband losses).

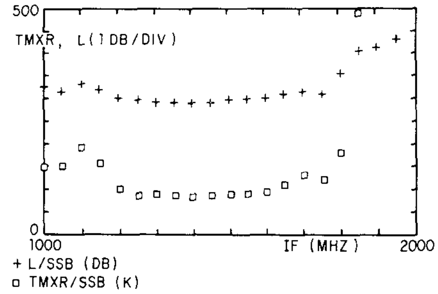


Fig. 6. Single-sideband mixer noise temperature $T_{MXR}$ and corresponding single-sideband conversion loss $L$ of the mixer versus IF frequency. (Temp. = 24 K, $f_{LO}$ = 110 GHz, $\Delta f_{IF}$ = 60 MHz. $V_D$ = 0.94 V, $I_{MXR}$ = 0.36 mA, equal sideband losses).

loss are plotted versus dc component of the diode current. The measurements were made at a temperature of 24 K, and LO frequency of 110 GHz, and IF = 1.45 GHz with a 60-MHz measurement bandwidth. The minimum SSB mixer noise temperature of 81 K was obtained at a LO level (dc diode current of 0.36 mA) lower than that ($I_{MXR}$ = 1.2 mA) required for minimum conversion loss. The sharp minimum measured for the cryogenic mixer is much more distinct than the flat minimums in both mixer noise temperature and conversion loss usually observed for room-temperature mixers at approximately the same LO levels. Thus, more care is needed in optimizing the operating conditions of cryogenic mixers than for room-temperature mixers.

At each LO frequency, mixer noise temperature and conversion loss were measured as a function of IF frequency. The measurements were made at a temperature of 24 K and the IF measurement bandwidth was 60 MHz in all measurements.

The computer printout resulting from measurements at 110 GHz is shown in Fig. 6. The SSB mixer noise temperature reaches 81 K with the corresponding conversion loss of 5.7 dB at an IF frequency of 1.45 GHz. The bandwidth over which the mixer noise temperature varies by less than 20 percent is at least 400 MHz. The IF response at other LO frequencies within the operating range is similarly broad.

TABLE I
RF PERFORMANCE OF THE FIXED-TUNED MIXER.

| $F_{LO}$ [GHz] | $T_M^{SSB}$ [K] | $L_c^{SSB}$ [dB] | $\|\Gamma_{IF}\|^2$ |
|---|---|---|---|
| 96.0 | 177 | 6.4 | 0.009 |
| 98.0 | 133 | 6.2 | 0.017 |
| 100.0 | 126 | 6.2 | 0.018 |
| 102.0 | 135 | 6.1 | 0.009 |
| 104.0 | 118 | 6.1 | 0.013 |
| 106.0 | 113 | 5.9 | 0.010 |
| 108.0 | 85 | 5.8 | 0.015 |
| 109.0 | 81 | 5.9 | 0.010 |
| 110.0 | 81 | 5.7 | 0.007 |
| 112.0 | 95 | 5.8 | 0.007 |
| 113.5 | 106 | 5.8 | 0.011 |
| 115.0 | 104 | 5.9 | 0.031 |
| 116.0 | 123 | 6.2 | 0.027 |
| 118.0 | 139 | 7.2 | 0.104 |
| 120.0 | 306 | 8.7 | 0.259 |

Diode bias 0.94 V, dc diode current 0.36 mA. Temp. = 24 K, IF = 1.45 GHz, $\Delta f_{IF}$ = 60 MHz. Equal sideband losses.

## IV. DISCUSSION OF THE RESULTS

The performance of the mixer is summarized in Table I and illustrated in Fig. 7, which was obtained as a result of data processing after the measurements. The single-sideband mixer noise temperature is less than 140°K between 98 and 118 GHz and is 81 ± 3 K with a corresponding SSB conversion loss of 5.7 ± 0.1 dB at a LO frequency of 110 GHz. When evaluating this result, it should be noted that a fixed-tuned mixer of similar design can be optimized for low-noise performance in a broader RF frequency range if higher noise temperature is acceptable. ($T_M^{SSB} \approx 150$ K in the 85–120-GHz frequency range was reported in [4].)

The filled square in Fig. 7 represents the lowest mixer noise temperature ever reported for a Schottky diode, *W*-band mixer [8]. That result was derived from DSB measurements of a receiver which was tuned at each

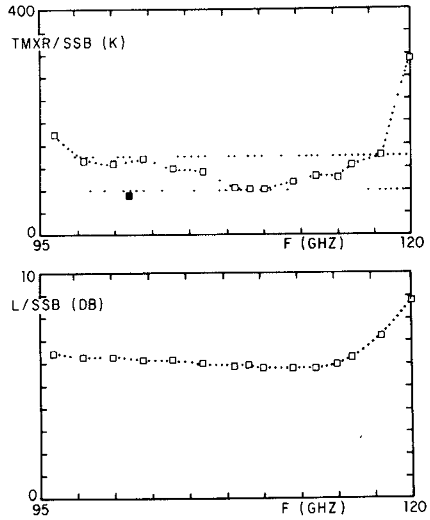


Fig. 7. Single-sideband mixer noise temperature $T_{MXR}$ and corresponding single-sideband conversion loss $L$ of the mixer versus LO frequency. (Temp. = 24 K, IF = 1.45 GHz, $\Delta f_{IF} = 60$ MHz, $V_D = 0.94$ V, $I_{MXR} = 0.36$ mA, equal sideband losses).

frequency. The derivations were made only at the frequency of 101 GHz at which an SSB mixer noise temperature of 70 K was specified. The results reported in this paper are direct measurements of the mixer noise temperature and conversion loss of the fixed-tuned, fixed-bias mixer (i.e., no tuning or adjustments of the mixer were made when the frequency was varied) optimized for best performance in the 20-GHz RF frequency bandwidth.

To further illustrate the usefulness of the accurate mixer characterization and to evaluate the excellent result obtained with the reported mixer, it is useful to examine how the mixer performance compares with the fundamental limits imposed on a Schottky-barrier diode mixer. In order to do that, it is necessary to determine contributions to the mixer noise from the diode itself and from the lossy mount. The measured total conversion loss $L_c^{DSB}$ is composed of: $L_{RF}$, the losses in the scalar feed, input quarter-wave transformer, reduced-height waveguide and fixed backshort; $L_D$, the diode conversion loss; and $L_{IF}$, the losses in the output microstrip choke and IF transformer. Because at 110 GHz measured $|\Gamma_{IF}|^2 = 0.007$, then[1] $L_c^{DSB} \approx L_a^{DSB}$ and

$$L_a^{DSB} = L_{RF} L_D L_{IF}. \qquad (1)$$

The mount RF and IF losses at cryogenic temperatures can only be estimated from room-temperature data on the basis of the increase in the conductivity of OFHC copper and the gold plating upon cooling. At room temperature, scalar feed loss is 0.1 dB, the input waveguide transformer is assumed to have a loss of 0.25 dB and the reduced-height waveguide and fixed backshort, 0.1 dB. The sum of these losses is assumed to decrease to $0.25 \pm 0.05$ dB when cooled. The IF losses are assumed to decrease upon cooling from

[1] $L_a$, an "available conversion loss," was defined in [1] as the ratio of available power of the RF source to available power at the mixer IF output and thus $L_a^{DSB} = (1 - |\Gamma_{IF}|^2) L_c^{DSB}$.

TABLE II
COMPARISON OF MIXER PERFORMANCE WITH LIMITS IMPOSED ON SCHOTTKY DIODE MIXER

| | | |
|---|---|---|
| PRACTICAL MIXER | MEASUREMENTS OF THE D.C. BIASED DIODE<br>$I_D$ = 360 μA<br>Temp. = 24K | $\eta = 4.3 \pm 0.1$<br>$R_s = 14.7 \pm 0.1$ Ω<br>$T_{DC} = 61 \pm 3$K |
| | MEASURED MIXER PERFORMANCE<br>$F_{LO}$ = 110 GHz<br>Temp. = 24K | $L_c^{SSB} = 5.7 \pm 0.1$ dB<br>$\|\Gamma_{IF}\|^2 = 0.007$<br>$T_M^{SSB} = 81 \pm 3$K |
| MODEL A | SHOT NOISE LIMITED MIXER LOSSLESS MOUNT<br>$L_{RF}$ = 0 dB<br>$L_{IF}$ = 0 dB | $L_c^{SSB} = 2L_D$<br>$T_D = 51.6 \pm 1.2$K<br>5.16 dB $\lesssim L_c^{SSB} \lesssim$ 5.46 dB<br>64.6K $\lesssim T_M^{SSB} \lesssim$ 80.0K |
| MODEL B | SHOT NOISE LIMITED MIXER LOSSY MOUNT<br>$L_{RF} = 0.25 \pm 0.05$ dB<br>$L_{IF} = 0.15 \pm 0.05$ dB | $L_c^{SSB} = 5.7 \pm 0.1$ dB<br>$T_D = 51.6 \pm 1.2$K<br>2.15 dB $\lesssim L_D \lesssim$ 2.45 dB<br>76.4K $\lesssim T_M^{SSB} \lesssim$ 88.2K |

Measured mixer performance is compared to limits [9] established for an ideal exponential resistive diode generating shot-noise only and operating as a mixer in which higher harmonics are reactively terminated. The diode is embedded in a lossless mount (Model A) and in a mount having losses equal to the losses of the practical mixer mount (Model B).

0.2 dB to $0.15 \pm 0.05$ dB. At a physical temperature of $T = 24$ K, the diode conversion loss $L_D$ may then be estimated from the measured data and (1) to be between 2.15 dB and 2.45 dB at a frequency of 110 GHz.

The total DSB mixer noise temperature is

$$T_M^{DSB} = (L_{RF} - 1)T + L_{RF}(L_D - 1)T_{eq} + L_{RF} L_D (L_{IF} - 1)T. \qquad (2)$$

The equivalent temperature $T_{eq}$ of the diode as a lossy element is limited by

$$T_D = \frac{\eta T}{2} \qquad (3)$$

derived in [9]. This only applies to a pumped ideal resistive exponential diode ($R_s = 0$, $C_j =$ const) operating as a mixer, for the case where higher harmonics are reactively terminated and only shot-noise is generated by the diode.

The Schottky diode used in the mixer, at a temperature of 24 K, was characterized by an ideality factor $\eta = 4.3 \pm 0.1$. This results in a shot-noise limit of $T_D = 51.6 \pm 1.2$ K which is used in (2) to derive limits for the mixer noise temperature. The results obtained for the shot-noise limited mixer diode embedded in lossy and lossless mount ($L_{RF} \to 0$ dB, $L_{IF} \to 0$ dB) are compared in Table II to the measured performance of the practical mixer. The noise temperatures of the reported mixer and the lossy mount model are equal to within the accuracy of measurements and uncertainty of derivations. This demonstrates that, through careful mount and diode development and optimization, it is possible to construct a $W$-band mixer which approaches the shot-noise limited ideal case, i.e., the diode series resistance and parametric effects due to the diode nonlinear capacitance are negligible, higher harmonics are reactively terminated, there is no excess noise in the diode, and correlated shot-noise components from high harmonics are minimized. The noise of the mixer is determined by the shot-noise generated in the diode and mount losses contribute only $\simeq 9$ K to the SSB mixer noise temperature (6.4 K and 2.6 K due to RF and IF losses, respectively).

## V. Summary

In the companion paper [1], a theory for accurate measurements of millimeter-wave mixers has been given and two computerized measurement systems allowing testing of mixers between 90 and 350 GHz have been presented.

In this paper, a $W$-band, ultra-low-noise, Schottky diode mixer has been reported. Computer printouts that resulted from testing of the mixer have been used to show versatility and thoroughness of the tests available for characterizing and evaluating mixer performance.

The fixed-tuned, fixed-bias, cryogenic mixer reported in this paper has a single-sideband noise temperature less than 140 K between 98 and 118 GHz and, at 110 GHz, achieves shot-noise limited performance with a SSB noise temperature of only 81 K and corresponding conversion loss of 5.7 dB.

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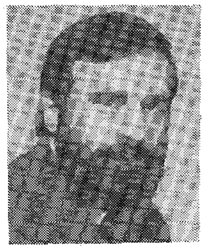

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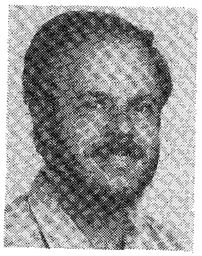

**John W. Archer** (M'82–SM'83) was born in Sydney, Australia, in 1950. He received the B. Sc., B. E. (with first class honors), and Ph. D. degrees from Sydney University in 1970, 1972, and 1977, respectively.

From 1974 to 1977, he was responsible for the successful development of a unique (at that time) variable baseline, phase-stable, two-element interferometer for solar astronomical investigations at 100 GHz. During this period, he was associated with both Sydney University and CSIRO, Division of Radiophysics, in Australia. From 1977 to 1979, he was with NRAO's VLA project. During this period, he was responsible for the evaluation and improvement of the performance of the over-dimensioned waveguide system, as well as for the design of the components for the IF section of the array. From 1979 to 1984, he was at NRAO's Central Development Laboratory, where his main responsibility was to coordinate the development of state-of-the-art millimeter wavelength receiver technology for use at the NRAO Kitt Peak antenna. This work entailed the development of low-noise mixers, harmonic generators, and novel mechanical and quasi-optical structures for millimeter-wave receivers. Since 1984, he has been with CSIRO Division of Radiophysics, where he leads a group developing microwave GaAs devices for commercial applications and for applications to radio astronomy.

Dr. Archer is a member of the Astronomical Society of Australia.