# APEX Band T2: A 1.25 – 1.39 THz Waveguide Balanced HEB Receiver

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***Abstract*— A waveguide 1.25–1.39 THz Hot Electron Bolometer (HEB) balanced receiver was successfully developed, characterized and installed at the Atacama Pathfinder EXperiment (APEX) telescope. The receiver employs a quadrature balanced scheme using a waveguide 90-degree 3 dB RF hybrid, HEB mixers and a 180-degree IF hybrid. The HEB mixers are based on ultrathin NbN film deposited on crystalline quartz with a MgO buffer layer. Integrated into the multi-channel APEX facility receiver (SHeFI), the results presented here demonstrate exceptional performance; a receiver noise temperature of 1000 K measured at the telescope at the center of the receiver IF band 2-4 GHz, and at an LO frequency of 1294 GHz. Stability of the receiver is fully in line with the SIS mixer bands of the SHeFI, and gives a spectroscopic Allan time of more than 200 s with a noise bandwidth of 1 MHz.**

## I. Introduction

According to recent atmospheric measurements, three windows between 1 and 2 THz center at 1.03 THz, 1.32 THz and 1.5 THz and could be available for ground based observations when an appropriate site is used [1]. The Atacama Pathfinder EXperiment (APEX) telescope is a 12 meter single dish located at Chajnantor Plato, in Northern Chile and offers one of the best opportunities for Terahertz observations from the ground. The telescope is equipped with heterodyne and bolometric receivers for radio astronomical observations in the 211 – 1500 GHz frequency range [2]. The multi-channel Swedish Heterodyne Facility Instrument (SHeFI) was installed at the telescope during March 2008 [3]. Being a part of SHeFI, the balanced waveguide THz receiver covers the frequency band from 1.25 THz to 1.39 THz. The atmospheric window centered at 1.32 THz is especially important because the Hershel Satellite Observatory [4] has no instruments covering this frequency range.

In the case of a single-end mixer, that is widely used in radio-astronomy instruments, the local oscillator (LO) injection is often established by using a diplexer, a beam-splitter made of a thin dielectric or a wire grid. A THz LO source [5] used for this project, provides 5-9 μW of power over the RF band. Therefore, the above described LO injection schemes, for this weak LO source, could contribute substantially to the receiver noise by adding insertion loss to the RF signal path. Moreover, thermal noise injected into the receiver input along with the LO will degrade the receiver noise performance noticeably [6]. Additionally, amplitude modulation of the LO power, introduced by microphonic and mechanical fluctuations of the beam-splitter [7], would lead to instability of the mixer output power.

The balanced mixer technique helps to improve on these issues. Balanced mixers offer suppression of LO AM noise, reject LO spurious signal, and allow better handling of the available LO power [6, 8]. On the other hand, a more complex layout of the balanced mixer and high operating frequencies above 1 THz, introduce significant challenges for manufacturing receiver components, and makes development more demanding.

Previously, a number of balanced mixer designs have been reported for different frequencies, such as 90 GHz [9], 530 GHz [10], 280-420 GHz [11]. However, to our knowledge, no balanced mixer has been proposed or implemented for frequencies above 1 THz.

In this paper, we describe the APEX Band T2 waveguide balanced HEB receiver covering 1.250-1.390 THz, which has been developed, characterized and successfully installed at the telescope. Further details, including the description of the receiver design, characterisation and first-light "on sky" results, are presented in [12].

## II. Receiver Design

A quadrature balanced receiver layout is shown in Fig.1. The signal from the telescope and LO are coupled to the individual HEB mixers by a 3 dB quadrature waveguide hybrid. In comparison to an earlier receiver prototype design [13], a 180° commercial IF hybrid is placed after the HEB mixers and combines the mixers' IF outputs. The IF signal appears at the difference-port of the hybrid (Δ), and then is amplified by two cryogenic 2-4 GHz IF low noise amplifiers (LNA) connected in series. The IF hybrid, positioned before the LNAs, contributes additional noise caused by an insertion loss of about 0.5 dB. Alternatively, two IF amplifiers may be used before the IF hybrid, but then possible amplitude and phase imbalances, introduced via unavoidable differences

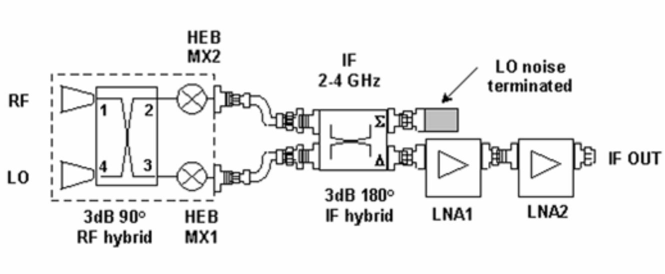


Fig. 1. Layout of the waveguide balanced HEB mixer.

between LNA gains, may lead to a receiver imbalance and deterioration of the noise temperature and stability. The amplitude component of the sideband LO noise is collected at the sum-port (Σ) of the IF hybrid and terminated by a 50 Ohm load. Both LNAs were designed at GARD and achieve input return losses better than 15 dB [14]. As such, a circulator may be avoided between the IF hybrid output and LNA1, which improves the IF system noise temperature. Noise temperature of the LNAs were measured to be about 5 K with a gain of about 27 dB over the entire IF band.

One of the key components of the receiver, the input waveguide 3 dB RF hybrid, distributes the LO and RF signal (ports 1 and 4, in Fig.1) between the two HEB mixers with 90° phase shift (ports 2 and 3, in Fig.1). The hybrid consists of two parallel waveguides with dimensions of 90 μm x 180 μm coupled through 6 branch waveguides between the broad walls [13, 12]. Optimized branch height and length are as small as 21 μm and 50 μm at minimum. In order to ensure the required amplitude and phase balance, the hybrid has to be fabricated with a linear error less than 2 μm. For fabrication of the hybrid we employed photolithography of a thick photoresist combined with fine electroplating described in detail in [15, 16].

Superconducting HEB mixers are based on 4-5 nm thick NbN deposited on a pre-heated substrate by reactive magnetron sputtering. The NbN film was deposited on top of a 200 nm thick MgO buffer layer placed on a 150 μm thick crystalline quartz substrate. The film is patterned using both optical and e-beam lithography to form the bolometer elements of 0.1-0.12 μm long and 1-1.2 μm wide [17]. Such a small volume of the bolometer was chosen due to the low available LO power. The typical critical temperature is about 10.5 K with a transition width of 0.6-0.7 K, which is expectably lower than that of bulk NbN. After fabrication, most of them were DC tested and then lapped down to a thickness of 17 μm and diced into the individual substrates (70 μm x 1000 μm). The measured room temperature resistance was within a range of 50-80 Ω. Critical current values varied from 150 μA to 250 μA at a 4.2 K bath temperature.

Each HEB mixer was integrated with an RF probe, a choke structure employing a hammer layout, and DC and IF leads. Both substrates fit into a suspended microstrip channel across the broad wall of a full height waveguide (180 μm x 90 μm) inside a copper mixer block with a fixed 70 μm backshort (see inset of Fig.2). The substrate channels are also fabricated using a micro-machining technique developed at GARD [16]. A SEM image of the micro-channel is shown in Fig.2 (inset).

In the probe design, the input RF signal coming from the waveguide port is coupled to the HEB mixer by an E-probe, and is isolated from the DC bias/IF output port using an RF choke [18] (inset Fig. 2). The small thickness of quartz substrate was chosen to prevent a waveguide mode propagation towards the IF port. Since the RF impedance of HEB mixers is practically real at frequencies above 1 THz (when the quantum energy exceeds double the gap energy, $h\nu > 2\Delta$), no addition matching circuitry is needed.

Initially, we had three designs of the RF probe providing different embedding impedances to the HEB elements of about 55 Ω, 70 Ω, and 90 Ω within the receiver frequency band. For the present work we have used mixer elements with $R_N$ values of about 65 Ω, therefore we used the 70 Ω RF probe design that was closest to the obtained $R_N$. Thus, we could expect optimal noise temperature of the mixers [19]. Critical current values of the mixers for this receiver were 190 μA and 235 μA.

The mixer assembly design is shown in Fig.2 and consists of two main sections. In the front section, two corrugated feed horns and the RF hybrid are housed. The RF hybrid was produced using a split-block technique and so the two parts should be well aligned. The RF hybrid alignment is illustrated within the inset of Fig. 2 showing a picture of the two RF hybrid waveguide outputs. The other part carries the back-pieces, with integrated IF / DC circuitries fabricated on alumina substrates. Another inset,

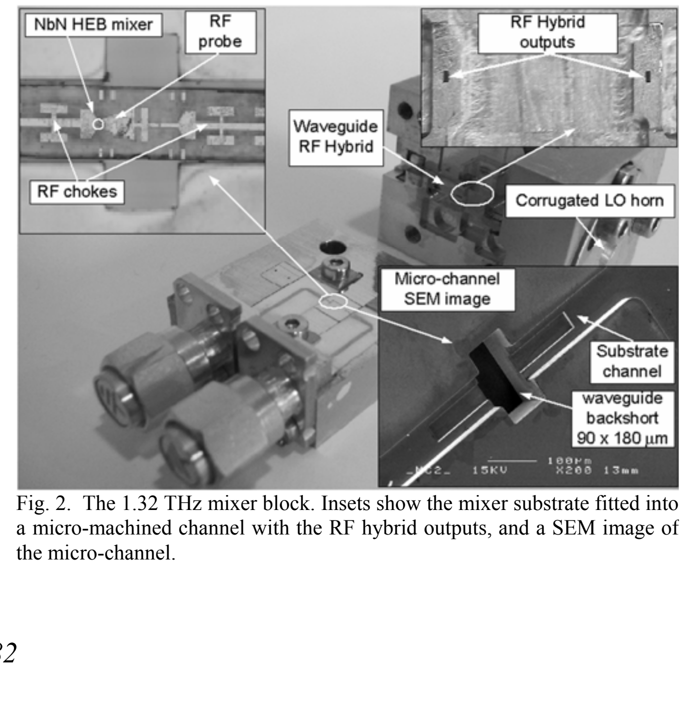


Fig. 2. The 1.32 THz mixer block. Insets show the mixer substrate fitted into a micro-machined channel with the RF hybrid outputs, and a SEM image of the micro-channel.

Fig. 2, shows the HEB mixer substrate aligned in the waveguide back-piece.

The mixer assembly is connected to the IF hybrid via standard bias-tees and short phase-matched coaxial cables. These components, along with LNA1 (Fig.1), are mounted on a sub-assembly plate, which is then fixed to the 4 K cold plate of the closed-cycle cryocooler. The second LNA (Fig. 1), providing further amplification of the IF signal, is mounted on the 12 K stage.

All IF signals of SHeFI are required to be centered at 6 GHz. The three SIS mixer channels have an IF band of 4-8 GHz. In APEX T2 the IF band is 2-4 GHz and this band is up-converted to 7-5 GHz.

## III. Receiver characterization

To measure double-side band (DSB) noise temperature we used the standard Y-factor technique. Room-temperature and liquid nitrogen cooled loads were alternately placed at the signal window. We determined the optimum low-noise operation point for both mixers experimentally by measuring the receiver noise temperature as a function of LO power and mixer bias voltage. The DC bias of the HEB mixers, for best noise performances, is around 0.9 mV.

In Fig. 3 the DSB receiver noise temperature measurements are displayed as a function of LO frequency. These measurements were taken at the APEX telescope site using a spectrum analyzer in the $6 \pm 0.1$ GHz IF range. Note that due to a lower atmospheric pressure temperature the hot and cold loads were 287 K and 73 K, respectively. The receiver noise temperature has a slope of about 200-250 K across the receiver IF band. Fig. 4 demonstrates the receiver noise temperature as a function of IF frequency. Results were obtained at an LO frequency of 1.270 THz (black curve with circles), 1.316 THz (gray curve with diamonds), and 1.370 THz (light gray curve with squares). Note, that the curves are flipped in IF due to the up-converter.As the input alternated between hot and cold loads, we observed less than a 1% change in the HEB mixer DC current. Therefore, the direct detection effect was considered negligible. This can be attributed to the waveguide mixer configuration providing a built-in restriction of the input RF band.

The stability of the receiver is crucial during astronomical observations when the signal is deeply embedded in the noise and long integration time is needed to provide sufficient a signal-to-noise ratio. The closed-cycle cryocooler used in the SHeFI dewar introduces an additional source of instability. Since HEB mixers are based on the hot electron effect, its frequency conversion mechanism is strongly coupled to the ambient temperature of the HEB [20]. Consequently, the temperature instabilities of the closed-cycle cryocooler may cause gain fluctuations of the HEB receiver.

Different methods may be used to minimize these temperature instabilities. For instance, in [21], compensation of instability caused by physical temperature variations has been achieved by a sophisticated regulation of the IF LNA gain. For the APEX T2 receiver we have implemented an active temperature stabilization of the mixer assembly, using a commercial solution [22] with resistive heaters installed onto the mixer assemblies. Our measurements in the laboratory have shown that physical temperature variations at the THz balanced mixer do not exceed 1 mK.

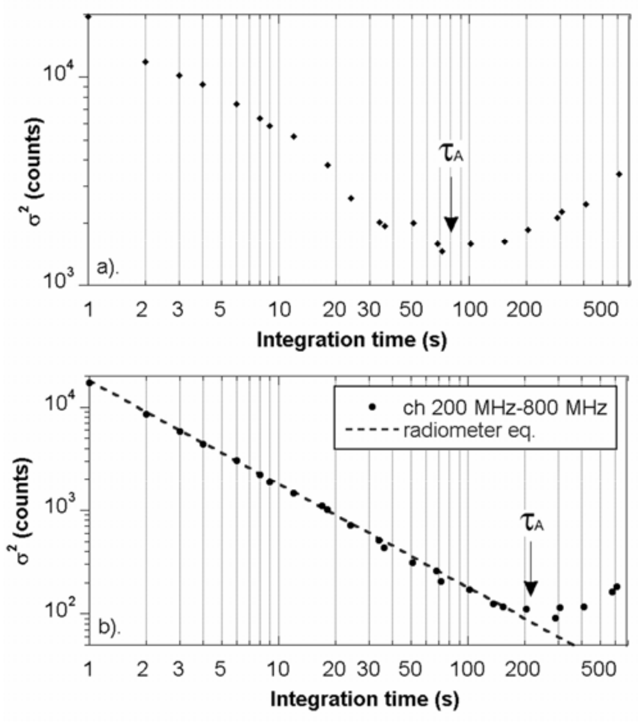


Fig. 5. a). Normalized total power Allan variance, for an RF of 1382 GHz and measured in the APEX telescope using the 200 MHz FFTS channel. The noise bandwidth is 1 MHz. b). Spectroscopic Allan variance measured by subtracting the 200 and 800 MHz channels. The dotted line shows the theoretical time dependence of Allan variance according to the radiometer equation.

A standard method to characterize receiver stability is to perform measurements of Allan variance [23]. Allan variances were measured on the APEX site for different RF frequencies. The measurements were done with the APEX facility Fourier transform spectrometer (FFTS) providing two, 1 GHz channels with a channel resolution of down to 61 kHz [24]. The input window was covered by an absorber at room temperature (287 K). The FFTS recorded 10 values across the IF band, spaced by 100 MHz and with each channel having a bandwidth of 1 MHz. Output power was sampled with 1 s rate. Stability measurements were performed using the 200 MHz and 800 MHz FFTS channels. The normalized total power Allan variance for 200 MHz FTTS channel taken at RF frequency of 1382 GHz (CO J–12→11 line) is shown in Fig. 5a. The mixers were optimally biased and pumped for low-noise operation. In Fig. 5b the spectroscopic Allan variance, calculated by subtracting those FTTS channels, is shown. The dotted line represents the radiometer equation (i.e., pure white noise). The total power and spectroscopic Allan time, $\tau_A$, are about 80 s and 200 s, respectively. Stability measurements performed at an RF frequency of 1267 GHz (CO J–11→10 line), demonstrated more than 35 s and 150 s, in the case of total power and spectroscopic Allan variance, respectively. Note that the results are fully consistent with stability measurements performed at GARD using another FFTS back-end [12].

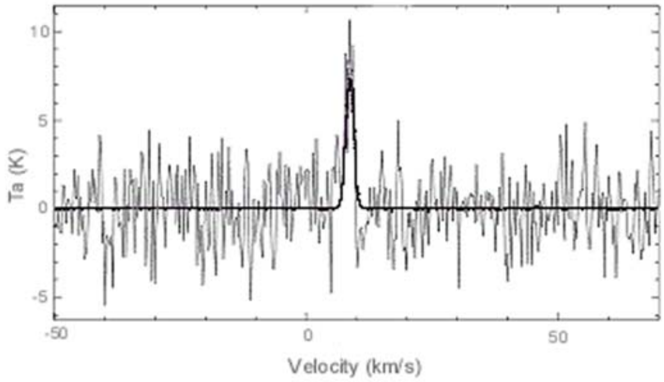


Fig. 6. "First light" APEX T2 receiver detection of the transition line J–11→10 of CO in the ORION-FIR4 star OMC.

After normalizing these measured values according to bandwidth, these times are larger than previously reported for small volume HEB mixers [7, 25] indicating excellent stability of the APEX T2 receiver. Moreover, we observe from the Allan variance plot that at integration times longer than $\tau_A$, drift noise (positive slope) is clearly seen, and $1/f$ noise (the plateau around the minimum) does not dominate. The measured stability of the APEX T2 HEB mixer is fully comparable with the stability of the SIS mixers used for other SHeFI bands.

For best performance, the receiver input beam should be well-matched to the antenna beam and properly aligned with respect to the receiver mechanical reference. In order to verify the APEX T2 beam and its alignment, we have performed measurements of the input beam using scalar beam measurements. Several transverse planes along the signal path were scanned. The input beam parameters were obtained by a 3D fit of the fundamental Gaussian beam to all measured data under the assumption that the beam axis was defined by the amplitude maxima of the performed scans [26].

The SHeFI instrument was installed at the APEX telescope from late February to the beginning of March, 2008. Measurements on sky can only be performed during the best weather conditions at the APEX site, with a precipitable water vapour (PWV) lower than 0.2 mm (something that happens only 10-20 nights per year). During April 2008, we had only 3 such nights; Fig. 6 shows APEX T2 "first light" detected spectrum of the transition J–11→10 of CO (1.267 GHz) in the ORION-FIR4 source from the Orion Molecular Cloud (OMC). The line looks weaker and narrower than expected due to not optimized pointing to the source [27].

## CONCLUSION

We have designed, built and characterized the first 1.25-1.39 THz balanced waveguide HEB receiver and have successfully commissioned it at the APEX telescope. The receiver IF band is 2-4 GHz and the minimum receiver noise temperature is 1000 K (across 1270-1295 GHz) measured in the APEX telescope at the center of the IF band. The APEX T2 HEB receiver demonstrates outstanding stability, presumably better than ever reported for HEB based receivers. Furthermore, the APEX T2 receiver stability is fully in-line with the other SHeFI bands based on SIS mixers. We believe that these improvements have been achieved by using the waveguide balance design, reducing the effects of the LO instability and eliminating receiver degradation due to the direct detection effects. The receiver performance has been confirmed by the detection of the CO J–11→10 line in the ORION-FIR4 star OMC. The APEX T2 receiver offers a great opportunity for ground-based THz observations.

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