THz Technology and its Applications

Motivation

Development of components for space-based heterodyne sensor technology at submillimeter wavelengths 125µm to 110µm (2.4THz to 2.7THz) for Astrophysics, Earth and Planetary Heterodyne and Direct-detection Remote Sensing Instruments (Herschel Space Observatory, EOS-MLS, ROSETTA).

Detection of molecular species in space and in the laboratory
HD (1-0) transition line at 112µm to determine H/D ratio
High resolution spectroscopy
CII and NII hyperfine structure chemistry in Interstellar Medium (ISM)

Solving of Specific Technology Goals
Fabrication of circuits at JPL Micromachining

THz Technology and its Applications

Exploration of the Solar System

Submillimeter Wave Observation Platforms

High Altitude Balloon
Airborne Platform (DC8/5OFIA)
Earth Orbiter/Sounder
Planetary Sounder

First UARS-MLS measurement of correlation between ozone depletion and chlorine enhancement from September 1991.

NASA’s Upper Atmospheric Research Satellite

Water vapor during 1997
El Nino from UARS-MLS

Frank Maiwald,
Imran Mehdi, Peter Siegel
Submillimeter-Wave Advanced Technology (SWAT) Team
Jet Propulsion Laboratory
California Institute of Technology

Presentation at the University of Korea, Moonil Kim
Microwave Group - Korea Univ, phone: 82-2-3290-3247
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August 4/5/6th 2003
**THz Technology and its Applications**

**THz Bands & Atmospheric Transmission**

**Space Platforms are Necessary in the Submillimeter Due to water/oxygen absorption in the atmosphere**

- **Wavelength**
  - Ionosphere Opaque
  - Radio Window Mountain
  - Atmospheric Transmission Acceptable
  - Optical, IR Windows
  - Atmosphere Opaque


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**Critical Technology: THz Detectors**

**Wavelength (μm)**

- **1000**
- **300**
- **200**
- **60**
- **30**

**Sensitivity**

- **SIS (4 K)**
- **Mixers**
- **HEB (4 K)**
- **Schottky (20 K to 300 K)**

**Frequency (THz)**

- **0.3**
- **1**
- **1.5**
- **5**
- **10**

- **Highest**
- **Photoconductors (≈ 2 K)**

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**Promising THz LO Source Techniques**

<table>
<thead>
<tr>
<th>Solid-State Multipliers &amp; Power Amps</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gas Lasers</strong> &amp; Sideband Generators</td>
</tr>
<tr>
<td><strong>Photomixers</strong> &amp; <strong>Intersubband Lasers</strong></td>
</tr>
<tr>
<td><strong>MicroTubes</strong></td>
</tr>
</tbody>
</table>

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**Heterodyne Superconducting Detectors for Astrophysics**

**Source Velocity Resolution**

- **Δv = c/R**
- **Δv = 0.3 km/s**
- **Δv = 10 km/s**
- **Δv = 30 km/s**
- **Δv = 200 km/s**

**SWAS uses whisker contacted 600 GHz GaAs Schottky mixers and multipliers**

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**How to generate THz power?**

- **Harmonic Multiplication from Schottky Diode capacitance-voltage nonlinearity**
- **Electronic RF Excitation (< 7 GHz)**
- **CO₂ laser, output at λ = 10 μm**
- **Methanol laser, e.g., output at λ = 120 μm**
- **THz Gas Laser @ f₁**
- **Schottky Diode Mixer (Sideband Generator)**
- **Electronic-Orbital Device (1.0 GHz)**
- **Electronic output at k₁ < f₁**
- **Current Bias Cooler Bath (Hz, L2)**
- **Output at λ < 100 μm**
- **Nanobase Electron Source**
- **Electric Field Modulation and acceleration**
- **Output via waveguide**

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**JPL - SWAT (Submillimeter Wave Advanced Technology)** - Visit at University of Korea, Seoul, S. Korea
**Silicon Nitride Micromesh 'Spider-web' Bolometers**

- Spider-web architecture
  - low absorber heat capacity
  - low mass
  - low-cosmic ray cross-section
  - low thermal conductivity

Sensitivity:
NEP = $1.5 \times 10^{-18}$ W/√Hz, at 100mK

To be used in Planck/HFI, FIRST/SPIRE

**Example:**
100 GHz bw, 1 sec integ., $10^{-18}$ NEP:
$\Delta T < 1 \mu K$

---

**Flight Qualified CO₂ Pumped Methanol Gas Laser**

- Compact 2.5 THz gas laser system: RF power>20mW, DC power~100W
- Built by Coherent DEOS – DeMaria Electro Optical Systems, for JPL

**THz Generation with Intersubband Lasers**

Direct THz intersubband solid-state laser emission showing power at ~4.44 THz.

The data shown is for a laser operated pulsed and cooled to 8K. Output power was reported to be about 2mW. At 50K ambient power dropped to 120 microwatts.

More recent results have shown CW operation and at higher ambient temperature.

(Slide courtesy R. Giles Davies, Cavendish Labs, Cambridge, UK)
THz Technology and its Applications

Photomixer Technology Developments at JPL

- Membrane-supported, or arrayed-antenna distributed gain region:
  - Low RF losses, high output power, avoid thermal burn-out
- Novel materials for 1.55 μm: GaAs:ErAs and InAlGaAs:ErAs

![Graph showing output power vs. frequency](image)

Collaboration: JPL, UCSB, Caltech

Courtesy of R. Wyss

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THz Technology and its Applications

Nanoklystron: THz Generation from Vacuum Tubes

**Schematic Construction with Realized Structures**

- Silicon host wafer - top
- Shaped Repeller
- Silicon wafer - bottom
- Grid V
- Integral grid
- Dielectric seal
- Silicon micromachined cavity (JPL)
- 2-mm line and 4-mm space mesh with micro-etch marks
- High density silicon nanotips made with RIE

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THz Technology and its Applications

**Summary of THz Source Performance**

- Strong CO2 pumped laser lines
- Cardioid
- Broadside Lobe
- NEW Inter-sub-band Lobe

![Graph showing output power vs. frequency](image)

Data collected from assorted references (see MTT50, no. 3, March 2002, pp. 910-928)

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THz Technology and its Applications

**THz Source Performance: Multiplier Chains at RT**

![Graph showing power vs. frequency](image)

Flight Multiplier Chains for MLS & Herschel

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JPL - SWAT (Submillimeter Wave Advanced Technology) - Visit at University of Korea, Seoul, June

NASA

THz Technology and its Applications

Nanoklystron: THz Generation from Vacuum Tubes
Why THz generation with planar Schottky diodes?

- Availability of high power power amplifier from 75-110GHz
- Micromachining of low loss waveguide structures
- Technology Development of fabrication processes for planar Schottky diodes from the THz range (MoMeD)

Ref:
R. Lai et al., "A high efficiency 0.15 um thick InGaAs/AlGaAs/GaAs V-band power HEMT MMIC," IEEE GaAs IC Symposium Digest, Nov. 1996.

M. D. Biedenbender et al., "A 0.1 um W-band HEMT production process for high yield and high performance low noise and power MMICs," 16th GaAs IC Symposium, 1994.
Herschel Amplifier Performance versus System Requirements

Typical Amplifier Performance

- Full frequency range covered by four amplifier types

- 71-78 Amp
- 80-92 Amp
- 92-106 Amp
- 88-99 Amp
- Required

Solid-state THz sources based on power amplifiers and planar diode frequency multipliers are being developed to support a range of scientific instruments including the Herschel Space Telescope (HIFI), the South Pole's AST/RO (Astronomical Radio Obs.), NRAO's ALMA (Atacama Large Millimeter Array), SOFIA (Stratospheric Obs. for Infrared Astronomy) and the CSO (Caltech Submillimeter Observatory).

An all-solid state 805 GHz Local Oscillator (LO) chain assembled for AST/RO (South Pole Radio Telescope). The JPL components enable a new 4x4 submillimeter wave array receiver being assembled by U of Arizona.

An all-solid-state broad band 1500 (left) and 800 GHz (right) Local Oscillator (LO) chains assembled for the HIFI instrument on the Herschel Space Telescope. These sources are two of several frequency chains being readied for flight delivery on this ESA cornerstone observatory mission. The power output of the 800 GHz unit is over 1 mW and has 12% conversion efficiency from 100 GHz. The 1500 GHz unit produces about one half microwatt. A 1200 GHz unit, also being developed, produces over 150 microwatts across a band from 1100-1200 GHz. These are the highest reported power levels produced by solid-state sources to date.

JPL - SMAT (Submillimeter Wave Advanced Technology) - Visit at University of Arizona, Tucson, Ariz.
THz Technology and its Applications

THz Frequency Multiplier Chain Optical Interface

LOU - Optical Design (Courtesy of T. Klein, MPIR)

The Heterodyne Instrument for Far Infrared

Focal Plane Unit

Optical paths for the 7 receivers

SPIRE

Herschel and Planck

Mission Overview
- ESA Cornerstone Mission (Great Observatory)
- Far Infrared Observatory with 3.5-m Telescope
- U.S. Participating in Two of Three Instruments
- U.S. Technology Input
  - High Frequency Heterodyne Receivers
  - Large Bolometer Arrays
- Launch Date: Mid-2007 to L2 orbit

Science
- Investigate the dynamical and chemical evolution of galaxies and stars and the exchange of matter and energy among stars and the interstellar medium
- Study the complete lifecycle of a star and the relationship with interstellar matter
- Study structure, energetics and dynamics of the interstellar medium
- Study star formation by high-resolution observations of protostars, disks, and outflows
- Study the origin and evolution of the elements
- Investigate how stars and planetary systems form together
- Study early evolution of large scale galactic clusters and early galaxy formation
- Observe and study galaxies near the time of their formation at very high red-shift
**Mission Overview**
- ESA Mid-Sized Mission
- Millimeter Cosmology Mission with 1.5-m Telescope
- U.S. Participating in Both Instruments
- U.S. Technology Contribution
  - Bolometer Detectors
  - Cryogenic HEMT Amplifiers
  - Sorption Cryocooler
- Launch Date: Mid-2007 to L2 orbit

**Science**
- CMB anisotropy with sensitivity and resolution set by astrophysical limits
- Determine how structure in our Universe emerged from the Big Bang
- Cosmological parameters to unprecedented accuracy
  - Curvature of space (equivalent to knowing total energy of the universe, \( \Omega_m \))
  - Total non-relativistic matter density (cold dark matter + baryons)
  - Upper limit on on the energy scale of inflation
- Investigate how dark and luminous matter determine the geometry and fate of the Universe
- All-sky surveys of the most luminous cm-farIR objects in the universe
- All sky surveys of galaxy clusters, including the first clusters formed

**Key Science Programs**
- Origin of Galaxies
- Evolution of Stars and Galaxies
- Origin of Stars and Planets

**Required Measurements**
- Telescope
  - \( \lambda \Delta \lambda < 5\) m, diffraction-limited at 130 \( \mu \)m (90 \( \mu \)m goal).
- Heterodyne Instrument
  - 0.48-2.7 THz (116-2090 \( \mu \)m)
  - \( \lambda \Delta \lambda > 10^3 \)
  - Physical temp. 1.7K
- Bolometer Instrument
  - >1000 pixels
  - Physical temp. ~0.3K
  - Fourier Transform Spectrometer
  - 200-670 \( \mu \)m
  - \( \lambda \Delta \lambda > 20-1000 \)
  - Imaging Photometer
  - 200-670 \( \mu \)m
  - \( \lambda \Delta \lambda = 3 \)

**Engineering Implications**
- Photomixers & MMIC Amplifier Drive
- Multiplier LO Sources
  - \( P > 50 \mu \)W
  - \( v < 1.25 \) THz
  - \( P > 1 \mu \)W for \( v > 1.41 \) THz
- Tuning range >10%
- SIS, HEB Mixers
  - \( T_{\text{base}} < 5 \text{ mK} \) (Goal)
  - 0.48-2.7 THz
- Spider or Pop-up Bolometer Arrays
  - 32 x 32
  - Response >10 Hz
  - NEP < 10^{-17} W/Hz^{1/2}
THz Technology and its Applications

Application: Earth Remote Sensing of the Upper Atmosphere

- Stratospheric and Tropospheric Chemistry
  - ozone layer modeling
  - economics vs. environment
  - water distribution/pollutants
- Clouds: Global Warming
  - ice crystals: size and distribution
- Aerosols, Volcanic Ejecta, Dust

Heterodyne measurements for T, P, and ppm abundances
- pressure / Doppler broadening ± 1 MHz
- line strength generally OK for RT detectors, i.e., Schottky's noise

Ozone Cycles

Red Species Measured by UARS

Remote Sensing with Fine Height Resolution (≈ 1 km)

Application: Microwave Limb Sounding

Submillimeter Spectra for Earth Remote Sensing

Spectra of some important molecules in the Earth's upper atmosphere and measurements being addressed by NASA heterodyne instruments. The peak power or minimum frequency for many emission lines occurs in the THz region.

(From: J. Waters, EOS Atmospheres presentation, Goddard Space Flight Center, 1991)
THz is the primary freq.
for line and continuum
radiation from cool (5-100 K) gas (atoms and molecules) and dust.
Useful for Studying Stellar
and Galactic Constituents and Evolution,
Cosmology, Dust & Gas
Chemistry, Cosmic
Background Physics.

LEFT: Radiated Energy vs.
Wavelength showing 30K
blackbody, interstellar dust
and key molecular line
emissions
(from Tom Phillips, IEEE

Energy output vs. wavelength for galaxies of
ascending ages showing advantages of THz
detection for probing the early universe

Spectrum of Milky Way galaxy showing luminous
power output vs. wavelength. Almost 50% of the
power is emitted at THz frequencies!
(From D. Leisawitz, SPIE Proc., 4013, Mar 2000)

from G. Rieke and S. Beckwith in the McKee-Taylor Decadal Review
JPL – SATH (Suborbital Advanced Technology) – Visi at University of Arizona, Tucson, Tucson
Planetary Science Drivers

- Comets
  * Oceans on earth? Life on earth?
- Kuiper Belt objects
  * Origin & evolution of solar system
- Planetary Atmospheres
  * Remote studies of gas giant planets
  * Venus orbiter (VESPER)
  * In situ studies of atmospheric dynamics
    - atmosphere - regolith interaction (e.g., on Mars)
    & evolution of atmospheres
    - in situ weather stations on remote planets (e.g., Mars)
- Planetary Volcanism and Life Signatures
  * Remote studies of subsurface gas emission from organic and volcanic sources (e.g., Mars/ Europa, Callisto)
- Long-Term
  * Large-baseline interferometers for atmospheric chemistry of extra-solar planets

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