

(Invited paper for RAWCON, 2004)

## THz Semiconductor-Based Front-End Receiver Technology for Space Applications

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### Abstract

Advances in the design and fabrication of very low capacitance planar Schottky diodes and millimeter-wave power amplifiers, more accurate device and circuit models for commercial 3-D electromagnetic simulators, and the availability of both MEMS and high precision metal machining, have enabled RF engineers to extend traditional waveguide-based sensor and source technologies well into the THz frequency regime. This short paper will highlight recent progress in realizing THz space-qualified receiver front-ends based on room temperature semiconductor devices.

### Introduction

The THz frequency regime (300 to 3000 GHz) is just beginning to receive significant attention in the commercial world. However, for more than three decades it has been a critical driver for Earth, planetary and space astrophysics. The measurements of THz molecular line thermal emission spectra in the relatively cool environment (10-100K) of planetary atmospheres and interstellar space, provides a wealth of information on cosmic chemistry, stellar origins and evolution, galactic structure, planetary dynamics, and upper atmospheric processes on the Earth. NASA, ESA (European Space Agency) and NASDA (National Space Agency of Japan) have all constructed space-based remote sensing instruments in this frequency regime. JPL, a long time player in this field, has fabricated and fielded THz superconducting and semiconducting components and instruments for mountain top observatories in Hawaii, Chile and the South Pole, for high altitude balloon and aircraft flights, and for three space-craft instruments. Continued development on higher frequency receivers, wider frequency coverage (tuning range) and much greater signal throughput (imaging systems) are currently in progress. This short paper will review some of the enabling technology that has allowed us to realize the goals of our NASA programs. Due to space constraints it is not possible to discuss all of the recent developments, so we will focus only on those programs that are directly within our sponsor base and that involve semiconductor devices and technology. Many of these developments spill over into other THz application areas and the reader is referred to two recent texts and a general review [1,2] for additional details.

### Sources

The generation of terahertz energy is a significant driver for technology development in this wavelength regime. All current submillimeter-wave molecular line receivers operate in *heterodyne* mode in order to realize the frequency resolution needed (kHz) to accurately resolve spectral features and Doppler velocities. Due to the lack of direct low noise amplification at these wavelengths, the incoming RF signal is down converted to the microwave band before detection. This process requires a locally produced RF signal (local oscillator or LO) large in magnitude compared to the signal under observation. Superconducting sensors generally require microwatts of LO power, whereas semiconductor-based receivers need 10 to 100 times more (mW). The generation of even modest amounts of THz radiation has been a challenging endeavor for many years and there is generally a recognized "THz Gap" which stems from the fact that the energy levels involved in creating THz radiation fall below those used in photonic sources and beyond the inherent speed of electronic devices. One way to bridge the gap from the low frequency side has been to extend the operating range of traditional electronic structures by relying on a few very fast materials (GaAs and InP for example) and device geometries (Schottky diodes and short gate transistors). By pushing fabrication limits with electron beam lithography and reducing circuit parasitics through unique device geometries, it has been possible to produce microwatts of power up to 1.8 THz by simple nonlinear reactive multiplication in one or a series of waveguide-mounted Schottky varactor structures. Drive power for the multiplication process can be supplied by microwave oscillators or synthesizers coupled to new commercially developed MMIC power amplifiers with impressive gain in the Ka- to-W band (30-120 GHz) range. Input power to the multipliers can be further enhanced by power combining to achieve close to one-half Watt at W-band [3]. Current development thrusts include

increasing the operating frequency of the amplifiers in order to reduce the number of multiplication stages as well as improving the power combining efficiency and overall DC-to-RF efficiency to allow greater drive power to be realized. In order to harness the available power at W-band and upconvert into the THz regime, a new class of high frequency multiplier diodes had to be realized—low parasitic planar structures that incorporated multiple anodes per chip for higher power handling capacity (power handling capability increases roughly as the square of the number of series connected anodes due to the heightened breakdown voltage).

Redesigning traditional GaAs Schottky varactor diodes to work well at THz frequencies took several steps. For many years (1960-1990) high frequency diodes were realized by direct extension of the “cat-whisker” technology first developed by the early pioneers of radio. By the early 1990’s, much simpler-to-assemble planar diode “chips” were shown to work just as well [4]. These chips however had to be small compared to a wavelength in order not to load the surrounding circuit and this limited their use to frequencies below about 300 GHz. Several improvements followed, including substrate substitution (to quartz) to help reduce circuit loading and improve device performance. Frequencies up to 600 GHz became accessible. A big breakthrough in THz device realization came in the late 1990’s when a new substrateless geometry was proposed [5] and demonstrated [6]. In this approach the diodes are integrated with their surrounding mounting and matching circuitry and most of the GaAs substrate is etched away to greatly reduce parasitic circuit loading. The ability to produce sculpted diode chips that incorporate not only the nonlinear upconverting elements but also contact leads, bias and RF probes and matching elements has made it possible to realize THz RF sources with improved efficiency, bandwidth, and power handling capability. A 400 GHz doubler chip is shown in Fig. 1 (left) mounted in a traditional split-block waveguide cavity. The chips are not only RF efficient but are designed to make the assembly process straightforward and more importantly, repeatable. Integrated metal beam leads allow easy handling and solderless interfacing with the waveguide block, and also provide seamless DC and RF returns. In order to push the devices towards even higher operating frequencies (above 1 THz), novel “membrane” devices have been developed. A unique feature of these devices is the removal of almost all of the GaAs substrate, leaving the entire circuit on a 3 micron thick membrane. Both the anode and critical circuit elements are submicron in area and require e-beam direct writing. The membrane technology is more complicated to implement but is necessary given the circuit requirements for high frequency operation. A tripler designed to work at 1200 GHz [7] is shown in Fig.1 (right). This technology has been used to successfully realize multiplier sources that reach 1900 GHz [8,9].

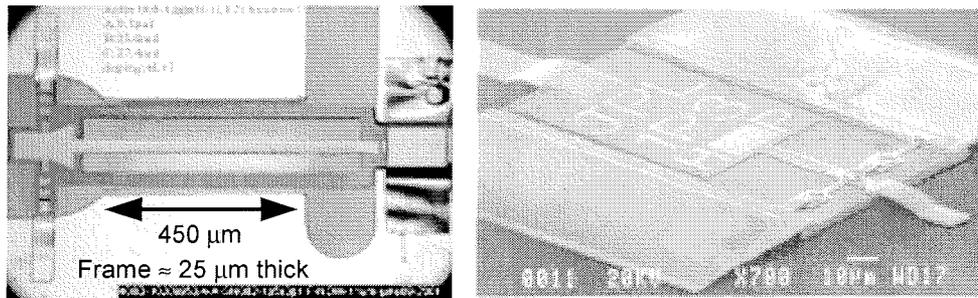


Fig. 1: Left: Photo of a JPL 400 GHz doubler chip inside a split-waveguide block. No GaAs is present under the metallic matching circuitry (middle region). Beam leads are used to locate the chip and provide DC electrical contacts. Right: 1200 GHz tripler circuit formed on a 3 micron thick GaAs membrane. Again, metallic beam leads promote handling and form both DC and RF coupling structures.

Starting at 200 GHz with a demonstrated peak output power of 45 mW and 30% doubling efficiency from a W-band power amplifier driver, and invoking other data points at 400, 800, 1200, and 1600 GHz, we have found that the peak efficiency of our multipliers follows empirically:  $\eta(f) = \eta_0 \cdot e^{f/f_0}$ . The constants  $\eta_0$  and  $f_0$  are different for doublers and triplers, as well as for varying device ambient temperature and instantaneous bandwidth. A summary of  $\eta_0$  and  $f_0$  determined from measured data is provided in [9]. A complete 1200 GHz chain is shown in Fig. 2. This chain can output 100 microwatts at room temperature over greater than 10% fix-tuned bandwidth and has been space qualified for the Herschel Telescope program. A similar chain at 800 GHz using three doublers has demonstrated 1 mW of peak output power and has been used at the South Pole to drive a 4 element SIS receiver array [10].

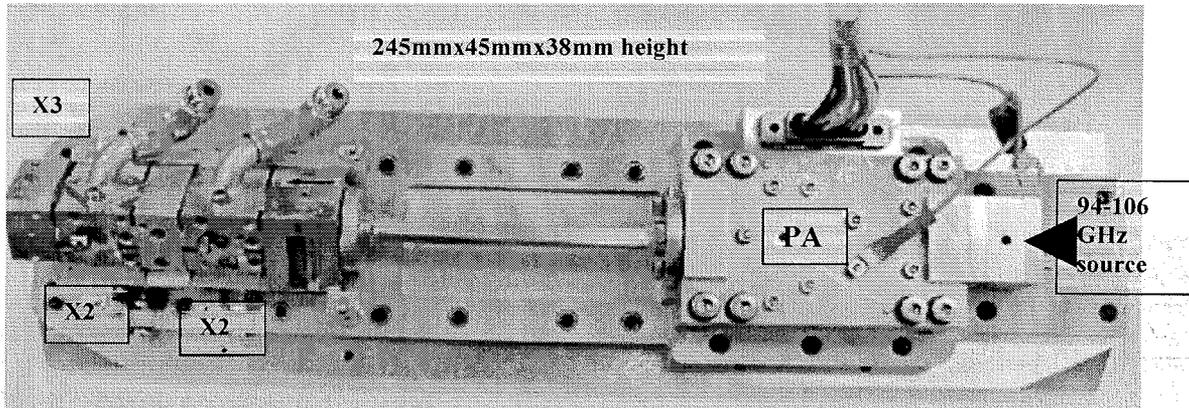


Fig. 2: A complete planar Schottky diode based LO chain to 1200 GHz (x2x2x3) for the Herschel Space Observatory.

### Detectors

The Schottky diode has also been the workhorse for high sensitivity room temperature detectors in the THz range. Paralleling the development of multiplier devices, GaAs cat-whisker or point contact diodes of the 1960's through 80's, were replaced by a series of planar realizations that revolutionized both circuit flexibility and performance. A major advantage with the planar diode topology is the realization of multiple anode circuits which was capitalized to fabricate dual-diode subharmonic mixers. These mixers allow one to inject the LO frequency at one-half the RF signal, eliminating the need for complicated diplexers and simplifying the requirements on the LO. Subharmonic mixers up to 640 GHz have been built and flight qualified at JPL [11] requiring only 2-3 mW of LO at 320 GHz. A variant on the GaAs multiplier membrane diode technology has also been used to produce fundamental mixers up to 2500 GHz, flown both on balloon and soon to be launched into space as part of the Earth Observing System's Microwave Limb Sounder instrument (stratospheric chemistry instrument) [12]. An SEM of the submicron mixer anode and contact finger is shown in Fig. 3 (left). The fully assembled dual-channel receiver with signal/LO diplexer is shown in Fig. 3 (right). This mixer requires 5mW of LO power (obtained from an FIR laser) and achieved <5000 K DSB noise temperature.

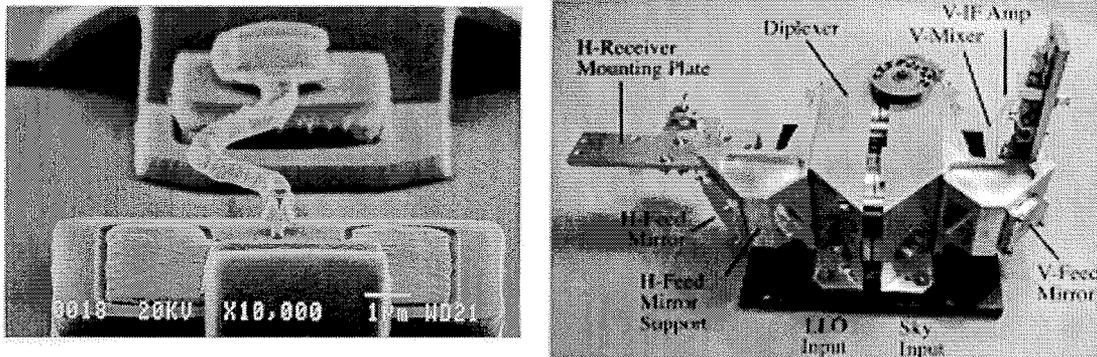


Fig 3. Left: 2500 GHz Schottky diode., Right: Complete dual-channel front end (laser LO not shown).

### Emerging Technologies

While the feasibility of implementing THz receivers has been demonstrated, a major hurdle that needs to be surmounted in order to bring this into the mainstream commercial market will be the reduction of cost/unit. This will continue to pose a significant challenge, as the circuit and device technologies for the best performing systems have not yet been integrated into a single topology. Emphasis is being placed towards 'receiver-on-a-chip' techniques that have already made significant gains in the millimeter bands [13]. Rapid progress has also been made

in photonic-based sources that may improve both bandwidth and power output in the now impossible to reach 2-10 THz bands. The most promising approach at the low frequency end involves optically pumped photomixers [14]. A number of research groups are working on implementing these sources and new material systems promise operation at 1.55 micron in fiber. Currently, it is possible to achieve approximately 1 mW at 100 GHz and a few microwatts at 1 THz. At the high end of the THz band quantum cascade lasers based on superlattice semiconductor material show great promise [15] and mW of output power have already been achieved from 2-5 THz for devices operating cryogenically.

### Conclusion

This brief review has attempted to highlight some recent progress on semiconductor-based THz receiver components. Though significant progress has been made, bringing this technology into mainstream commercial applications requires further innovation and overcoming some very difficult technical and cost challenges. Meanwhile the one-of-a-kind space-based market will continue to thrive, as nowhere else in the electromagnetic spectrum can we learn so much about our universe.

### Acknowledgements

We wish to acknowledge the many contributions of the JPL Submillimeter Wave Advanced Technology Team (SWAT) that has made this work possible. This program was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena under contract with National Aeronautics and Space Administration.

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