# A HETERODYNE DETECTOR FOR TERAHERTZ SPECTROSCOPY OF PLANETS AND COMETS.

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**Introduction:** Gaseous species on comets and in planetary atmospheres have unique spectral fingerprints between 100 GHz and 5 THz. The Microwave Instrument for the Rosetta Orbiter (MIRO)[1] with heterodyne receivers based on Schottky diodes at 188 GHz and 562 GHz, is currently demonstrating the power of high-resolution sub-THz spectroscopy in planetary missions as it records spectra of volatile molecules sublimating from a comet. Both the density and strength of microwave transitions increases with increasing frequency, so high-resolution spectroscopy at frequencies between 1 and 5 THz is even more attractive. High resolution spectroscopy in the 1-5 THz region with a nearly quantum limited heterodyne receiver will greatly improve spectral coverage and sensitivity over existing submillimeter heterodyne receivers designed for planetary space applications. The improved sensitivity will reduce the column abundances needed to detect known spectral lines, and open up the possibility of detecting new molecular species never before detected in space.

We are developing a new class of heterodyne detector called a Tunable Antenna-Coupled Intersubband Terahertz (TACIT) detector.[2] TACIT heterodyne detectors promise nearly quantum-limited noise performance at frequencies above 1 THz using only microwatts of local oscillator (LO) power while operating at temperatures compatible with passive cooling. TACIT detectors are sensitive in a ~100 GHz wide frequency window that can be tuned broadly in the THz frequency range by simply varying gate voltages.[3] Thus the detection frequencies on an instrument flying a TACIT heterodyne receiver could be reconfigured during a mission, adding the flexibility to search for a range of species with spectral signatures in different frequency bands.

**Concept:** A TACIT mixer is a four-terminal transistor-like device, shown schematically in Fig. 1a. The heart of a TACIT mixer is a GaAs "quantum well" containing a 2-dimensional electron gas (2-DEG) whose resistance is a strong function of the electron temperature. The signal and LO are coupled into the 2-DEG by an antenna that is terminated by front- and back-gate contacts located above and below an active region in the 2-DEG. When the signal and LO are resonant with an "intersubband transition"—a transition between quantum-confined states in the quantum well-- the THz radiation is efficiently absorbed, heating the 2-DEG and changing its mobility. The intermediate frequency (IF) of a TACIT mixer is read out through a pair of ohmic contacts (source and drain) to the 2-DEG. The frequency of the intersubband resonance can be broadly tuned by changing the voltage difference between the front and back gates. Independently, the impedance presented by the active region to the signal and LO can be matched, *in-situ*, to the antenna impedance by varying the carrier concentration in the active region via the field effect, ensuring high quantum efficiency.[2]

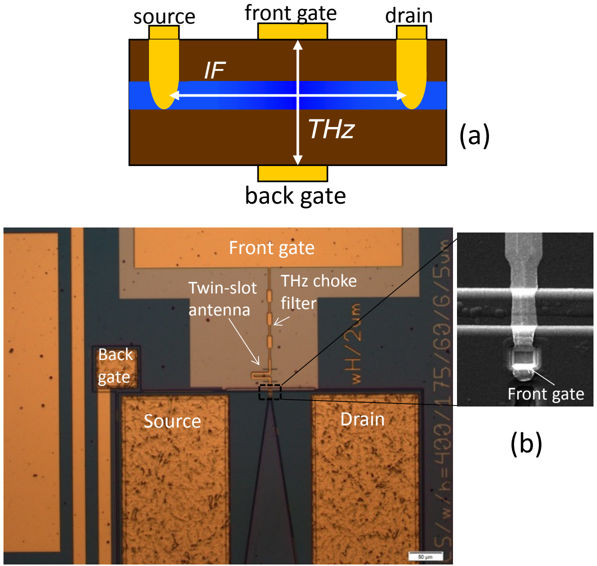

*Fig. 1 (a) Schematic of THz detection and intermediate frequency (IF) generation in a TACIT device, where 2DEG channel is shown in blue. (b) Microscopic image of a fabricated TACIT device showing source, drain, antenna, THz choke filter, front and back gates. A scanning electron micrograph of the active region (the square is the front gate) is shown in the inset.*

**Implementation:** A TACIT detector has been designed and fabricated (Fig. 1b). A 40 nm GaAs quantum well with very low impurity concentration containing a 2-DEG whose mobility is a strong function of temperature above 10K was grown by molecular beam epitaxy (MBE) at Princeton University. A novel rf embedding circuit was designed at JPL which enables coupling of signal, LO, IF, and DC biases to the four terminals of the device. A fabrication procedure involving multiple photolithography, wet and dry etching steps was developed at UCSB.

**Results:**

*High mobility.* In order to have a high responsivity, it is necessary for the resistance of the 2-DEG near the TACIT detector's operating temperature to be dominated by thermally-excited phonons rather than impurities or other quenched disorder. This means that the 2-DEG must have a mobility in excess of $10^6$ cm$^2$/V-s at 10 K. As-grown, the samples had a mobility of $3.6 \times 10^6$ cm$^2$/V-s even though they were close to a heavily-doped back gate. After the complete fabrication process, the mobility was $1.1 \times 10^6$ cm$^2$/V, meeting the design goal.

*Frequency response depends on gate voltage.* Fabricated devices were mounted on a silicon lens, and their response to cw radiation from a molecular gas laser was measured as a function of gate bias. Fig. 2 shows the response (changes in source-drain voltage under constant current bias) to chopped radiation with frequencies ranging from 1.63 to 3.11 THz as a function of the voltage between top gate and drain. The back gate and drain were shorted. The response exhibits a step-like feature at a voltage that decreases approximately linearly with terahertz frequency. Neither the carrier concentration under the front gate nor the DC electric field between front and back gate were known or optimized in these experiments, and thus the applicability of the theory described in ref. 2 cannot be guaranteed. However, the sensitivity of the device's frequency response to a DC voltage shows that TACIT detectors are frequency-agile.

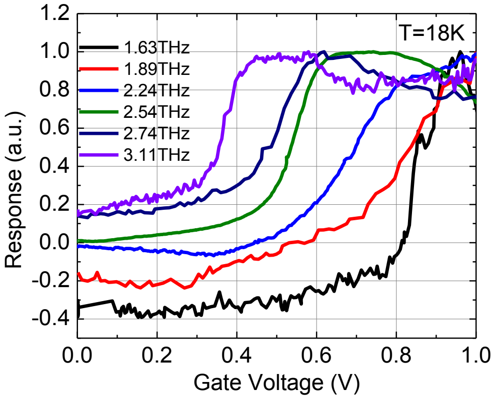

*Fig. 2: Voltage-tunable response of TACIT detector to illumination at frequencies between 1.6 and 3.1 THz.*

*Mixing.* Mixing experiments were carried out on a two-terminal device with only a source and drain, and no front and back gates or antenna. A weak microwave signal at 19 GHz was mixed with a stronger local oscillator whose frequency and amplitude were varied to maintain the device at the same bias point. The IF signal power is plotted as a function of the IF frequency in Fig. 3. The -3 dB roll-off is at roughly 3 GHz. It is likely that parasitics associated with coupling between the back gate and the 2-DEG are limiting the IF bandwidth in these experiments, that is, the intrinsic IF bandwidth due to the electron gas temperature relaxation is much broader.

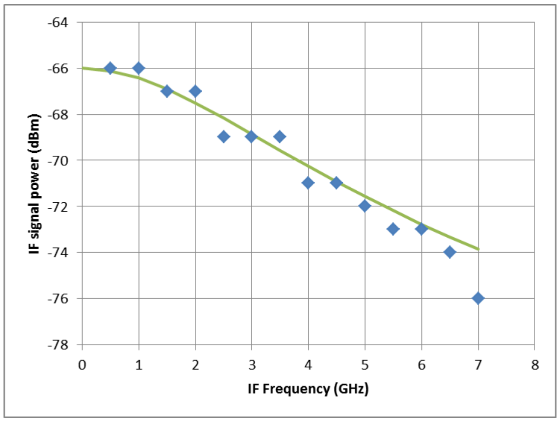

*Fig. 3: IF response of a 2-terminal test structure (diamonds) measured by beating two ~20 GHz microwave signals, and Lorentzian. -3dB roll-off is ~3 GHz, likely dominated by parasitics*

**Conclusion:**

We have demonstrated a complete cycle of design, fabrication and testing of a new generation of TACIT detectors. This cycle included materials science (growth and characterization of a specially-designed, very clean quantum well by molecular beam epitaxy), rf engineering (design of novel antenna and rf embedding circuit), the development and implementation of a new microfabrication procedure, and testing of TACIT detector response to DC, microwave and terahertz fields. We have thus brought TACIT detectors much closer to realizing their enormous potential for studying gases near comets and planets.

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