Terahertz-frequency waveguide NbN hot-electron bolometer mixer

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Abstract—**We have developed a low-noise waveguide heterodyne receiver for operation near 1 THz using phonon-cooled NbN hot-electron bolometers. The mixer elements are submicron-sized microbridges of 4 nm-thick NbN film fabricated on a quartz substrate. Operating at a bath temperature of 4.2 K, the double-sideband receiver noise temperature is 760 K at 1.02 THz and 1100 K at 1.26 THz. The local oscillator is provided by solid-state sources, and power measured at the source is less than 1 μW. The intermediate frequency bandwidth exceeds 2 GHz. The receiver was used to make the first ground-based heterodyne detection of a celestial spectroscopic line above 1 THz.**

Index Terms—**Superconducting receiver, Hot-electron bolometer mixer, Terahertz techniques.**

I. INTRODUCTION

ABOVE about 1 THz, low temperature superconductor-based hot-electron bolometers offer the best sensitivity of any technology for the coherent detection of radiation [1–3]. In applications such as radio astronomy where the prime goal is to detect very weak celestial signals, there is high demand to integrate this technology into practical receiver systems. Anticipating their arrival, the ESA/NASA Far-infrared and Submillimeter Telescope (FIRST) mission and the NASA Stratospheric Observatory for Far-infrared Astronomy (SOFIA) had adopted superconductive HEB mixers as the technology for the heterodyne instruments operating in the highest frequency bands well before any real systems were tested on a telescope.

In 1998 we built a superconductive HEB receiver to cover the 350 μm atmospheric window and successfully used it on the 10-m Heinrich Hertz Telescope (HHT) on Mt. Graham, AZ to conduct astronomical observations [4]. This receiver was the first of its kind ever deployed in the field and used outside the laboratory environment. The test receiver was upgraded and installed the following year as a facility instrument [5]. Long term use of this receiver over the course of 2 observing seasons uncovered no serious problems with the mixer. The receiver was generally robust and stable enough to allow long integration on weak sources.

Since then, we have extended the frequency of operation of our receivers up to 1.26 THz by scaling the lower frequency mixers [6]. Our approach differs from those of other workers, who have mainly used quasioptical techniques to couple the radiation to the mixer [1–3]. We have instead continued to use waveguide technology. To prove that the THz receiver works as a practical instrument, we took it to the telescope and used it to detect celestial emission lines near 1.037 THz. This frequency is well above the range where superconductor-insulator-superconductor (SIS) mixers have operated in the field

II. INSTRUMENTATION

The receiver employs a phonon-cooled hot-electron bolometer mixer [7] in a waveguide mount. The bolometer is made from thin-film NbN, which is reactively sputtered on a single-crystal quartz substrate to a thickness of about 4 nm. The film has a normal-state sheet resistance of approximately 1000 Ω per square. The active area of the bolometer is defined by electron-beam lithography to form a microbridge 0.2 μm long by 2 μm wide. These dimensions are chosen so that the bolometer couples well to the waveguide circuit, and also to ensure that the power from the solid-state local-oscillator sources is sufficient to optimally pump the mixer. The ends are contacted by TiAu metallization, which provides electrical contact to the mixer circuitry. The completed mixer has a critical temperature, T_c, of about 9 K, with a transition width of 0.5 K. The wafer is lapped and polished to a thickness of 23 μm, and then cut into individual chips that measure 90 μm wide and 1.4 mm long. The −3 dB gain bandwidth of these mixers is about 2 GHz.

The mixer assembly is essentially a scaled version of the fixed-tuned SIS mixer designed for the Submillimeter Array of the Smithsonian Astrophysical Observatory [8]. The first of two sections carries the corrugated feed, and the second a shorted section of waveguide. The chip is clamped between the two pieces so that it is suspended across the waveguide. The waveguide embedding circuit provides a real impedance in the range from 35 to 100 Ω, depending on the reactance of the RF filter.

The schematic of the optical layout of the receiver is shown in Fig. 1. The mixer assembly is bolted to the cold-plate of a liquid-helium cooled cryostat vessel. The beam from the feedhorn illuminates an off-axis parabolic mirror and passes through several layers of porous Teflon at 4.2 K. The beam then passes through additional infrared filtering on the 77 K

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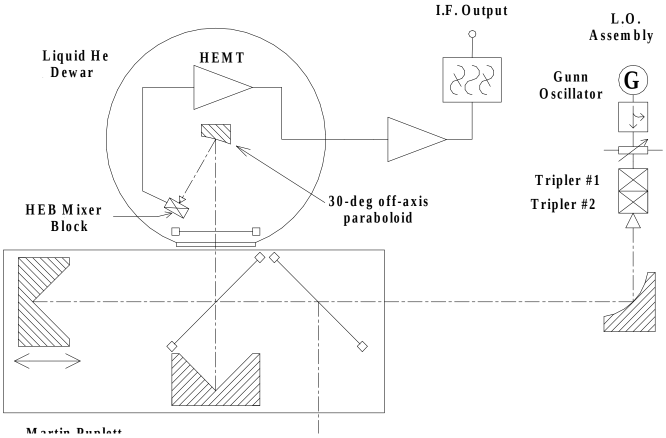

Fig. 1. The optical layout of the receiver. Enclosed in the circle are the components in the vacuum cryostat, including the mixer block, off-axis parabolic mirror and the first-stage IF amplifier. The LO and signal beams are combined in a polarizing diplexer.

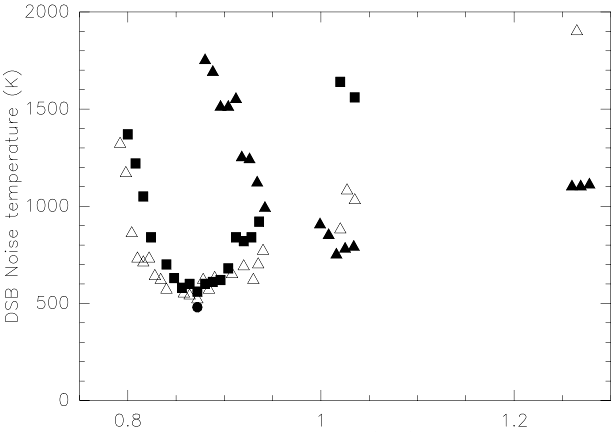

Fig. 2. Noise performance of three mixers as a function of LO frequency. The data shown in solid black squares were taken with the receiver taken to the telescope, and the black circle is a noise measurement made using a beam splitter instead of the diplexer.

radiation shield and exits the cryostat through a 0.5-mm-thick Teflon sheet vacuum window. The LO is provided by 4 solid-state sources, which are comprised of a Gunn oscillator followed by 2 stages of varactor multipliers. These 4 units cover the following frequency ranges: 0.78-0.84 THz, 0.84-0.96 THz, 0.99-1.05 THz, and 1.26-1.28 THz. The first 3 sources provide a minimum of 10 μW of output power across the operating band. The power from the 1.26 THz source is about 2.5 μW. The LO is combined with the signal radiation in a polarizing interferometer. The polarizers are made from free-standing wire-grids and are highly efficient up to several THz. The total insertion loss from the diplexer is estimated to be about 1 dB near 1 THz. Even at 1.26 THz, we were able to pump the mixer with power to spare.

The first-stage intermediate frequency (IF) amplification is provided by a low-noise high-electron mobility transistor amplifier, which is mounted on the same 4.2 K cold plate as the mixer block. The IF amplifier has 38 dB of gain with an average input noise temperature of 5 K from 1.25 to 2.45 GHz. The IF is then further amplified and filtered before detection. For laboratory noise temperature measurements, we use an IF center frequency of 1.5 GHz with 200 MHz bandwidth.

The noise performance of the receiver was measured using the standard Y-factor method, by terminating the input of the receiver with a room temperature load and a load submerged in liquid nitrogen (77 K). Fig. 2 shows the noise temperature as a function of frequency of 3 mixers. The best noise temperatures are 480 K (double sideband) at 0.87 THz, 760 K at 1.035 THz and 1100 K at 1.26 THz.

III. ASTRONOMICAL RECEIVER

The mixer used in the astronomical receiver has a room temperature resistance of 350 Ω and a critical current of 85 μA. The mixer block is a hybrid assembly composed of a front-section carrying a horn designed for operation near 850 GHz terminating in a section of reduced-height waveguide measuring 254 × 64 μm, and a back-piece with a 200 × 50 μm waveguide stamped to a depth of 60 μm. This hybrid configuration was chosen to center the receiver's response near 850 GHz, because the receiver was mainly to be used for observations near 800 GHz. The IF center frequency is 1.8 GHz with 1 GHz bandwith.

The current-voltage characteristics of the mixer is shown in Fig. 3, along with the IF output power in response to the input terminated by a hot and cold calibration loads. At an LO setting of 1.037 THz, the receiver noise temperature was 1600 K. The noise performance of the receiver is plotted against frequency in Fig. 2. The mixer does not appear to be measurably affected by direct-detection or output saturation. At the optimal operating bias point, the mixer bias current changed by 0.3 % when switching from an ambient temperature to 77 K loads. This introduces a calibration uncertainty on the level of a few percent. With regard to output saturation, we have previously estimated that for similar mixers, the 1 dB gain compression occurs when the input load temperature is ~10^4 K. When the receiver was operational on the telescope, the receiver IF output power fluctuated by less than 0.5% over about 1 minute.

The THz observations took place 6 Jan 2000, when the sky opacity as measured by a 225 GHz tipping radiometer, fell below 0.04. The atmospheric transmission at zenith at 1.035 THz was approximately 3%. Towards the source we observed, the Orion Molecular Cloud, the transmission was ~1%. The single-sideband system noise temperature (referred above the atmosphere) was about 400,000 K. However, we were able to clearly detect an emission spectrum from carbon monoxide, which is displayed in Fig. 4, with less than 8 minutes of integration time.

IV. SUMMARY

We have developed a low-noise waveguide phonon-cooled HEB mixer receiver for terahertz frequencies, and have used it to successfully detect a spectroscopic line from a celestial source above 1 THz. We expect in the future to scale the mixer to even higher frequency, as waveguide mounts have

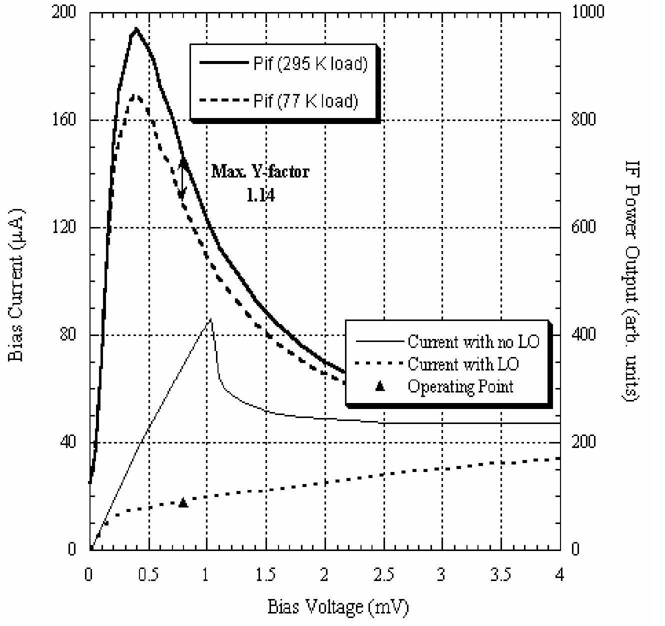

Fig. 3. The current-voltage characteristics of the mixer in the astronomical receiver. The bath temperature is 4.2 K and the LO frequency is 1.035 THz. The figure shows the IV curves with optimal LO power and no LO power applied. The operating point is indicated by a solid triangle, and at this bias position, a Y-factor of 1.14 is recorded, corresponding to a receiver noise temperature of 1600 K.

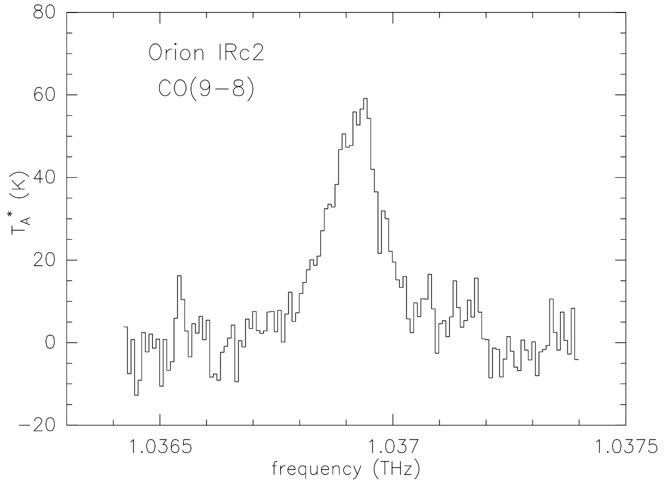

Fig. 4. Spectrum of carbon monoxide in the Orion nebula. The LO was set at a frequency of 1.0352 THz, to place the line in the upper sideband. The temperature scale is calibrated against an ambient temperature load. The data has been smoothed to a frequency resolution of 8 MHz. Note that the IF bandwidth is a full 1 GHz wide.

already been produced for use up to 2.5 THz [9,10].

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