Cryogenic Millimeter-Wave Receiver Using Molecular Beam Epitaxy Diodes

RICHARD A. LINKE, MARTIN V. SCHNEIDER, FELLOW, IEEE, AND ALFRED Y. CHO

Abstract—**A millimeter-wave cryogenic receiver has been built for the 60–90-GHz frequency band using GaAs mixer diodes prepared by molecular beam epitaxy (MBE). The diodes are mounted in a reduced-height image rejecting waveguide mixer which is followed by a cooled parametric amplifier at 4.5–5.0 GHz. At a temperature of 18 K the receiver has a total single-sideband (SSB) system temperature of 312 K at a frequency of 81 GHz. This is the lowest system temperature ever reported for a resistive mixer receiver. The low-noise operation of the mixer is seen to be a result of 1) the short-circuiting of the noise entering the image port and 2) an MBE mixer diode with a noise temperature which is consistent with the theoretical shot noise from the junction and the thermal noise from the series resistance.**

I. INTRODUCTION

A CRYOGENICALLY cooled receiver has been designed and built in the 60–90-GHz (WR-12) waveguide band for the 7-m offset Cassegrainian antenna at Bell Laboratories, Crawford Hill, NJ. The receiver is used for studies of spectral-line radiation from molecules in the interstellar medium. The mixer diode is fabricated from a slice of epitaxial gallium arsenide which is prepared by molecular beam epitaxy (MBE). The doping concentration in the epitaxial layer is specifically designed for low-temperature operation [1]. The diode is incorporated into a reduced-height waveguide block mount using a coaxial RF choke and a noncontacting backshort. The intermediate frequency (IF) is amplified by a cryogenic parametric amplifier at 4.5–5.0 GHz which is followed by room-temperature transistor amplifiers. The mixer and the IF amplifier are both cooled to 18 K by a helium closed-cycle refrigeration system. Signal and local oscillator injection is provided by a quasi-optical injection system described in [2]. The injection system provides 18 dB of image rejection. The total single-sideband (SSB) receiver noise temperature including the feed system is below 480 K from 62 to 92 GHz and has a minimum of 312 K at a signal frequency of 81 GHz.

II. THE MIXER

Fig. 1 is a schematic cross-sectional view of the mixer block, and Fig. 2 is a photograph of the open mixer block with its components. The transition from a full-height waveguide (0.122 in × 0.061 in) to a one-fifth height waveguide (0.122 in × 0.012 in) is made by a linear taper with a length of 0.980 in which was measured to match 97 percent of the incident power to the reduced-height waveguide. This low waveguide height was chosen to reduce the total length and, therefore, the inductance of the contact whisker/post combination. The contact wire is a phosphor-bronze wire with a diameter of 12 μm. The wire is mounted on a nickel post which is pressed into the waveguide block.

Tuning is accomplished by means of a phosphor-bronze noncontacting waveguide backshort which consists of alternating low- and high-impedance sections (each 1/4 wavelength long), and it is insulated from the waveguide by a 19-μm thick mylar tape. A noncontacting short was

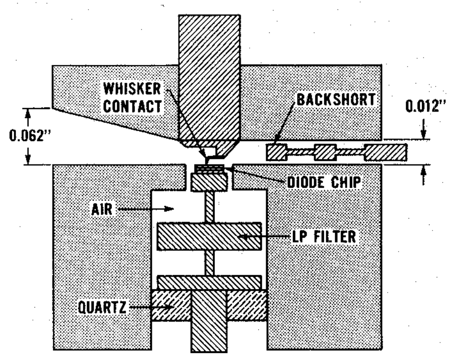

Fig. 1. Cross-sectional view of mixer block with a Schottky-barrier diode mounted in a reduced-height waveguide section.

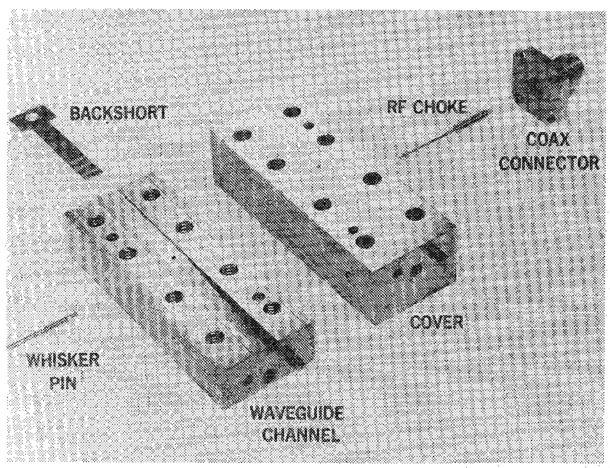

Fig. 2. Photograph of a mixer block with associated components. The waveguide channel with a linear taper is milled into the block shown in the lower left part of the figure.

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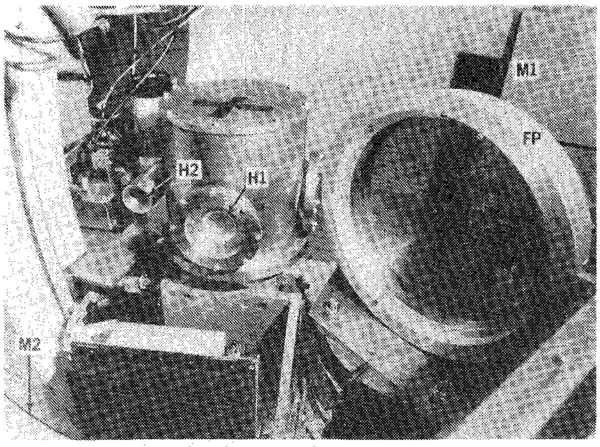

Fig. 3. Photograph of millimeter-wave receiver in the 7-m antenna cab. The mixer is located in the cylindrical Dewar in the center of the photograph. The signal path is as follows—the signal enters from the lower right and is reflected by mirror M1. It passes through the Fabrey–Perot filter FP and is then reflected by M2 toward the dewar window where it is focused on the receiver feed horn, H1. The LO power is transmitted from a second feed horn H2 toward M2 and is reflected by M2 toward the filter FP. It is then reflected by the filter and joins the signal on its path to the receiver feed horn H1.

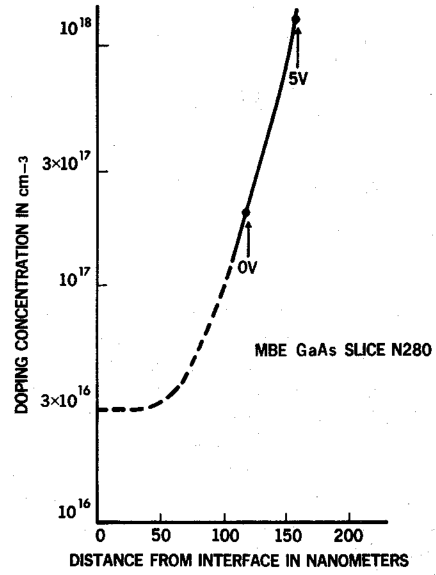

Fig. 4. Doping profile of an epitaxial GaAs slice grown by MBE as a function of depth from the surface. The dashed portion of the curve is inferred from measurements on a thicker sample.

chosen in place of a contacting type because of the difficulties encountered in maintaining a low-loss contacting short for these small waveguide dimensions.

The 250 μm $\times$ 250 μm diode chip with a thickness of 100 μm is soldered to a machined brass pin which provides the IF and dc connections and serves as an RF choke. The choke is a low-pass filter design with a cutoff frequency of 47 GHz. Measurements on a low-frequency model of the choke imply an insurtion loss >40 dB at frequencies up to 180 GHz. The diameter of the first choke element is kept small, and the gap is left free of dielectric material in order to avoid waveguide propagation modes in the filter. The post is supported below the choke by fused-quartz cylindrical sections which are secured to the block and post by epoxy glue.

Fig. 3 is a photograph of the receiver dewar and the quasi-optical components mounted in the 7-m antenna cab.

III. Mixer Diode

The nonlinear device which is used for the mixing process is a moat-etched elliptical junction (bathtub diode) prepared on a heavily doped GaAs substrate by MBE [3]. The doping profile achieved for the deposited epitaxial gallium arsenide on a heavily doped n-type substrate with a carrier concentration of 3×10^{18} cm^{-3} is shown in Fig. 4. The surface doping density is quite low (3×10^{16} cm^{-3}) in order to minimize conduction by electron tunneling and thereby to minimize shot noise [4], [5]. In spite of this low doping, the series resistance is kept low by virtue of the extremely small thickness of the low-doped region (increasing to 10^{17} cm^{-3} at $\sim$1000 Å).

The growth process and the fabrication technique for preparing an array of these junctions are described in [1]. The junctions are fabricated by means of contact photo-

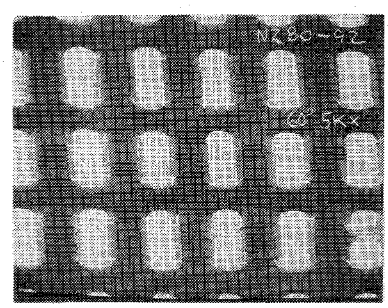

Fig. 5. Electron micrograph of bathtub diodes fabricated on an epitaxial gallium-arsenide slice. (MBE-GaAs batch N280-92. Junction size 1.8$\times$6.2 μm.)

TABLE I
I Versus *V*: Characteristics of Mixer Diode

T_{amb}	R_s (Ω)	V_o (mV)	n
295	4.5	28.2	1.11
77	6.8	11.3	1.70
18	7.4	11.9	7.67

lithography using a pattern on a chromium mask which is generated with an electron beam exposure system [6], [7]. An electron micrograph of the junctions is shown in Fig. 5. Each individual junction has a series resistance of 4 Ω and a zero bias capacitance of 14.7 fF at room temperature. The breakdown voltage of each junction is 7.6 V at a current of 10 μA, and the idealty factor is 1.08. The characteristics of the diode used in this mixer are given in Table I for ambient temperatures of 295, 88, and 18 K. In this table, R_s is the series resistance, n is the idealty factor, and V_0 is defined by

$$I(V)=I_s(e^{V/V_0}-1)$$

where I_s is the saturation current.

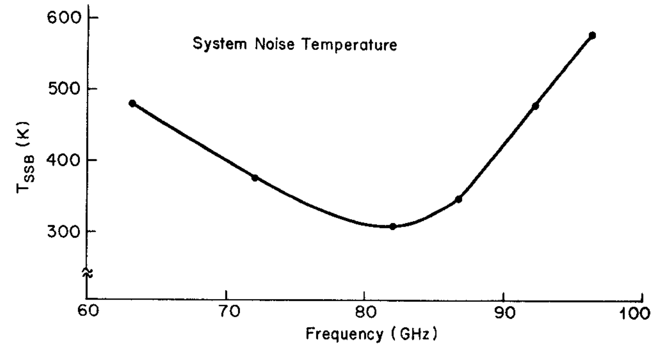

Fig. 6. Total SSB system noise temperature of cooled receiver as a function of frequency. The minimum system temperature of 312 K is obtained at a frequency of 81 GHz.

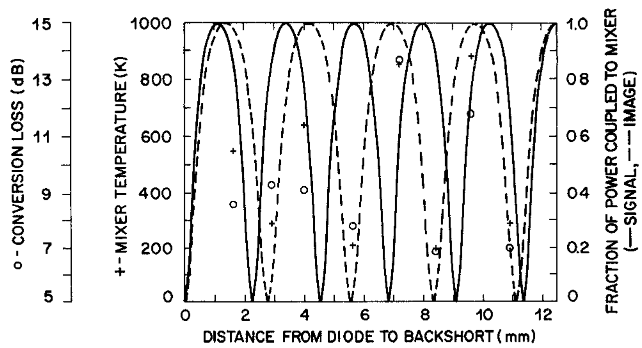

Fig. 7. The mixer temperature minima (filled circles) and the associated conversion loss (open circles) are plotted versus the backshort position. The curves give the efficiency of the coupling power to the diode at the signal frequency (solid) and image frequency (dashed) for the simple case of a diode shunted by a shorted waveguide section. Note that the lowest noise operation occurs for the positions of the backshort which give a short-circuit at the image frequency.

IV. Receiver Performance

A cold (18 K) reference termination on the refrigerator cold station and an external noise diode coupled to the paramp through a 30-dB directional coupler are used to determine the IF-system noise temperature which is found to be 22±3 K. Hot (ambient temperature) and cold (liquid-nitrogen temperature) millimeter-wavelength reference signals are coupled into the mixer by the quasi-optical injection system through a 0.100-thick (one wavelength at 75 GHz) rexolite window in the Dewar. The window has a <0.1-dB loss at 75 GHz and a 0.8-dB reflection loss at 60 and 90 GHz. The signal is converted to waveguide propagation by means of a corrugated scalar feed horn which is cooled to 18 K along with the mixer and IF amplifier. The mixer's IF port was measured to have a VSWR of 2.5 at room temperature. This results in a reflection loss of ~0.85 dB. The data reported here have not been corrected for this loss.

Using the calibrated IF system to measure noise from the mixer's IF port for the two different RF termination temperatures, the conversion loss, mixer temperature, and total receiver noise temperature are determined as a function of the frequency and backshort position. The receiver noise temperature is shown in Fig. 6 for signal frequencies from 63 to 98 GHz. A broad minimum in receiver temperature is seen at ~81 GHz. At this frequency, T_{rec} is 312 K, the conversion loss is 6.7 dB, and the mixer noise temperature is 209 K. Here T_{rec} is the total SSB system temperature including feed system losses and IF noise. The mixer temperature and conversion loss are related to T_{rec} by

$$T_{rec} = T_m + LT_{IF}$$

where all quantities are SSB.

Measured mixer parameters for $f_{sig} = 81.9$ GHz are given in Table II for the first eight positions of the backshort which give a minimum in system noise. It is apparent that the best operating point is the sixth noise minimum rather than the usual first position of the backshort. It is interesting to note that the mixer alternates between high- and low-noise operation with successive positions of the backshort. In Fig. 7 we have plotted the

TABLE II
MIXER PARAMETERS VERSUS BACKSHORT POSITION FOR MINIMA IN T_{REC} ($f_{sig} = 81.9$ GHz)

Diode to Backshort Distance (mm)	L_s (dB)	L_i/L_s (dB)	T_M^{SSB} (K)	T'	$\frac{T_m}{L_s}$ (K)
1.63	8.6	~0.5	550	41	75
2.90	9.3	>18	290	39	35
3.99	9.1	~0.5	640	[illegible]	78
5.61	7.8	>18	210	41	35
7.19	13.7	>18	860	30	37
8.38	6.9	>18	190	42	38
9.60	11.8	~3	880	53	59
10.90	7.0	>18	290	[illegible]	59

$$T^* = \frac{T_m}{L_s - 1}\left(1 - \frac{T_0}{T_m}\frac{L_s}{L_i}\right),$$

mixer noise temperature minima and the associated conversion loss as a function of the backshort position. In addition, we have plotted theoretical curves for the efficiency of coupling power into the diode at the signal and image frequencies as a function of the backshort position. These curves correspond to a simple mixer circuit model in which a real diode impedance, equal to the guide impedance, is shunted by a shorted waveguide section of varying length. It is clear from Fig. 7 that the best operation of the mixer occurs at the backshort positions which correspond to a short-circuited diode at the image frequency. Thus the improvement in mixer noise performance is a result of short-circuiting the noise entering the mixer through the image port.

In order to check this interpretation, we measured the image rejection of the mixer itself by tuning the Fabrey–Perot filter in the quasi-optical injection system to pass the image frequency and block the signal frequency. At the backshort positions corresponding to a shorted image, the DSB system temperature was found to be consistent with the known leakage through the filter at the signal frequency and no mixer sensitivity at the image frequency.

We conclude that the image rejection ratio is >18 dB (i.e., the filter rejection) at these backshort settings. Since the image is effectively shorted for each of the four lowest noise minima, the observed differences in performance result from the fact that the impedance presented by the backshort at the signal frequency (which varies with a different period from that of the image) takes on different values at each of these positions. In fact, the broad minimum in the mixer noise observed near 81 GHz may be a result of a favorable signal impedance occurring at a position of a short-circuited image.

We have attempted to determine the effective temperature of the mixer diode when it is viewed as a lossy element at some assignable temperature [8], [9]. In order to do this, we must subtract the noise contribution from the image termination which is taken to be at ambient temperature T_0 (295 K) since the feed system terminates the image in a room-temperature attenuator. The resulting effective diode temperatures, given in the column headed T^* in Table II, are seen to be nearly independent of image rejection while the value labeled T_m/L, which is the equivalent noise temperature of the mixer's IF port, is seen to double when the image rejection is poor indicating that noise from the image termination is in fact converted to the IF when the image is not shorted. We feel that the average T^* of 47 K is a reasonable measure of the mixer diode's effective temperature. It is interesting to compare this temperature with the value [8], [10], [11]

$$\frac{1}{2}nT=69 \text{ K}$$

obtained from the n and T given in Table II. When we allow for the fact that a significant portion of the conversion loss results from the diode's series resistance which is at a temperature of 18 K, we see that our measured mixer noise is consistent with a purely theoretical shot noise. That is, we see no evidence for excess noise as discussed in [9]. We attribute this to an absence of parametric effects since the Mott barrier used in this mixer shows very little change in capacitance with the bias voltage.

V. Conclusions

We have designed and built a cryogenic millimeter-wave resistive mixer receiver which operates with a system noise temperature (SSB) below 480 K from 62 to 92 GHz. The system is observed to have a broad minimum in noise temperature near 81 GHz where the system temperature is 312 K, the mixer temperature is 209 K, and the conversion loss is 6.7 dB. If a correction is made for the IF mismatch measured at room temperature, the conversion loss is found to be 5.9 dB. The low-noise operation of the mixer is seen to be a result of 1) the short-circuiting of the noise entering the image port and 2) the MBE mixer diode with a noise temperature which is consistent with a theoretical shot noise in the junction and thermal noise in the series resistance.

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