Superconductive Hot-Electron-Bolometer Mixer Receiver for 800-GHz Operation

Jonathan Kawamura, Raymond Blundell, C.-Y. Edward Tong, *Member, IEEE*, D. Cosmo Papa, Todd R. Hunter, Scott N. Paine, *Member, IEEE*, Ferdinand Patt, Gregory Gol'tsman, Sergei Cherednichenko, Boris Voronov, and Eugene Gershenzon

***Abstract*—In this paper, we describe a superconductive hot-electron-bolometer mixer receiver designed to operate in the partially transmissive 350-μm atmospheric window. The receiver employs an NbN thin-film microbridge as the mixer element, in which the main cooling mechanism of the hot electrons is through electron–phonon interaction. At a local-oscillator frequency of 808 GHz, the measured double-sideband receiver noise temperature is $T_{\rm RX} = 970$ K, across a 1-GHz intermediate-frequency bandwidth centered at 1.8 GHz. We have measured the linearity of the receiver and the amount of local-oscillator power incident on the mixer for optimal operation, which is $P_{\rm LO} \approx 1 \mu$W. This receiver was used in making observations as a facility instrument at the Heinrich Hertz Telescope, Mt. Graham, AZ, during the 1998–1999 winter observing season.**

***Index Terms*—Submillimeter-wave mixers, superconducting devices.**

I. Introduction

In THE frequency range from 100 to 700 GHz, niobium-based superconductor–insulator–superconductor (SIS) mixers have developed to the point where their noise performance is nearly quantum limited [1]. Above 700 GHz, which is the gap frequency of niobium, the noise performance rapidly deteriorates due to resistive losses in the tuning circuits. By using materials with gap frequencies higher than that of Nb to form the junction circuitry, such as NbN or NbTiN, it should be possible to extend quantum-limited noise performance using SIS mixers above 700 GHz. Recent progress with NbN- [2] and NbTiN-based [3] mixers shows promise that this might be achieved. Nevertheless, for either material, the high-frequency limit for low-noise operation is about 1.2 THz.

Thus, in the effort to develop mixers for terahertz frequencies, considerable attention has recently turned to superconductive hot-electron-bolometer (HEB) mixers. Superconductive HEB mixers are simply very fast transition-edge bolometers. The early work on this type of mixer indicated they should have good low-noise performance and reasonably high conversion efficiency. Some of the advantages of HEB mixers over SIS mixers are: 1) there does not appear to be any severe limitation to their performance at very high frequencies; 2) they do not have any large parasitic capacitance at the signal frequency and, therefore, do not require an additional on-chip tuning circuit; and 3) they do not require a magnetic field for low-noise operation. One possible limitation with low-T_c HEB mixers is that the IF bandwidth will most likely be limited to less than 10 GHz.

There are two types of superconductive HEB mixers. The first, proposed by Gershenzon *et al.* [4], relies on a strong electron–phonon interaction and a fast phonon escape time from the film to achieve a large IF bandwidth. This type of mixer is usually referred to as "phonon-cooled" or "lattice-cooled." In this type of mixer, a fast response time depends critically on the film thickness. The upper limit to the IF bandwidth is given by the inverse of the film material's electron–phonon relaxation time $\tau_{\rm e-ph}$ at T_c. For NbN films, the theoretical upper limit for the IF bandwidth is $B \approx 10$ GHz [5]. To realize this theoretical limit, the film must be fabricated as thin as possible, i.e., $d < 5$ nm, on a substrate that provides a good acoustic match to the film. Failing to do so generally results in a reduction of the IF bandwidth.

The phonon-cooled mixer inspired Prober to propose a variant of the HEB mixer in which the dominant cooling mechanism is the out-diffusion of hot electrons to a heat sink [6]. This type of mixer is usually referred to as "diffusion-cooled." In this mixer, the ends of the microbridge are connected to normal metal pads that serve as heat reservoirs, and the length of the microbridge determines the IF bandwidth. Diffusion and phonon cooling occur in parallel, and for out-diffusion to dominate over phonon cooling, the length of the microbridge must be $l \ll \sqrt{12 D \tau_{\rm e-ph}}$ [6], where D is the diffusion constant of the film. Out-diffusion becomes the dominant cooling mechanism when $l \approx 0.3$ μm in Nb [7] and $l \ll 0.1$ μm in NbN.

Efforts to quantitatively understand these mixers have proven difficult, although the proposal papers [4], [6] and the paper by Ekström *et al.* [8] define important quantities and provide insight into their qualitative behavior. Understanding the mixers on the microscopic level is now thought to be crucial in predicting their detailed behavior, and recent efforts have been directed to this end, e.g., [9]. Nevertheless, guided by the ideas set forth in the papers mentioned above, very significant experimental progress has been made with both the NbN phonon-cooled [10]–[12] and Nb diffusion-cooled variety [13]–[15]. The mixer performance achieved for both

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J. Kawamura is with the California Institute of Technology, Pasadena, CA 91125 USA.

R. Blundell, C.-Y. E. Tong, D. C. Papa, T. R. Hunter, and S. N. Paine are with the Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138 USA.

F. Patt is with the Submillimeter Telescope Observatory, Tucson, AZ 85721 USA.

G. Gol'tsman, S. Cherednichenko, B. Voronov, and E. Gershenzon are with the Moscow State Pedagogical University, Moscow 119435, Russia.

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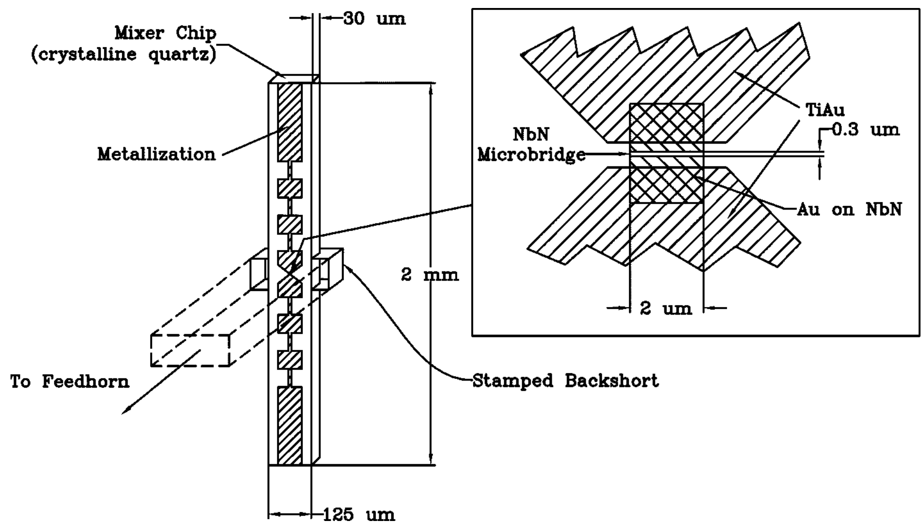

Fig. 1. Schematic of the mixer. To the left-hand side is a sketch of the quartz mixer chip. The drawing on the right-hand side gives the layout of the active area of the mixer defined on the chip.

types of mixer has largely been very similar, despite the different film material used. Notwithstanding the poor theoretical understanding, superconductive HEB mixers have already met the basic requirements for their application to astronomy and radiometry at submillimeter wavelengths: low-noise performance: typically $T_{\rm RX}/\nu < 1$ K GHz^{-1}, low local oscillator (LO) power requirement: $P_{\rm LO} < 1$ μW, and large usable IF bandwidth: $\Delta B > 1$ GHz. Currently, between 800–1000 GHz, the receiver noise temperatures of HEB mixers are comparable to SIS-based receivers operating in the same frequency range; beyond 1 THz, HEB mixers are the most sensitive of any existing heterodyne technology.

II. Instrument Design

Our receiver employs a phonon-cooled HEB mixer made from thin-film NbN. In addition to assessing important mixer properties such as input signal bandwidth, sensitivity, and IF bandwidth, our experiments have been aimed at answering the question of whether or not this type of mixer could be used in a practical instrument outside the laboratory. Our experiments have unambiguously answered this question in the affirmative [10], [16]. We subsequently initiated an effort to develop a working receiver to take to a telescope where its performance could be definitively tested. In March 1998, we installed our receiver [17] at the 10-m Heinrich Hertz Telescope (HHT), Mt. Graham, AZ [18]. The receiver was successfully used to detect molecular emission lines from a number of astronomical sources at 690 and 810 GHz. We used the observatory's facility IF processing system and spectrometers, which were designed to accommodate the facility SIS receivers. Generally speaking, the receiver was very robust and was reasonably stable, and could be handled by observers with little experience. The double-sideband receiver noise temperature $T_{\rm RX}$ was 1300 K, flat across the 600-MHz IF bandwidth, centered at 1.5 GHz. In later experiments, using a different mixer from the same fabrication batch, we were able to improve the receiver noise performance to better than $T_{\rm RX}/\nu \approx 1$ K GHz^{-1} across 780–870 GHz [19]; e.g., at 804 GHz, $T_{\rm RX} = 720$ K.

We have since then focused on improving other aspects of the receiver design, including changing the IF amplifier to provide wider instantaneous bandwidth. In November 1998, the modified receiver was installed at the HHT, where it has since been used to make astronomical observations on a regular basis. In this paper, we outline the design of this 800-GHz receiver, present measurements of the receiver's linearity and LO power requirement, and describe its performance on the telescope.

A. HEB Elements

The mixer elements are made from high-purity NbN film deposited on heated 100-μm-thick z-cut crystalline quartz substrates. The fabrication process is discussed in detail in [20]. The film is $d \approx 4$ nm thick and has a normal-state sheet resistance $R \sim 1$ kΩ per square. The critical temperature is $T_c \approx 9$ K, with a transition width of 1 K. The active area of the mixer is defined using electron-beam lithography, and the microbridges, typically 2-μm wide and 0.3-μm long, are contacted on the ends by TiAu metallization, which forms the antenna and choke structures. With these dimensions, the mixer's room-temperature resistance is about 100 Ω. The normal-state resistance R_N near T_c is about 15% higher than the room-temperature value. The small mixer area $A < 1$ μm^2 was chosen in order to reduce the required LO power to a level that can be readily provided by standard frequency-multiplied solid-state oscillators [12], [19]. The quartz wafer is lapped to a thickness of 30 μm and then diced into small chips, which fit in a suspended microstrip channel across a reduced-height waveguide machined in a copper mixer block. The schematic of the mixer is shown in Fig. 1.

Mixers fabricated at the same time on the same substrate show good uniformity in their electrical properties, with fairly uniform values for both R_N (about 10% variation) and I_c, the critical current. For the present study, we use a mixer with room-temperature resistance of $R = 90\,\Omega$ and $R_N(T_c) = 110\,\Omega$. The critical current is $I_c = 150$ μA at 4.2-K bath temperature.

In order to keep the overall mixer design simple, we have continued to use crystalline quartz as the mixer substrate. NbN films of higher quality, however, have been deposited on sapphire, Si, or MgO substrates. The associated increase in T_c allows considerable broadening of the IF bandwidth [20]. We have measured the IF gain response of a representative mixer from our batch of mixers at microwave frequencies [19]. When the gain response is fitted to the function $\eta(f) = (1 + (f/f_c)^2)^{-1}$, the parameter f_c, which is usually called the 3-dB rolloff frequency, is about 2.0 GHz.

B. Mixer Design

The mixer design is essentially a scaled version of our earlier HEB mixers [10], [16]. These were based on SIS mixers we developed [21] for the Submillimeter Array, Smithsonian Astrophysical Observatory, Cambridge, MA. The mixer is of the waveguide type and is made in two sections. The front section carries the integrated corrugated horn feed, which is electroformed and press-fit into a copper block. The back section houses a short length of waveguide, i.e., 254 μm $\times$ 63.5 μm, the length of which is chosen so as to provide a reasonable input match to the mixer element over the signal input frequency band. According to scale-model measurements, the mixer circuit presents a real impedance of about 100 Ω near 800 GHz. The quartz chip is suspended across the waveguide and is clamped between the two halves of the mixer block.

C. Receiver System

The mixer is housed in a liquid helium-cooled cryostat equipped with a liquid nitrogen-cooled radiation shield. The mixer block is bolted directly to the cryostat cold plate, which is cooled to 4.2 K. The corrugated feed illuminates a cold off-axis paraboloid, and the beam passes through two stages of near-infrared filtering, provided by several layers of porous Teflon sheets at 4.2 and 77 K. A 0.5-mm-thick Teflon sheet, which is 2λ thick at about 840 GHz, serves as the vacuum window. The LO and signal beams are combined in a Martin–Puplett polarizing interferometer placed directly in front of the cryostat vacuum window. The LO chain consists of a Gunn oscillator, followed by a waveguide isolator and two stages of self-biased varactor multipliers, and provides $\sim$10μW output power across 800–840 GHz.

The IF output from the mixer is fed through a bias tee to a low-noise high electron-mobility transistor amplifier, which is bolted to the cryostat cold plate. The amplifier has a gain of 38 dB, a center frequency of 1.85 GHz, and a bandwidth of 1.2 GHz. Its noise temperature is 2 K at band center, and rises to about 5 K at the band edges. The signal output from the receiver passes through a filter, a simple single-pole gain equalizer, and several stages of amplification. Successive filters set the IF center frequency at 1.8 GHz and the bandwidth to 1 GHz. The resultant signal is upconverted to 3–4 GHz, then branched to a number of spectrometers.

This IF configuration was chosen for the following reasons. First, a full 1-GHz IF bandwidth was desired to have it match the capability of the observatory's spectrometers. Though the upper end of the IF can be made somewhat higher than f_c without dramatically hurting the sensitivity, in a practical receiver such as ours, we wish to avoid having a slope in either the sensitivity or the gain across the IF. The former effect makes data reduction quite difficult; the latter would entail additional circuitry to compensate for the gain variation. The upper end of the IF is thus limited to about 2.0 GHz. The center frequency was increased from 1.5 to 1.8 GHz in order to reduce losses at the band edges caused by the polarizing diplexer, at the same time keeping the upper edge of the IF not too far above 2 GHz. With a fractional bandwidth of 56%, we incur less than 1-dB loss at the edges of the band compared to an estimated 3-dB loss at the lower band edge if we keep the center frequency at 1.5 GHz.

The receiver sits at the telescope's Nasmyth focus on a platform extending from the elevation axis flange. This location is relatively free from mechanical vibrations, which ensures stable operation of the receiver, as it is quite sensitive to LO coupling variations. The beam of the receiver looks through the bore in the elevation axis, and is reflected off a flat tertiary mirror to illuminate the secondary mirror with a -14-dB edge taper. With a 10-m primary mirror, the diffraction-limited beam size is $\theta \approx 9''$ at 810 GHz.

III. RECEIVER PERFORMANCE

A. Mixer Bias Point

The receiver noise temperature is measured using the standard Y-factor method, in which the receiver's IF output power is measured as a function of bias voltage in response to alternating hot (295 K) and cold (77 K) input loads. First, the bias point for optimal noise performance is located on the current–voltage (*I–V*) plane by varying the voltage bias and LO power. In our experience, the optimum bias point is easily located as follows. In all of the mixers we have tested, the LO power level is always set slightly past the transition from where the mixer *I–V* curve has some negative differential resistance to where it has none. Theoretically, this condition is realized when the mixer self-heating parameter C becomes less than one [8]. This has the interesting consequence that for any practical receiver system, the mixer conversion efficiency will be no better than the classical limit of $\eta \leq -6$ dB. An optimally pumped *I–V* curve is smooth and monotonic, and IF output power has a smooth and rounded peak as the bias is swept in voltage. Once the LO power level is fixed, the voltage bias for optimum low-noise performance is always near the point where the IF output power is a maximum. An unpumped *I–V* curve and an optimally pumped *I–V* curve with corresponding IF output are shown in Fig. 2.

The mixer gain is very sensitive to slight changes in the operating point, though the receiver noise temperature is not. This fact is demonstrated in Fig. 3, in which the IF output power, estimated LO power, and receiver noise temperature are plotted against the mixer current at the fixed voltage bias chosen for optimum low-noise performance. Over a span of a factor of two in bias current, the receiver noise is virtually unchanged; this span reflects varying the absorbed LO power by approximately 1 dB. However, over the same range, the IF output has changed by 6 dB. This behavior is different from that of SIS and Schottky mixers, which are usually operated with the mixer essentially driven into LO saturation. Therefore, the superconductive HEB mixer is very vulnerable to LO power fluctuations. In practice, LO power coupling can be changed by mechanical vibration, small temperature fluctuations of the dewar, unwanted standing waves, or simply an unstable power output from the LO source.

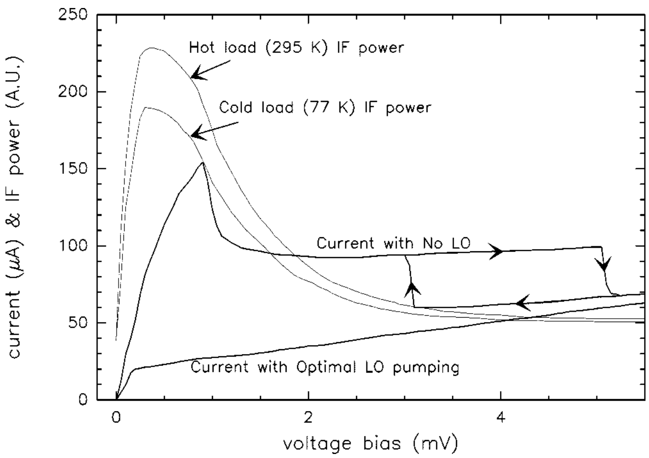

Fig. 2. *I–V* characteristics of the mixer operating with optimal amount of LO power applied and no LO power applied at 4.2-K bath temperature (heavy lines). The LO frequency is about 804 GHz. The unpumped curve is hysteretic and has regions of negative differential resistance. In contrast, the pumped curve is smooth and single valued everywhere, and has no regions of negative differential resistance. The IF output power in response to 295- and 77-K loads when the mixer is pumped with an LO as shown is also plotted as function of bias voltage (light lines). The voltage bias for best noise performance is set at 0.8 mV.

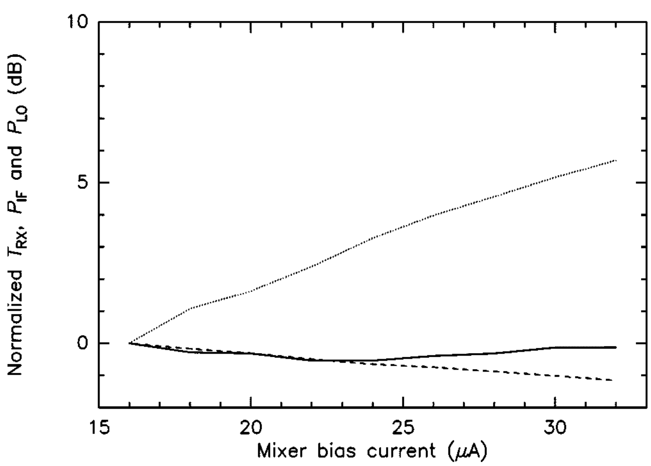

Fig. 3. Change in sensitivity and mixer gain near the optimal operating point. The receiver noise temperature (solid line), IF output power (dotted line), and estimated LO power (dashed line) are plotted against the bias current. The receiver noise temperature, IF output power, and LO power are normalized to their respective values at 16 μA, and plotted in decibels. The bias voltage is fixed at 0.4 mV.

It is, therefore, crucial to have constant LO coupling for stable receiver operation. In order to ensure stable operation at the telescope, we slightly overpump the mixer to move the bias current to a smaller value where $dP_{\rm IF}/dP_{\rm LO}$ is smaller. We roughly estimate that its overall stability is a few parts in 10^3. This suggests that the LO coupling is stable to better than 1 part in 10^3.

B. Receiver Sensitivity

With the Martin–Puplett diplexer tuned to an IF center frequency of 1.8 GHz, the receiver sensitivity at an LO of 808 GHz is $T_{\rm RX} = 970$ K averaged across the full 1-GHz bandwidth. The receiver noise temperature measured with this configuration is plotted against LO frequency in Fig. 4. Inserting a 100-MHz-wide filter centered at 1.5 GHz, we

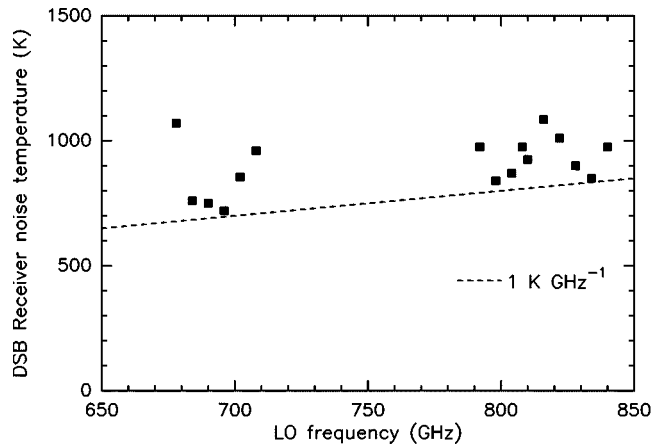

Fig. 4. Double-sideband receiver noise temperature across the operating bands of the LO sources. The diplexer is tuned to an IF center frequency of 1.8 GHz, and the IF power is measured across 1.3–2.3 GHz. The dashed line indicates 1 K GHz^{-1}.

measure $T_{\rm RX} = 840$ K, reflecting the higher sensitivity toward the center of the IF band. This receiver is reasonably sensitive down to the cutoff frequency of the waveguide, which is 600 GHz. At an LO frequency of 690 GHz, the receiver noise temperature is 750 K.

The conversion gain of a mixer that had similar overall performance was estimated in a nearly identical receiver setup in the laboratory. In this case, a cryogenic isolator is inserted between the mixer and IF amplifier and the conversion gain is estimated as follows. Under zero bias, the mixer becomes purely reactive at the IF. Hence, by virtue of the isolator, the IF amplifier sees a matched load at 4.2 K and, provided the input noise $T_{\rm IF}$ of the IF amplifier is known, the gain of the IF chain can be determined. The total receiver gain, including the contribution from the IF chain, is given by the difference in the IF output powers in response to hot and cold loads, which were recorded in the Y-factor measurements. The mixer conversion gain may then be determined from the ratio of this difference IF power and the IF output measured with no LO and zero-voltage bias applied to the mixer. Using this method, we estimated that the conversion loss is $L \approx 15$ dB. Our present receiver has $T_{\rm RX} = 970$ K; with an average $T_{\rm IF} \approx 3$ K, we deduce that the mixer noise temperature is $T_{\rm MIX} \approx 880$ K. Thus, the receiver noise is dominated by mixer noise.

At the telescope, we retuned the diplexer to operate at a higher IF to flatten out the sensitivity of receiver across the IF passband. As we noted earlier, the 3-dB rolloff in mixer conversion gain occurs at $f_c = 2.0$ GHz. This implies that the mixer conversion loss at 2.3 GHz, the upper end of the IF, is about 2 dB larger than at 1.3 GHz, the lower end. With the diplexer tuned to a center frequency of 1.8 GHz, the receiver noise temperature is about 25% worse at the highest portion of the IF passband than at the lowest. Since it was desirable to have a flatter response, the diplexer was tuned to a center IF of 1.95 GHz. With this diplexer setting, the overall receiver noise temperature does not change: $T_{\rm RX} = 970$ K averaged over the full 1-GHz IF. The receiver noise temperature as a function of IF with this diplexer setting is shown in Fig. 5. The spectrometers show that, over the central 250 MHz of the IF band, $T_{\rm RX} = 890$ K. The modest

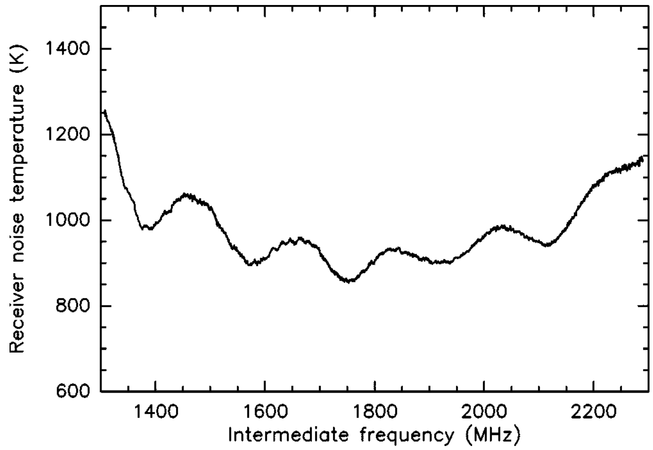

Fig. 5. Receiver noise temperature at an LO frequency of 808 GHz, measured across the IF, which is centered at 1.8 GHz and is 1-GHz wide. The average noise temperature is 970 K. The 200-MHz ripple is caused by the mismatch between the mixer and amplifier since an isolator is not used.

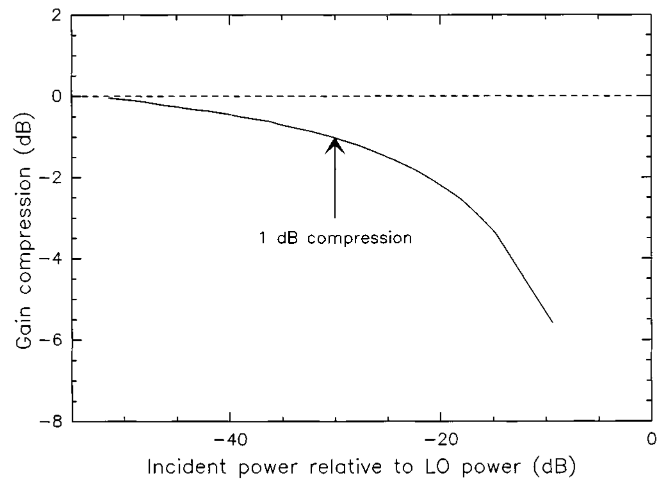

Fig. 6. Gain compression measurement. The dashed line indicates linear response. The 1-dB compression point occurs at 30 dB below the LO power required for optimal mixing. Reproduced from [19].

ripple across the IF is caused by a mismatch between the mixer and IF amplifier since no isolator was used between them.

C. Linearity and LO Power Measurements at 800 GHz

One of the concerns surrounding the development of superconductive HEB mixers is that they may be prone to saturation effects. This concern arose as the first results on superconductive HEB mixers were being presented, and many workers speculated that their two notable qualities, i.e., broad-band response and low LO power requirement, might adversely conspire together to cause saturation even at modest input signal levels. This concern has persisted as even recent results show obvious effects from direct detection loading, e.g., [14]. Receiver sensitivity is usually determined by the Y-factor method in which the receiver's input is terminated with a broad-band load. However, if the mixer were saturated or nonlinear, the receiver noise temperature calculated from the Y-factor method may not represent the actual heterodyne sensitivity of the receiver. More importantly, in radio astronomy, spectral line observations are often most conveniently calibrated by terminating the receiver input with an ambient-temperature load. This method of calibration assumes that the receiver is linear at the load temperature. It is possible to terminate the receiver with a load with a lower temperature. However, considering the rather large brightness temperature of the sky from ground-based sites at these frequencies and the relative simplicity of using an ambient-temperature load for calibration purposes, it is desirable that a mixer be well within its linear regime when the input is terminated by a 300-K load.

We have previously addressed the issue of nonlinearity in an experimental receiver operating at 200 GHz by directly measuring its linearity and LO power requirements [16] using a technique described in [22]. In this method, a monochromatic signal source, usually another LO chain, is coupled to the input of the receiver. The output power from this signal source is monitored using a harmonic mixer connected to a spectrum analyzer. By comparing the receiver IF output power at different incident signal power levels to the receiver's IF output in response to hot and cold loads, we can infer the compression characteristics of the receiver. The LO power drive to the mixer can also be derived in the same setup if the signal source is strong enough to pump the mixer. This technique assumes that the receiver's response to monochromatic and thermal radiation are equivalent. Here, by measured LO power, we mean the incident LO power referenced to the input port of the receiver, instead of the actual power absorbed by the mixing device.

Since it is difficult to directly monitor the power output from an 800-GHz source due to the lack of a room-temperature mixer with large dynamic range, a variation of the above method is implemented. In this case, we assume that the receiver has linear response below some input power level, so that the receiver itself can be used as a linear detector of weak incident signal power. As in the lower frequency measurements, we again employ a second Gunn oscillator/multiplier chain as a test signal source. An isolator, an attenuator, and a directional coupler are inserted between the Gunn oscillator and multipliers, so as to allow the power incident on the multiplier chain $P_{\rm Gunn}$ to be varied and monitored. The receiver IF power output is first measured as a function of $P_{\rm Gunn}$. Next, the coupling of the signal source to the receiver under test is reduced to decrease the incident signal power to the receiver. The receiver IF power output is again measured at the same set of values of $P_{\rm Gunn}$. By repeating this procedure at various signal coupling, it is possible to reach a point where the receiver is operating in the linear regime. Thus, we are able to translate the values of $P_{\rm Gunn}$ into relative output powers at 800 GHz from the Gunn oscillator/multiplier chain used as a test signal source. Once this is achieved, we can rely on the hot/cold load measurement to calibrate the signal power coupled to the receiver, and the gain compression and incident LO drive can be measured as previously described.

In Fig. 6, we display the results of a gain compression measurement made at 810 GHz. From the measurements, we determine that $P_{\rm LO} \approx 1\ \mu$W, and that the 1-dB compression point occurs at an input power level of about 1 nW. This value is consistent with the 1-nW value [19] that can be estimated from the IF output power versus bias voltage curve. This measurement clearly indicates that the Y-factor measurements were made well within the linear regime of the mixer and, thus, it is suitable for us to use ∼300 K loads to calibrate the receiver.

From an inspection of the *I–V* curve with and without LO power, it is possible to estimate the *absorbed* LO power by using the so-called isotherm method [8]. By this method, we estimate that the LO power absorbed by the mixer is $P_{\rm abs} \approx 0.13\ \mu$W. This absorbed LO power is lower than the measured incident LO power by as much as 9 dB. The possible causes of the discrepancy are losses in the optical path, impedance mismatch of the device, and potentially, absorption of the RF power by lattice heating. A more thorough investigation is necessary to allow a better understanding of the mixer's loss mechanisms.

IV. Conclusions

We have developed a receiver for operation in the 350-μm atmospheric window. It incorporates a phonon-cooled NbN HEB mixer, and the sensitivity across 680–830-GHz input frequency is usually better than 1000 K with the full 1-GHz-wide IF. This receiver's performance is comparable to the best Nb-based SIS receivers currently in operation as facility instruments at any submillimeter observatory. The receiver was successfully used to make astronomical observations at the HHT during the 1998–1999 winter observing season [23].

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Jonathan Kawamura received the B.S. degree from the California Institute of Technology, Pasadena, in 1992, and Ph.D. degree in astronomy from Harvard University, Cambridge, MA, in 1997.

He is currently a Post-Doctoral Scholar at the California Institute of Technology, where he is involved with the development superconducting mixers and detectors for astronomical applications.

Raymond Blundell was born in Liverpool, U.K. He received the B.Sc. and Ph.D. degrees in electrical and electronic engineering from the University of Leeds, Leeds, U.K.

In 1977, he joined the Thorn-EMI Group, where he was engaged in the development of scale-model radar systems. From 1980 to 1989, he was with the Institut of Radio Astronomic Millimétrique, Grenoble, France, where he lead a small group responsible for the development of low-noise millimeter heterodyne receivers. In 1989, he became Director of the Sub-Millimeter Receiver Laboratory, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, as well as being a Lecturer in astrophysics in the Department of Astronomy, Harvard University, Cambridge, MA. His research interests include millimeter and submillimeter techniques, superconducting tunnel-junction mixers, solid-state oscillators and frequency multipliers, low-noise amplifiers, quasi-optical components, and 4-K refrigeration systems.

C.-Y. Edward Tong (M'89) was born in Hong Kong. He received the B.Sc. (Eng.) degree from the University of Hong Kong, in 1983, the Diplôme d'Ingénieur degree from the Engineering School, ENSERG, Grenoble, France, in 1985, and the Ph.D. degree from the Université de Joseph Fourier, Grenoble, France, in 1988.

From 1985 to 1988, he was with the Institut de Radio Astronomie Millimétrique, Grenoble, France, where he studied low-noise superconducting receivers for millimeter wavelengths. From 1989 to 1991, he was a Post-Doctoral Fellow at the Communications Research Laboratory, Tokyo, Japan. Since 1991, he has been with the Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, where he is a staff member responsible for the development of ultra-sensitive superconducting receivers for submillimeter waves. He is also an Astronomy Lecturer at Harvard University, Cambridge, MA. His research interests include superconducting devices and their applications to high frequencies, low-noise heterodyne instrumentation, submillimeter and quasi-optical techniques in microwave and antenna measurement, and the time-domain solution of three-dimensional electromagnetic problems.

D. Cosmo Papa joined the Massachusetts Institute of Technology, Cambridge, in 1942, where he was involved with microwaves and mechanical engineering in the Radiation Laboratory and then in the Research Laboratory of Electronics. In 1961, he joined the Radio Astronomy Group, and continued with them until 1988. In 1989, he joined the Submillimeter Receiver Laboratory, Harvard-Smithsonian Center of Astrophysics, Cambridge, MA, where he is involved in the development of receivers in the submillimeter-wavelength range.

Todd R. Hunter received the B.S. degree in astronomy from Pennsylvania State University, University Park, in 1991, and the Ph.D. degree in astronomy from the California Institute of Technology, Pasadena, in 1996. For his dissertation research, he helped to design and construct the first facility bolometer array camera for the Caltech Submillimeter Observatory on Mauna Kea.

Since October 1996, he has been with the Submillimeter Receiver Laboratory, Smithsonian Astrophysical Observatory, Cambridge, MA. His current interests include high-frequency LO and receiver control, submillimeter interferometry, and the multiwavelength study of massive protostars.

Scott N. Paine (M'92) received the B.S. degree in applied physics from the California Institute of Technology, Pasadena, in 1984, and the Ph.D. degree in atomic physics from the Massachusetts Institute of Technology, Cambridge, in 1992.

Since August 1992, he has been with the Submillimeter Receiver Laboratory, Smithsonian Astrophysical Observatory, Cambridge, MA. His current interests include millimeter- and submillimeter-wave techniques and numerical methods for optical beam propagation and diffraction.

Ferdinand Patt joined the Receiver Laboratory, Institut de Radio Astronomie Millimétrique, Grenoble, France, in 1980, where he was involved with receiver electronics, down converters, and phase-lock systems for LO's for the 30-m radio telescope in Granada, Spain, and the Plateau de Bure Interferometer, near Grenoble, France. From 1990 to 1992, he was with ILL Grenoble, Grenoble, France, where he was involved with a 1600-channel neutron detector. In 1992, he joined MPIfR Bonn, Bonn, Germany, as a Cryogenic Microwave Engineer for the Submillimeter Telescope Observatory (SMTO), Tucson, AZ, where he is responsible for the installation and testing of facility and PI instruments at the SMTO and for the development of a new-generation multichannel closed-cycle receiver for the telescope.

Gregory Gol'tsman, photograph and biography not available at time of publication.

Sergei Cherednichenko, photograph and biography not available at time of publication.

Boris Voronov, photograph and biography not available at time of publication.

Eugene Gershenzon, photograph and biography not available at time of publication.