Next Generation of Terahertz Sources and Detectors

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E/M Attenuation vs Frequency
Limitations of Current Technology

ATTENUATION (DB/KM) vs FREQUENCY

ATTENUATION (DB/KM) vs WAVELENGTH

- H$_2$O
- O$_2$
- CO$_2$
- O$_3$
- Terahertz
- Millimeter
- Submillimeter
- Infrared
- Visible

- Excessive Rain (150mm/h)
- Heavy Rain (25mm/h)
- Drizzle (0.25mm/h)
- Heavy Rain
- Drizzle
- Fog (0.1g/m$^3$)
- Visibility 50m

- 20°C
- 1ATM
- H$_2$O : 7.5g/m$^3$

- Visibility 50m
Using a limitation to our advantage!!!
Program Objectives

Explore innovative semiconductor device and circuit concepts for the demonstration of high power sources and high sensitivity detectors for the region of the electromagnetic spectrum between 0.3-10 THz (1 - 0.03 mm)
Technical Challenges

**THz Sources**
- Achievement of high output power (at least mWs)
- Efficiency
- Compactness
- Tunnability for certain applications

**THz Detectors**
- High Sensitivity and Detectivity
- Quantum Efficiency
- Compactness
Technical Approaches

**THz Sources**
- Electrical
  - InP-and Sb-based HEMTs
  - GaN-based Gunn diodes
  - Sb-based Stark Ladders and Quasi-optic Combiners
  - Passives and Waveguides
- Optical
  - Optical Photomixing
  - SiGe VCSELs

**THz Detectors**
- RTD-based
- Electro-acoustic Detectors (HEMTs)
- Photon assisted tunneling in QWs
**OBJECTIVE:**
Develop monolithic integrated circuits capable to generate power at 0.33 THz, 0.66 THz, 1 THz and 3 THz.

**APPLICATIONS:**
• Remote sensing
• High resolution imaging
• High data-rate space communication

**APPROACH:**
• Develop high performance HEMT MMIC sources with integrated antennas for 0.3 THz to 1 THz frequency range
• Develop novel superlattice oscillators and multipliers for 1 THz to 10 THz frequency range

State of the art HEMT MMIC

Quasi-optical superlattice array for harmonic generation
0.3 THz to 1 THz SOURCES

CHALLENGES

- MMIC design
- Low-loss passive components
  - Antennas
  - Transmission lines
  - Power combiners
- Spatial power combining
- Packaging
- Testing
InAs/AlSb/GaSb Materials Effort

- 1-10 THz source development
  - collaboration with UCSB (Allen)
  - InAs/AlSb superlattice devices
  - emphasis on harmonic generation

- Materials support for Raytheon (Frazier)
  - RTD structures
  - High Jp
  - IMSC MBE Capability

Quasi-optical superlattice array for harmonic generation
**OBJECTIVE:**
Develop and demonstrate an electrically excited solid-state Terahertz sources, capable of delivering >1 mW of power in the range above 1 THz

**APPROACH:**
- Implementation of InAs/AlSb superlattice, Stark ladders for THz generation
- Implementation of Quasi-optic arrays for power combining
- Demonstration of THz harmonic generation

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*Solid State Terahertz Sources for Sensing and Satellite Communications*

InAs/AlSb Superlattice in an electric field

Superlattice in Capacitive grid

Inductive grid

THz Cavity

Center for Terahertz Science and Technology

UC Santa Barbara
http://www.qi.ucsb.edu/
**Solid-State Terahertz Sources**

**TECHNICAL APPROACH:**
- Unique approach combining new semiconductor and micromachined concepts
- Semiconductor device potential for high-power fundamental or harmonic sources
- Possibility to apply micromachined concept to other sources developed under this program

\[ \text{GaN NDR Diodes} \quad + \quad \text{Micromachined Resonator; Filter/Multiplier} \quad = \quad \text{Solid-State Terahertz Source} \]
III-N Terahertz Gunn Diodes

**OBJECTIVE:**
Take advantage of the electron transport and material properties of III-N semiconductors for the demonstration of Gunn diode THz sources

**CHALLENGES:**
- Achieve good quality GaN materials
- Demonstrate NDR performance in WBG semiconductors
- Demonstrate generation of THz radiations
**Passive Silicon Micromachined Structures for THz Applications**

**APPROACH:**

*Use Silicon Micro-machining Technology for the Development of:*

- THz waveguides for high-performance low-loss circuits
- Electric and magnetic transitions from planar transmission lines to micromachined waveguides
- Transitions between waveguides and planar micromachined antennas
- Compact resonators for GaN Gunn sources
All-Solid-State Photomixing Transmitter

OBJECTIVES:
Develop a solid-state source for the THz region having up to 1 mW output power and:

- Stable continuous-wave performance
- Room-temperature operation
- Tunability up to ~1 octave
- Instantaneous frequency stability > 1:10^6
- Phase lockability (required for comms)
- Good beam characteristics (TEM_{000} Gaussian desirable)

TECHNICAL APPROACH:

- Optical mixing in an ultrafast photoconductor (LT-GaAs)
- Couple internal THz photocurrents to a THz load (antenna)
- Implementation of power combining techniques

\[
P_3 = \frac{R}{2} \eta_1 \lambda_1 \eta_2 \lambda_2 \left( \frac{e g}{hc} \right)^2 \left[ 1 + \left( \frac{\omega_3 \tau}{1 + \omega_3 RC} \right)^2 \right] P_1 P_2
\]
**OBJECTIVE:**

To demonstrate a SiGe, micro-disk cavity, intersubband laser suitable for communication systems.

**APPROACH:**

- Silicon micromachining for novel resonator design
- SiGe unipolar architecture
- E/M simulation for device optimization
- 1-10 THz operation

Quantum well transitions between $E_3$ and $E_2$. Proposed device will use SiGe quantum wells and hole intersubband transitions.
Vertical Cavity Silicon-Germanium Quantum Cascade Lasers for Terahertz Emission

**OBJECTIVE:**
Develop and demonstrate a vertical cavity SiGe quantum cascade laser capable to operate in the THz region of the electromagnetic spectrum

**APPROACH:**
- Characterization of ISB lifetimes in p-SiGe QWs
- Demonstrate FIR emission in p-SiGe tunnel barrier structures
- Demonstrate surface emission in p-SiGe quantum cascade structures
- Demonstrate vertical cavity SiGe quantum cascade device
**OBJECTIVE:**

- Develop high-sensitivity, solid-state RF detector MMICs for the 0.3 - 3 THz frequency band.

**APPROACH:**

- Design and develop low-parasitic InP & GaSb resonant tunneling diodes (RTDs)
- Use epitaxial transfer to integrate RTDs with low-loss THz antenna structures.
- Demonstrate passive and super-regenerative RTD detector-antenna MMICs
- Demonstrate simplex THz communication link. (with HRL & UCSB)

**DOD FUTURE USES:**

- Man-portable, ultra-secure THz communication links
- Space-based imaging of upper atmosphere
- Phased array missile seekers/munitions
**Objectives:**

- Demonstrate resonant terahertz detector with high sensitivity
- Observe terahertz radiation from a field effect transistor
- Explore applications of plasma wave electronics to silicon

**Approach:**

- Implement detectors using GaN based HEMTs
- Increase the growth of plasma waves using resonant tunneling structure
- Use “light” electrons in deep submicron silicon
THz Molecular Interactions

**OBJECTIVE:**

Build test bed for compact THz sources and detectors.

Experimentally determine rotational energy level spectrum of various gas phase molecules

**TECHNICAL CHALLENGES:**

- Specific identification of chemical species
- Quick response (< 1 second)
- Small (<< 1 ft3)
- Low Power
- Simple-Based on FASSST Concept
- Potentially Inexpensive in Quantity

![FASSST Point-Sensor Test Bed](image)
**OBJECTIVE:**

Demonstrate tunable, narrowband photon-assisted tunneling in double quantum well (DQW) heterostructures.

**TECHNICAL APPROACH:**

- Use bandgap engineering to optimize photodetector performance.
- Develop antenna structure compatible with THz detectors
- Bench-demonstration of THz detector system
Summary

DARPA is Creating Future Opportunities for THz Technology in:

- Environmental sensing
- Upper-atmosphere imagery
- Covert satellite communications
- Chem/Bio Detection (Near Distance)