Deployment of *TREND* - A Low-Noise Receiver User Instrument at 1.25 THz to 1.5 THz for AST/RO at the South Pole

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ABSTRACT - We have developed and constructed a low noise receiver user instrument based on HEB technology, *TREND* (*Terahertz REceiver with NbN HEB Device).* The plan was to install *TREND* on the 1.7 meter diameter AST/RO submillimeter wave telescope at the Amundsen/Scott South Pole Station during the austral summer season of 2002/2003. The frequency range of 1.25 THz to 1.5 THz was chosen in order to match the best windows for atmospheric transmission and interstellar spectral lines of special interest. The South Pole Station is the best available site for ground-based THz observations due to the very cold and dry atmosphere over this site.

The *TREND* team is now able to report that this receiver has been installed on schedule and met our goals for its performance. *TREND* is thus ready to perform astronomical observations in the upcoming austral winter season as soon as the weather becomes suitable for THz work. The first spectral lines which will be observed are the CO $J = 11 \rightarrow 10$ line at 1.27 THz and the 1.46 THz line of NII. *TREND* is an NbN Hot Electron Bolometer (HEB) type receiver, and the double sideband noise temperature at 1.27 THz has been measured on the telescope to be 1,200 K. The local oscillator is a CO_2 laser pumped, amplitude stabilized CD_3OH gas laser. The *TREND* receiver will pioneer observations from a ground-based telescope at frequencies well above 1 THz. This is also the first time that a receiver can potentially perform an extensive study of the ubiquitous NII ion, first noted by COBE.

I. INTRODUCTION

A number of significant technological research efforts aimed at the development of terahertz low-noise heterodyne instruments are under way in laboratories around the world. Instruments that will be operational in a few years include the far infrared space telescope (HERSCHEL) and other platforms in the upper atmosphere (SOFIA, balloons). Low-noise receivers based on HEB devices deployed on ground-based telescopes at the best available sites are becoming operational now, however. It has only recently been realized that observations above 1 THz are feasible at such sites. Ground based telescopes can be dedicated to specific tasks for longer periods of time compared with facilities in space. Furthermore, larger diameter telescopes, such as the 8 meter one under construction at the South Pole, will be superior to air and space borne dishes in terms of angular resolution. Presently, the 1.7 meter diameter AST/RO submillimeter wave telescope is operated at the South Pole by the Smithsonian Astrophysical Observatory, and has successfully performed observations up to the 800 GHz (350 μm) window for several years.

NbN HEB THz receivers have been under development at the University of Massachusetts for a few years and are now ready to be used for astronomical observations. *TREND* ("*Terahertz REceiver with NbN Device*") is a low-noise heterodyne receiver for the 1.25 THz to 1.5 THz frequency range. The receiver takes advantage of the atmospheric transmission windows in the above frequency range, as well as the availability of AST/RO.

II. SITE CONSIDERATIONS

The Antarctic Plateau, with an altitude of 2847 meters, is unique among observatory sites for unusually low wind speeds, absence of rain, and an extremely cold and dry atmosphere. The *median* Precipitable Water Vapor (PWV) value is less than 0.3 mm during the austral winter season. Available atmospheric models can be used with the measured amount of PWV to predict the atmospheric transmission in two windows near wavelengths of about 200 μm, occurring from about 1.25 THz to 1.4 THz, and from 1.45 THz to 1.6 THz. Expected *median* transparency at frequencies corresponding to important spectral lines is from 5% to 11%, and on unusually good days may reach values 2 or 3 times higher. Atmospheric transmission measured with an FTS instrument from the South Pole site [2] is shown in FIG. 1. These measurements show good atmospheric transparency and confirm the above model predictions. It is clear that installing a low noise terahertz receiver at the South Pole site is thus well justified.

We have identified two spectral lines, located in the above atmospheric windows, which are of special interest. The first is the NII (singly ionized nitrogen) line, at 1461.3 GHz (205.4 μm), which is the second strongest spectral line overall in a typical galaxy (only CII at 156 μm is stronger). NII

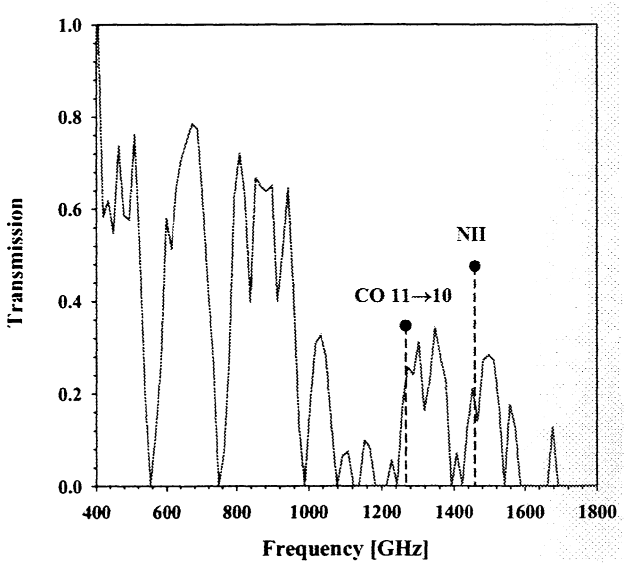


FIG. 1. Atmospheric transmission at the South Pole measured with an FTS [2].

should be ubiquitous in the warm interstellar medium (WIM) of our galaxy. The other line is the J=11→10 line of CO at 1267.014 GHz. It is important to observe higher order CO lines and compare these with the well studied millimeter lines of CO in warmer, denser sources. The locations of the above lines relative to the atmospheric transmission spectrum are marked in FIG. 1.

III. RECEIVER DESIGN

We have chosen the quasi-optical coupling design for our phonon-cooled HEB (PHEB) mixers. Typical state-of-the-art DSB receiver noise temperatures for PHEB receivers measured at about 1.5 THz are in the range of 500-1000 K [1,3]. NbN HEB mixers are also very insensitive to changes in bias conditions and LO power and should be easy to adapt to the observing logistics at AST/RO, where all observations in the austral winter season are performed by one or two "winter-over" operators. Whereas multiplier LO sources are expected to be available in the future, a laser LO was chosen for *TREND*, since it is a mature technology in the terahertz regime and will lend itself well to a future upgrade of the system to incorporate a multi-pixel focal plane array.

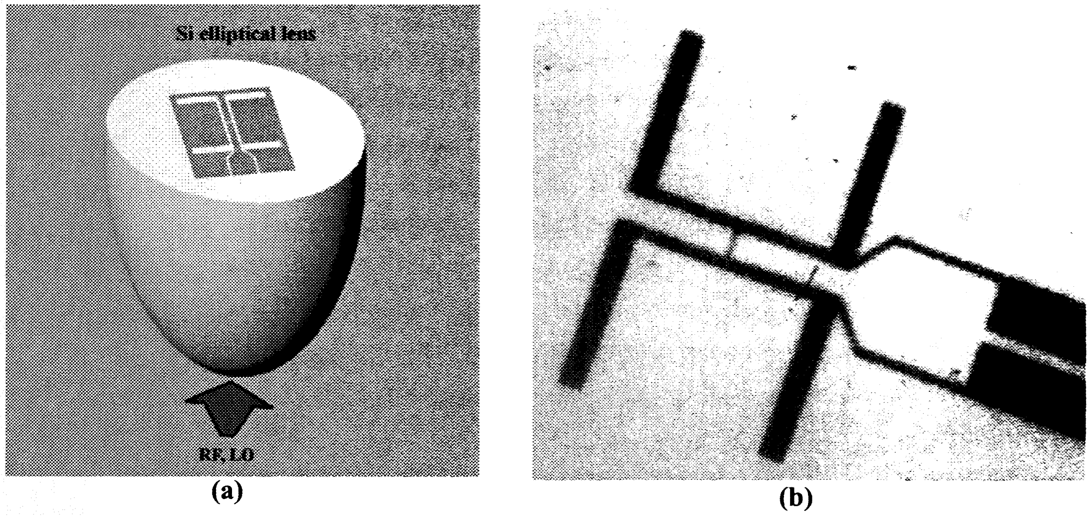
Active Device

Phonon-cooled HEB mixers are typically fabricated from NbN films on either silicon or MgO substrates. The MgO substrate potentially results in a wider IF bandwidth than for NbN on silicon. The IF bandwidth requirement for *TREND* (1 – 2 GHz) can be satisfied by using silicon substrates, however, and our devices for *TREND* were fabricated on this substrate. We have developed devices using (1) UV lithography and (2) e-beam writing. Devices fabricated with UV lithography at UMass/Amherst are 1 µm (length) × 4 µm (width) whereas a set of smaller devices, written with e-beam at Chalmers University of Technology, are 0.4 µm × 4 µm. The 1 µm long devices have somewhat higher resistance (200 – 400 Ω) and recent devices have shown noise temperatures from 1,500 K to 2,000 K. The shorter e-beam devices are better matched to the antenna and have yielded noise temperatures below 1,000 K as discussed below.

Quasi-Optical Coupling

In our NbN HEB development work, we have made use of a quasi-optical coupling scheme consisting of a 4 mm diameter elliptical silicon lens, coupled to a self-complementary toothed log-periodic antenna on a silicon substrate. The optimum polarization direction is frequency-dependent for log-periodic antennas. We have therefore chosen a twin-slot antenna designed for a center frequency of 1.3 THz for the *TREND* receiver, as shown in FIG.2. This antenna is linearly polarized, perpendicular to the slots. The bandwidth of similar twin-slot antenna HEB mixers has been shown to be wider than required for matching the entire 200 µm atmospheric window, about 1.25 to 1.6 THz. Our NbN HEB mixers show no saturation due to thermal noise, and also no direct detection effects.

The beamwidth of the quasi-optical system is primarily determined by the diameter of the elliptical lens and has been measured for an earlier version as reported in [4]. The 3 dB beamwidth of the *TREND* lens/antenna combination was determined to be 3.6 degrees roughly in the center of the band (1.4 THz) by using ring-shaped cut-outs in the hot load while doing Y-factor measurements. The



(a) (b)

FIG.2. (a) A quasi-optical design illustration; (b) A photograph of the twin-slot antenna. The PHEB device in the center is too small to be seen.

beamwidth varies linearly with the wavelength, and the focusing optics for the LO and sky beams on the AST/RO telescope were designed to match the measured beam width of the *TREND* system in the center of the band, see below for further details on the optics.

Laser Local Oscillator

The LO source is a model # SIFIR-50 FPL terahertz gaseous laser system that was designed and built by the Coherent/DEOS company [5]. As other terahertz gas lasers, it is pumped by a CO_2 laser. In the case of the *TREND* laser, the pump laser is sealed, and is expected to be able to operate at least 10,000 hours before it needs to be refilled with gas, a feature which facilitates operation at a remote site. The pump laser is RF excited and thus does not require a high-voltage power supply. Its maximum power output is 50 W on one of the strongest lines. The CO_2 laser is grating tuned through a PZT translator, and is actively frequency locked to one of the resonance frequencies of a high-Q temperature-stabilized Fabry-Perot resonator. The terahertz laser uses a thermally compensated design for amplitude and frequency stability. Its cavity length can be adjusted either by a micrometer or a PZT translator. All of the above components are integrated into a rugged, transportable package, with dimensions of about 185 cm × 50 cm, and height of about 25 cm. The laser system requires liquid cooling. FIG. 3 shows a photograph of the *TREND* laser system while being tested at AST/RO.

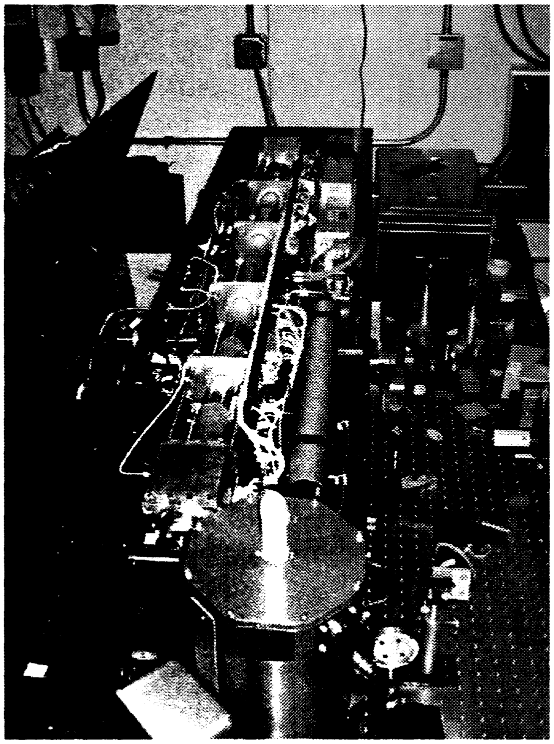


FIG.3. Photograph of the *TREND* laser system with the laser cover off.

It is usually possible to find a terahertz laser line which matches a particular line in the ISM. within the IF bandwidth of typical HEB mixers (about 5 GHz). However, some portions of the terahertz range may not have a strong laser line available. At the present time, the best known laser line sufficiently close to the required frequency of 1461.31 GHz for NII is a line produced by CD_3OH at 1459.3913 GHz (205.423 mm wavelength), which yields a convenient IF of 1.7 GHz. The output power on this line in stable operation is about 1 mW, which is sufficient since we found that less than 10 µW of laser power at the dewar window was needed to pump the mixer to its optimum point. We use a 6 µm thick beam splitter, which reflects about 1 % of the power. The CD_3OH laser line demonstrates some of the constraints on obtaining a laser local oscillator at a specific terahertz frequency. The center of the CO_2 pump laser line (10P36) is offset from the center of the CD_3OH line to be pumped. Since the offset is larger than the free spectral range of the particular pump laser used, the laser cannot be operated at the optimum pump frequency. This results in lower than typical laser gain and thus less output power. There are actually two lines in CD_3OH which are pumped by the same pump line; the second one is located at about 215.8 µm, with the same polarization as the 205.4 µm line. We distinguish between the two lines by using a silicon etalon, which has different attenuation for the two lines. CD_3OH has an additional line (with a different CO_2 pump line) measured to be at 1265.513 GHz. This line matches that of the $J = 11 \rightarrow 10$ transition of CO, with a conveniently low IF of 1.5 GHz.

The *TREND* Laser power is actively stabilized to ±0.01 dB (±0.25 %) over many minutes by a feedback system which senses the DC bias current of the HEB device directly, and applies this signal through an amplifier/filter circuit to the FIR laser PZT translator, thus keeping the operating point very stable. The time-constant of this circuit is about 10 seconds. Additional long term stabilization is achieved by controlling the continuous flow of the gas in the FIR laser using a gas manifold.

Mixer Block and Biasing

We have designed a new mixer block that is compatible with other mixer blocks used at the AST/RO facility. The mixer block contains the lens, the substrate on which the NbN device and the antenna were fabricated, and a circuit board that supplies the DC bias and connects the mixer through a capacitor to the IF amplifier. FIG.4 shows the present configuration of the bias circuit, as well as photographs of the mixer block. The bias scheme utilizes a total of five wires plus ground (three wires plus ground inside the dewar). Chip resistors of about 2 kΩ are placed in series with all leads, while chip capacitors inside the mixer block shunt transients to ground. Furthermore, the DC ground is separate from the mixer block/IF ground. This bias scheme protects the devices and minimizes line and other pickup. The bias electronics was built at the University of Arizona. The IF amplifier is a 1-2 GHz balanced amplifier design, which was originally designed at CalTech and has been used on earlier AST/RO receivers. The noise temperature contribution of the IF chain is about 5 K.

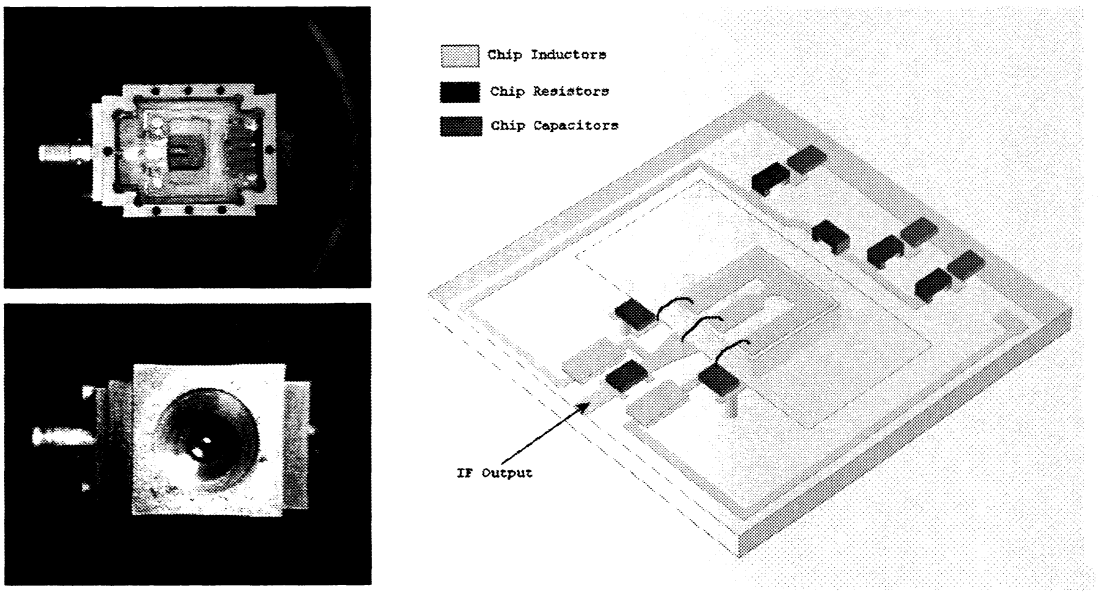
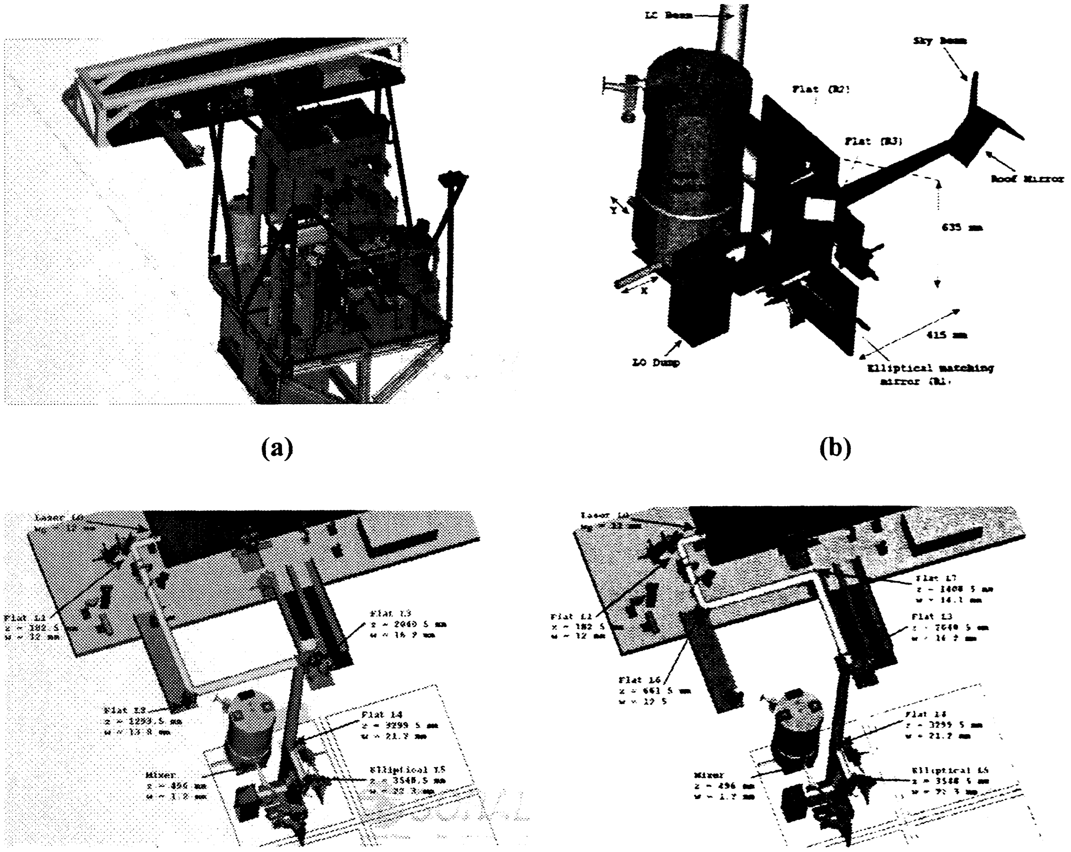


FIG.4. Photographs of the mixer block and a drawing of the bias circuitry.

IV. OPTICAL SYSTEM FOR *TREND* AT AST/RO

The AST/RO telescope has provisions for four different receivers, each occupying a receiver pallet/optical breadboard of size 75 cm × 75 cm. FIG.5 shows the position of the *TREND* receiver on one of these pallets. The laser is located on a separate optical breadboard in the ceiling, together with a HeNe laser for alignment, a pyroelectric detector for power monitoring, and an attenuator/polarizer (two crossed wire grids). The laser beam is guided to the receiver by mirrors L1 through L5. The "sky beam" from the telescope is guided through a hole in the ceiling onto a rooftop mirror system, which is used to select the particular receiver one wants to use for observing. It is then directed to the *TREND* receiver through three further mirrors. A 6 μm thick mylar beam splitter is located in front of the dewar window that allows low-loss transmission of the sky beam, while reflecting only a small fraction of the laser LO beam toward the *TREND* cryostat window. Most of the laser power is dissipated in an LO "beam dump". This flexible arrangement eliminates the need for a diplexer for the LO injection. The *TREND* cryostat is mounted on an x-y translator system for alignment with the two beams. Further alignment degrees of freedom are available by turning the elliptical injection mirrors (L5 and R3, the closest mirrors for the respective beams). We have constructed two optical paths for the LO beam to compensate for the different polarization of the LO beam at the two frequencies of operation (see FIG.5).



(a) (b)

(c) (d)

FIG.5. Optical system for the *TREND* receiver at the AST/RO telescope. (a) 3-D simulations of the receiver room; (b) *TREND* dewar with LO and Sky beams; (c) LO beam configuration for the 205 μm line; (d) LO beam configuration for the 237 μm line.

V. RESULTS AND CONCLUSION

Four mixer blocks with PHEB devices were constructed and transported to AST/RO. The mixer blocks are readily exchangeable and provide redundancy in case a device fails during the winter season. The best noise temperature results measured at UMass with one of the smaller devices are shown in FIG.6. These measurements show that the receiver covers the required tunable bandwidth with about a 30 % variation in receiver noise temperature across the band. The minimum of the noise temperature agrees with the design frequency of the twin-slot antenna, centered at 1.3 THz, and the bandwidth is what is expected for this antenna. The best double sideband total receiver noise temperature

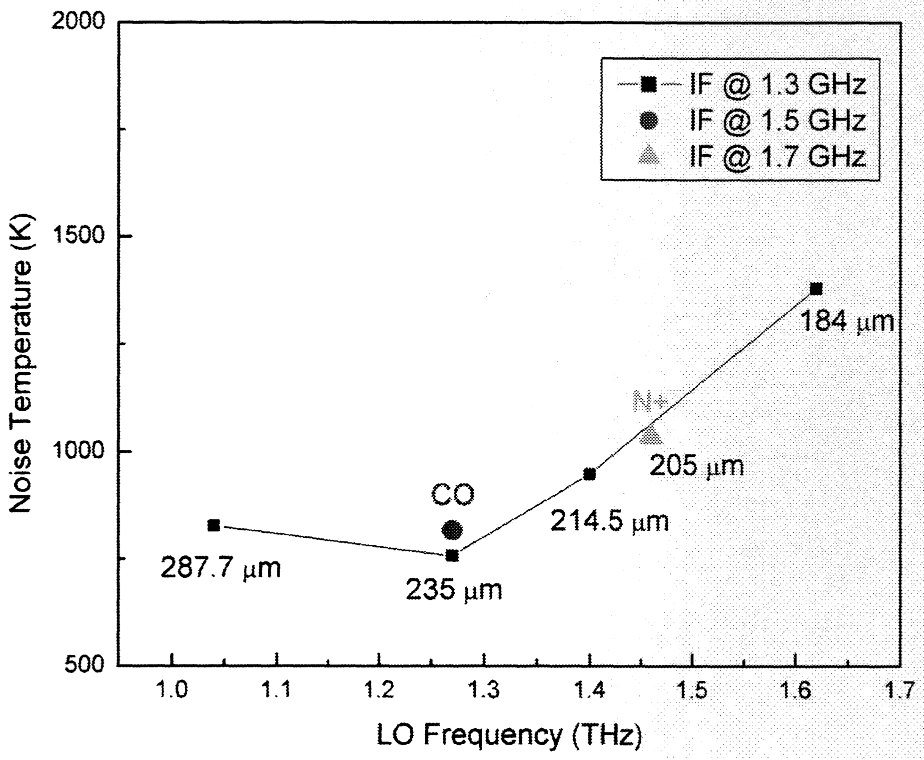


FIG.6. Double sideband receiver noise temperatures at different LO frequencies measured on one of the PHEB devices fabricated by e-beam. The IF was 1.3 GHz. A measured point at the IF for the CO 11→10 line is also plotted. The noise temperature point for the NII line was found by interpolation.

measured on the telescope was 1200 K at the 237 μm line. Other measurements in the laboratory prior to shipping the *TREND* system showed that the noise temperature was essentially unchanged for a 1 dB variation in LO power, when the bias voltage was low (about 0.6 mV). The total noise output power varied by 2.5 dB for the same change in LO power. Such variations do not occur on the telescope system since the LO power is actively stabilized in a way that maintains a constant bias current. We also measured short term fluctuations of the output power and derived the Allen variance from such data. Due to space limitations, we will defer the publication of this data to a future paper.

In conclusion, we have shown that a complex, laser-pumped, HEB receiver system can be transplanted from the laboratory to a fairly remote site and demonstrate similar performance to that measured in the laboratory. The system will now be used for actual observations as the best terahertz weather conditions at the South Pole usually occur during the months of June through August.

ACKNOWLEDGMENTS

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