Upgrade to the *TREND* Laser LO at the South Pole Station

Sigfrid Yngvesson[a], Eyal Gerecht[a], John Nicholson[a], Fernando Rodriguez-Morales[a], Xin Zhao[a], Richard Zannoni[a], Jason Dickinson[b], Thomas Goyette[b], William Gorveatt[b], Jerry Waldman[b], Dathon Gholish[c], Jacob Kooi[d], Christopher Martin[e], and Eric Mueller[f]

[a]University of Massachusetts at Amherst
[b]Submillimeter Wave Technology Laboratory, University of Massachusetts at Lowell
[c]Department of Astronomy and Steward Observatory, University of Arizona
[d]California Institute of Technology
[e]Smithsonian Astrophysical Observatory
[f]Coherent-Deos, Inc.

ABSTRACT

The *TREND* (*Terahertz REceiver with NbN HEB Device*) system was deployed during the austral summer 2002-2003 on the 1.7 meter AST/RO submillimeter telescope. *TREND* is a 1.25 THz to 1.5 THz low noise heterodyne receiver user instrument based on HEB technology [1]. The AST/RO telescope is located at the Amundsen/Scott South Pole Station, which is the best of the presently available sites for ground-based terahertz observations due to the very cold and dry atmosphere over this site. The *TREND* system was operating stably on the CO J = 11→10 line at 1.27 THz after the installation was completed in February, 2003. The DSB receiver noise temperature was typically measured on the telescope to be 1,000K. The local oscillator is a CO_2 laser pumped, CD_3OH gas laser, which allowed many hours of continuous operation without adjustments. During the winter season of 2003 a tentative detection was obtained of the J= 11 → 10 line of CO in NGC6334a, but the laser LO became less stable. The laser did not stabilize sufficiently well at the higher frequency of 1.46 THz, required for the NII line.

During the austral summer of 2003-2004, the entire local oscillator (LO) optical system was redesigned and re-aligned. With the addition of an acousto-optic modulator (AOM) to the CO_2 pump laser system beam path, the CO_2 laser output was frequency shifted by 40 MHz, allowing optimal absorption in the CD_3OH far-infrared (FIR) laser. The improved gas absorption in the FIR laser produces several milliwatts of stable power, more than adequate for use as an HEB LO. The system is now ready for detection of the NII transition. This paper describes this upgrade to the *TREND* laser LO in detail.

1. INTRODUCTION

A number of significant technological research efforts aimed at the development of terahertz low-noise heterodyne instruments are underway 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 or in the upper atmosphere. Furthermore, larger diameter telescopes, such as the 8 meter one under construction at the South Pole, and APEX (12 meters) at the ALMA site, will be superior to air and spaceborne dishes in terms of angular resolution. Several other telescopes are also in various stages of planning.

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. 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. 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 measurements with an FTS instrument from the South Pole site [2] confirm the above model predictions (see Figure 1). It is clear that installing a low noise terahertz receiver at the South Pole site is thus well justified.

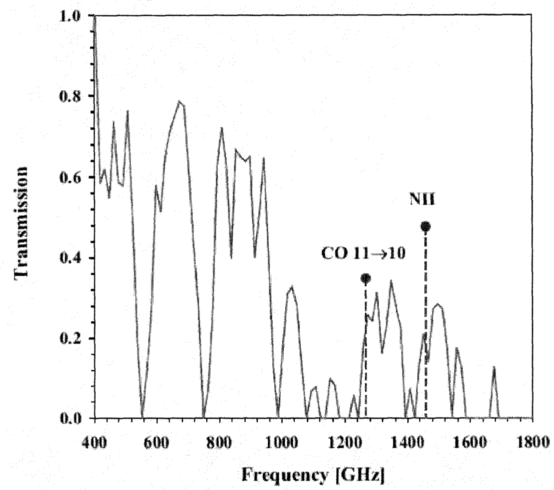

Figure 1. Atmospheric transmission at the South Pole measured with an FTS [2].

NbN HEB THz receivers have been under development at the University of Massachusetts for a few years [3] and are now ready to be used for astronomical observations. *TREND* (*"Terahertz Receiver with NbN Device"*) is a low-noise heterodyne receiver system for the 1.25 THz to 1.5 THz frequency range, which was deployed on AST/RO during the austral summer season of 2002-2003. We identified two spectral lines, located in the above atmospheric windows, which are of special interest (marked in Figure 1). The first is the NII (singly ionized nitrogen) line, at 1461.3 GHz (205.4 μm), which is the second strongest spectral line in a typical galaxy (only CII at 156 μm is stronger). 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 *TREND* system was operating stably on the CO J = 11→10 line at 1.267 THz after the installation was completed in February, 2003. The DSB receiver noise temperature was measured on the telescope to be 1,000K. The local oscillator is a CO_2 laser pumped, CD_3OH gas laser. During the winter season of 2003 a tentative detection was obtained of the J= 11 → 10 line of CO in NGC6334a, shown in Figure 2. The laser LO did not stabilize as well at the higher frequency of 1.46 THz, required for the NII line.

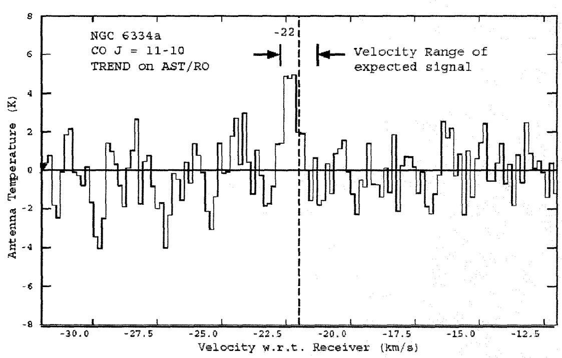

Figure 2. Tentative detection with *TREND* of the J=11→10 line of CO in NGC6334a.

During the austral summer of 2003-2004, we have re-aligned the entire system and re-established stable operation. In addition, we tested a new addition to the CO_2 laser system that allows the laser line required for observing the NII line to be operated stably. In doing this we rely on an innovative solution of shifting the CO_2 laser line to the required frequency for optimum pumping of the CD_3OH molecules in the FIR cell. As a result, the laser line required for NII is now very stable, with a power output of a few mW. This paper describes the upgrade to the *TREND* laser LO in detail.

2. THE *TREND* LASER

The LO source for *TREND* is a model # SIFIR-50 FPL gaseous terahertz laser system that was designed and manufactured by the Coherent/DEOS company [4]. Similar to 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 filled 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. The CO_2 laser is grating tuned, and utilizes a PZT translator, to actively frequency lock the laser frequency 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 laser components are integrated into a rugged, transportable package, with dimensions of about 185 cm by 50 cm by 25 cm. The laser system requires liquid cooling. Figure. 3 shows a photograph of the *TREND* system after installation at AST/RO. The laser was installed on an optical breadboard, which was bolted to the steel-beam structure which supports the telescope as well as the pallets on which all receivers are mounted.

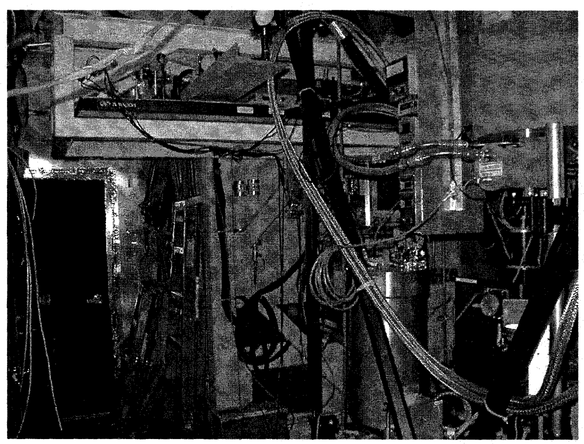

Figure 3. The TREND system as installed at AST/RO in the austral summer 2002-2003.

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 μm wave length), which yields a convenient IF of 1.7 GHz. The output power on this line in stable operation is a few milliwatts, 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 problem is that the center of the CD_3OH line to be pumped is offset from the tunable range of the CO_2 pump laser line (10P36). Available laser line tables did not list a value for the offset, but on initial experimentation with this line, it became clear that there was a rather large offset. Specifically, we found that the offset is larger than the free spectral range of the particular pump laser used, and that the CO_2 laser therefore can not be operated at the optimum pump frequency for CD_3OH. This results in lower than typical laser gain and thus less output power, as well as greater sensitivity to small variations of any parameters effecting the stable operation of the sub-millimeter wave laser. During the first operational season, we therefore concentrated on observing the $J=11\rightarrow10$ CO line.

3. MODIFICATIONS TO THE *TREND* LASER

3.1. Re-alignment of the Fabry-Perot Cavity

Stability problems had also developed during the austral winter for laser line used with the J=11→10 CO line. As members of the *TREND* team revisited the site beginning in November, 2003, the stability problems were diagnosed as being caused by misalignment of the portion of the CO_2 beam which was being fed to the Fabry-Perot used for frequency stabilization. The misalignment caused a decreased signal to noise for the lock-signal and the excitation of additional modes in the FP cavity The overall effect of this was that frequency locking of the CO_2 laser became erratic, and could only be maintained for very short periods. Optical components in the CO_2 beam path were also found to have been damaged, and were cleaned and re-aligned. A new Eltec detector and a revised lock-circuit for the feedback loop were installed. The new lock-circuit was designed to allow more user-friendly and robust operation, which is especially important during the winter season at POLE The modified feedback loop installed in the TREND system consisted of a simple lock-in amplifier arrangement with a variable gain. A 100 Hz sine wave was used to modulate one of the two reflectors of the FP resonator cavity. This modulation traces out the line width of the CO2 radiation passing through the FP cavity. The signal generated by the Eltec detector, accessed through a signal junction and bias circuit installed outside the laser housing, was fed into a lock-in amplifier, using the 100 Hz sine wave as a reference. The signal was also fed into an oscilloscope to provide the visual reference needed for monitoring and locking the laser system. The output of the lock-in amplifier, which represented the derivative of the line shape, was fed into a bias circuit designed to drive the PZT which tunes the cavity length of the CO_2 laser. This circuit consisted of a 0-10 volt bias circuit with a summing amplifier section. The summing amplifier added the output of the lock-in onto the variable bias of the circuit. This circuit also had a variable amplification section, allowing the signal generated in the lock-in to be either removed completely or amplified up to a factor of 100 times. These modifications allowed a more robust feedback loop with a wider frequency band which led to a more stable long term performance out of the CO_2 laser. After these modifications the signal-to-noise from the Fabry-Perot was substantially improved and the frequency-locking of the CO_2 laser was working well.

3.2. Modifications to allow stable operation of the 1.46 THz laser line

We described above that there was a substantial offset between the CO_2 pump laser operating on the 10P36 line, and the optimum pump frequency required to produce the 205.4 μm submillimeter laser line. In order to circumvent this problem we have used an innovative solution, which as far as we are aware has never been employed before. The CO_2 laser was shifted with the help of a commercially available [5] Acousto-Optical Modulator (AOM). This AOM functions as a Bragg diffraction device. The active component is a bar of germanium with anti-reflection coatings for CO_2 laser frequencies. The germanium bar also has an acoustic transducer attached to one end. Application of 40 MHz RF modulation to this transducer sets up an ultrasonic wave in the crystal, which scatters most of the incident laser radiation into the first order diffraction, with approximately 80-90 percent efficiency. The diffraction process sets up conditions that require frequency matching of the incoming radiation, the outgoing radiation and the acoustic wave [6]. As a result, the diffracted CO_2 laser beam experiences a frequency shift equal to the frequency of the RF modulation. The frequency shift can be either positive or negative, depending on the relative orientation of the wave-vectors of the three waves. We used this 40 MHz frequency shift to compensate for the frequency offset between the CO_2 laser pump transition and the center frequency of the CD_3OH absorption envelope. Since the Bragg diffraction process also requires wave vector matching, the diffracted beam will exit a different angle than the incident beam (typically a few degrees). The non-diffracted beam is absorbed by a beam dump. Initial tests of the AOM were performed in the THz Laboratory (UMass/Amherst), using a laser configuration for our laboratory laser very similar to that of the TREND. These experiments confirmed that we could now obtain very stable operation on the 205.4 μm line.

The installation of the AOM in the *TREND* system at the South Pole required substantial modification of the beam path coupling the CO_2 laser into the FIR cell. It was not feasible to accommodate the new optical components within the original laser package, so the CO_2 laser was directed out of the laser housing through an existing sample port, via a new primary mirror. Beam diagnostics were performed on the CO_2 laser consisting of a power measurement, and an inspection of the mode shape of the CO_2 beam. The CO_2 laser required a slight adjustment to the alignment of the diffraction grating. Adjusting the grating for maximum power also decreased a vertical ellipticity of the mode. With power adjustments completed, the CO_2 laser produced approximately 32 Watts and a slightly elliptical mode.

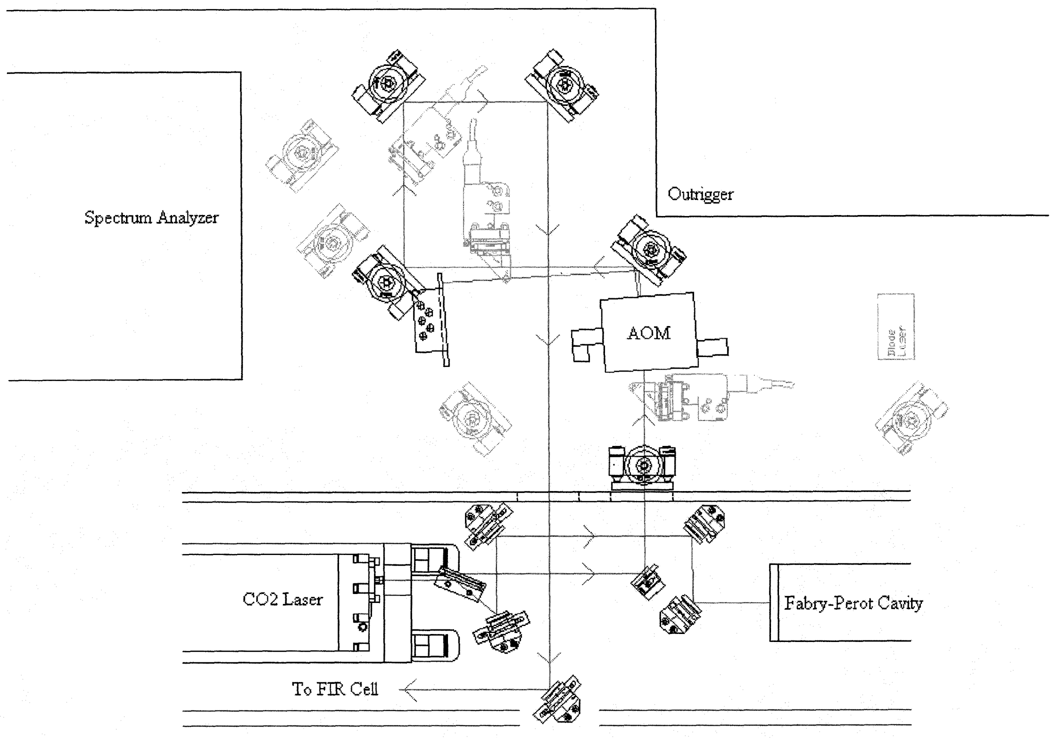

Figure 4. The new beam path and the placement of the AOM.

With the beam directed through the sample port of the laser housing, the remainder of the optics path was established as shown in Figure 4. The original laser housing is in the lower part of the figure. The components outside the housing were placed on the original optical breadboard which supported the laser. The 19.68 inch focal length lens, located just outside the TREND laser enclosure, produced a collimated beam with a waist of 1.6mm, which could then be passed through the AOM. It was essential to collimate the beam at this point to minimize divergence over the total path length, ensure the proper beam waist for the next focusing optic, and to ensure maximum efficiency through the AOM. After the installation of the AOM was completed, we measured a coupling efficiency of 80 percent of the incident power into the first order diffraction. Note the beam dump for the un-shifted CO_2 beam, both beams are indicated after the AOM in Figure 4. The 40 MHz upshift of the CO_2 frequency produced by the AOM causes a skew in the CO_2 laser beam path that is a function of the CO_2 frequency passing through the device. Since future research utilizing the TREND LO might involve pumping FIR laser lines at other frequencies, a bypass path was created around the AOM using two motorized flip mirrors, not shown in figure 4. For both beam paths, the AOM shifted and bypassed, the return beam re-enters the laser housing through a hole drilled in the laser enclosure. This beam was aligned to coincide with the original beam path, and an appropriate new lens was used to focus the CO_2 beam at the input hole of the FIR laser, as shown in the lower part of Figure 4.

In addition to the installation of the AOM, a third motorized flip mirror was integrated into the design for the purpose of directing the full power CO_2 beam into the spectrum analyzer. Previously, the spectrum analyzer could only be activated by directing the FP beam out of the sample port; however, due to the low power of this beam, about 5 mW, the process of changing CO_2 laser lines had been difficult. With access to the full power beam this process has greatly improved. The position of the spectrum analyzer on the optical breadboard can also be seen in Figure 4. The blue beam path indicates how a small portion of the CO_2 beam is reflected from an (intentionally) slightly misaligned Brewster window, and directed to the FP cavity, as described.

To aid in the overall alignment, and possible future modifications to the beam path, a red diode laser was aligned onto the beam path of the CO_2 laser following the AOM. This laser was left as a permanent addition to the system to aid in the realignment of the CO_2 spectrum analyzer should this be necessary. Coupling of this diode laser into the CO_2 beam path required sending the diode laser over the top of the flip mirror closest to the AOM input. Because of the orientation of the diode laser and the nature of the AOM device, it was not possible to follow the beam path of the CO_2 through the AOM, only the path around the AOM could be illuminated. At the third mirror both paths were axially aligned and remain so for the rest of the optics path.

Two photographs in Figure 5 show the completed installation of the AOM and nearby components.

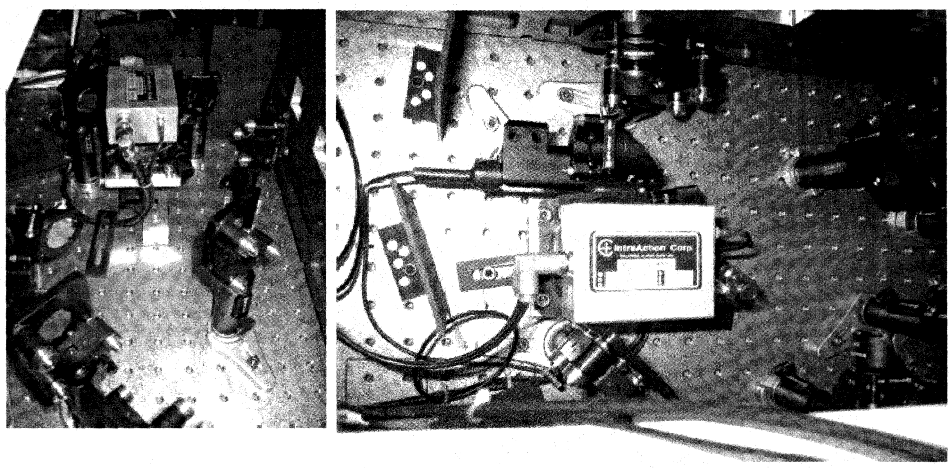

Figure 5. The acousto-optical modulator (AOM) installed into a new optical path of the CO_2 laser.

3.3. Alignment of the CO_2 Beam with the FIR Cell

An alignment telescope was used to project a diode laser along the axis of the FIR laser bore. This procedure allowed for proper orientation of the mirrors in the FIR laser perpendicular to the axis of the cell. In order to align the FIR laser with the CO_2 path, the diode pointer was also oriented to pass out the input coupling hole of the FIR cell. The beam was brought into alignment with the diode laser established along the CO_2 beam path requiring adjustment of the location of the secondary lens and the remaining mirrors.

The FIR laser cell was opened and inspections were made to the input and output resonator coupling mirrors. Minor damage, caused by the CO_2 radiation, was found on the surface of both coupling mirrors. This damage had little effect on the performance of the submillimeter laser lines, however. The damaged 1.5mm hole coupler at the output of the laser was replaced with a new 2mm hole coupler.

The CO_2 laser was tuned to the proper pump line for the 205.4 μm CD_3OH laser line. Bright glowing on the input coupling hole is a typical first point of reference for evaluating the quality of the alignment between the CO_2 and FIR lasers. No glowing of the input coupling hole was observed with the CO_2 traveling down either the AOM shifted or the AOM bypassed beam path. This observation demonstrates that the alignment procedure had been successful. Using a small bolometer, a significant amount of power was measured at the output of the FIR cell. Estimates of the power, based upon the amount of attenuation required by the bolometer, were made. Conservative estimates place the power output at a minimum of 3 mW, more than adequate power for the TREND experiment.

3.4. Other modifications to the TREND system

We installed a modified feedback system for stabilizing the FIR laser output power. This system diverts a small amount of the FIR power via a mylar beam splitter, chops it at a low frequency, and detects it in a liquid helium cooled semiconductor bolometer. The signal from the bolometer is amplified in a lock-in amplifier, compared to a reference level, and fed back to the PZT cavity tuning element of the FIR laser after further amplification and low-pass filtering. In tests on the TREND system before shipment to the South Pole we showed that this type of system can keep the laser power stable within a fraction of a percent. This is important for performing long astronomical observations since the IF output power level from the HEB depends quite strongly on the LO power.

Stabilizing the laser power over even longer times requires maintaining the FIR laser gas at a stable pressure. Since the FIR laser tube inevitably has small vacuum leaks, we designed a system to trickle flow gas into the FIR tube (see Figure 6). The CD_3OH gas is quite expensive, so a system which produces only a small flow is required. The system uses solenoid operated valves and a capillary glass tube to solve this problem.

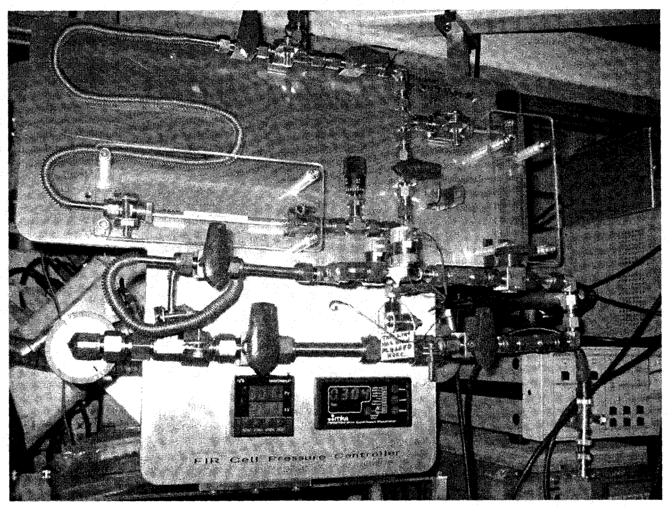

Figure 6. The manifold for creating a trickle flow of CD_3OH gas to the FIR laser tube.

4. CONCLUSIONS

As a result of this year's modifications, the TREND laser

- *was very stable on the 205.4 μm (NII) line; the laser amplitude can be stabilized to a fraction of 1 %*
- *had output power ~ 3 mW*
- *an alternative beam path allows by-passing the AOM for lines which do not require it*
- *system was completely re-aligned. The re-alignment fixed problems which had occurred during the first winter*
- *had a total DSB receiver noise temperature measured through the telescope Acousto-Optic Spectrometer of 1,000 K at 1.46 THz (the NII line)*

We have demonstrated a general method for substantially extending the number of laser lines which can be used for THz LOs. This method should be useful in the future, for example for array receivers for the NII line, and for HEB receivers at higher frequencies. We expect to be able to perform extensive high-resolution observations of NII for the first time from a ground site using the upgraded *TREND* system.

5. ACKNOWLEDGEMENTS

We gratefully acknowledge support for this project from the National Science Foundation, NSF Award Numbers: 0126090; 0350871.

6. REFERENCES

1. E. Gerecht et al., "Deployment of *TREND* - A Low-Noise Receiver User Instrument at 1.25 THz to 1.5 THz for AST/RO at the South Pole", Proc. 14th Intern. Symp. Space THz Technology, Tuscon, Arizona, April, 2003, p. 179-188.

2. Chamberlin R A, Martin B, Martin C, Stark A A, "South Pole Submillimeter Fourier Transform Spectrometer [4855-83]", in Millimeter and Submillimeter Detectors, Proceedings of SPIE (Volume 4855), Kona, Hawaii, 2002),

3. E. Gerecht, C.F. Musante, Y. Zhuang, K.S. Yngvesson, T. Goyette, J. Dickinson, J. Waldman, P.A. Yagoubov, G.N. Gol'tsman, B.M. Voronov, and E.M. Gershenzon, "NbN Hot Electron Bolometric Mixers - A New Technology for Low Noise THz Receivers," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2519-2527, Dec. 1999.

4. Coherent/DEOS, 1280 Blue Hills Ave, Bloomfield, CT 06002.

5. IntraAction Corporation, 3719 Warren Avenue, Bellwood, IL 60104, Model AGM-406B21; power amplifier model PA-4030-8.

6. See for example A. Yariv, "*Quantum Electronics*", Third Edition, John Wiley and Sons (1989), p 329 ff.