Generation of THz Signals: From Chips to (space) Ships:

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Outline

- Introduction (JPL, SWAT Team, …)
- Generation of THz signals
- Multiplied sources
  - Power amplifiers
  - Planar diode technology
  - State-of-the-art
- Challenges
- Concluding remarks
TERAHERTZ TECHNOLOGY

• Despite great scientific interest since at least the 1920’s, the THz frequency range remains one of the least tapped regions of the electromagnetic spectrum.

• Sandwiched between traditional microwave and optical technologies where there is a limited atmospheric propagation path, little commercial emphasis has been placed on THz systems. This has, perhaps fortunately, preserved some unique science and applications for tomorrow’s technologists.

• For over 25 years the sole niche for THz technology has been in the high resolution spectroscopy and remote sensing areas where heterodyne and Fourier transform techniques have allowed astronomers, chemists, Earth, planetary and space scientists to measure, catalog and map thermal emission lines for a wide variety of lightweight molecules.

• As it turns out, no where else in the electromagnetic spectrum do we receive so much information about these chemical species. In fact, the universe is bathed in THz energy, most of it going unnoticed and undetected.
THz Markets

**NASA:**
- Earth and Space Science have been dominant sponsors thus far
- Planetary atmospheres and the search for volcanic and life signatures may soon take front row seats
- Currently there is no consistent long term support partly due to the lack of any large missions

**Other:**
- THz applications are expanding rapidly and have entered the commercial market
- World-wide interest in THz technology has led to commercial as well as governmental support in the US, Europe and Japan
- Parallel funding and additional development efforts under other sponsors are essential to sustain future development
Spacecraft with THz on-board

Space-borne

SWAS—measurement of water
UARS-MLS—ozone monitoring
MIRO—rendezvous with a comet

Future

HIFI on Herschel Space Observatory—Early universe study
SAFIR—Astrophysics mission
VESPER—Venus Discovery Mission
SIGNAL—Mars Scout Mission

Earth Orbiter/Sounder

High Altitude Balloon

Airborne Platform (DC8/SOFIA)

Planetary Sounder
LO Sources

- Solid state oscillators (IMPATTs, Gunn diodes etc)
  - Limited to about 300 GHz ($2^{\text{nd}}$ harmonic operation)
  - Limited bandwidth
  - Few commercial vendors

- FIR chemical lasers
  - Bulky, huge power supply, narrow-band …

- Quantum Cascade Lasers
  - Rapidly maturing technology
  - Cryogenic operation, narrow-band

- MMIC based VCOs, Amplifiers, multipliers etc
  - Limited to about $\sim 300$ GHz with current technology

- Diode based multiplier technology
  - Very high cutoff frequency
  - Can be designed for broadband operation
  - Can be designed to handle large input power
  - Can work cryogenic as well as at room temperature
  - Used for a number of space missions
Multipliers for Space

Requirements

– Figure of merit
  • Frequency
  • Power
  • Bandwidth
  • Efficiency

– Output power:
  • Milliwatt’s for Schottky mixers
  • 10’s of microwatts for SIS mixers,
  • 1-2 microwatts for HEB mixers

– Mechanical--stability, compact, low mass, thermal viability

– Environmental--radiation, vibration, thermal
MMIC PA Chip/Modules

- 0.1 um PHEMT process
- 50 um thick substrate
- \( f_t = 200 \text{ GHz} \)
- 64 finger device cell (output)
- on-chip bias network
- 50 ohm matching in/out
- 2.3 mm x 1.8 mm

>> details at 10:30 am

Figure 2. Power output from single and dual power combined packaged TRW MMIC amplifiers at W-bnd.
Power combined amplifier modules

HIFI PA module output power at 300K

HIFI PA module output power at 120K

+0 dBm input

Wilkerson Splitter

Magic Tee

GHz

mW

GHz

mW

-0.8V

-1.01V

-1.24V

-1.42V

-1.68V

-1.87V

-2.09V

-2.31V

-2.54V

-2.76V

GHz

mW

GHz
Flight Qualified PA performance at 120K

Typical PA module at 120K (3dBm Pin)

Output Power (mW)

Freq (GHz)
First generation discrete chips

Whisker contacted anode

6-anode 170 GHz chip

Performance at room temperature
(Erickson, STT 2000)
• Able to handle 220 mW of input power
• > 30% efficiency, 65 mW at 150 GHz

Q: Can this approach be extended in frequency?
Anodes: circular versus rectangular

\[ R_s = R_{oc} + R_{spr} + R_{bl} + R_e \]

- \( R_s(1\text{um} \times 1\text{um}) = 10.3 \text{ Ohms} \)
- \( R_s(0.2\text{um} \times 5\text{um}) = 4.4 \text{ Ohms} \)
Substrateless Technology

A: Yes—but it gets very difficult to implement
Solution: Integrate circuitry with device!

Q: Can this technology be scaled higher?

Frame ≈ 12 μm thick

250 μm
A: Yes—but GaAs thickness difficult to scale
Solution: remove most of the GaAs substrate→membrane devices

Q: Can this technology be scaled higher?
A: Demonstrated up to 2700 GHz!

- Membrane is 3 microns thick
- Extensive use of beam-leads
- Extremely simplified assembly
- Bias less design

1200 GHz tripler chip
Device design & simulations

First generation model—fitting parameters!

output Frequency (GHz)

output Power (uW)

Measured – Expected Cj(0)=1fF

Calculated with

Rs1(380 GHz) = 44Ω
Rs2(760 GHz) = 84Ω
Rs3(1140 GHz) = 124Ω
Cj(0) = 1.15fF

Calculated with Rs (all freq) = 83Ω
Cj(0) = 1.15fF

First generation model—fitting parameters!
Thermal Modeling

\[ T = T_{\text{BLOCK}} + R_{T1} P_{\text{DISS}} + R_{T2} P_{\text{DISS}}^2 \]

Hottest anode temperature

Modeled system has:
1. No convection, heat escapes through beam leads only.
2. Temperature dependent GaAs thermal conductivity.
3. Assumes dissipated power is 75% of input power
Preliminary Diode thermal imaging

- Diode was assembled in an open multiplier block.
- Convection was not considered.
- DC power was used to mimic RF heating.

Measured and calculated temperature at hottest anode

<table>
<thead>
<tr>
<th>Equivalent DC power per anode [mW]</th>
<th>Measured</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
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<tr>
<td>10</td>
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<td>15</td>
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<tr>
<td>20</td>
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</tbody>
</table>

Temperature profile

Temperature [K] measured vs calculated

• Expected lifetime at 300K (400K anode) with $P_{in} = 150\text{mW}$: approx. 0.8 years.
• Expected lifetime at 120K (177K anode) with $P_{in} = 150\text{mW}$: >>1 Million years!!
JPL Schottky Diode Model

- Builds on work done by groups at University of Virginia, University of Michigan, Chalmers University, and Helsinki
- Model includes time-dependent velocity saturation, carrier inertia and shunt capacitance in the undepleted active layer, tunneling through the Schottky barrier and heating of the junction at high powers. The model is calibrated using ensemble Monte Carlo calculations of material parameters, but otherwise no parameters are fitted other than to DC I-V measurements
- Chip temperature and diode transport properties are solved iteratively
- Diode model for given input power and temperature is used in a harmonic balance technique
Calculated Effect of Tunneling Current on Doubler Efficiency

Reverse:
- $J_s(100) = 0.2 \text{ A/m}^2$
- $n(100) = 50$
- $J_s(300) = 4 \text{ A/m}^2$
- $n(300) = 20$

Forward:
- $J_s(100) = 10^{-10} \text{ A/m}^2$
- $n(100) = 2.5$
- $J_s(300) = 0.01 \text{ A/m}^2$
- $n(300) = 1.2$

Reversed Parallel Diode Fit

**Parameters**
- $N_D = 3 \times 10^{17}$
- $C_{j0} = 55 \text{ fF}$
- $R_s = 3 \Omega$
\[ \mu_0 = \text{low field mobility} \]
\[ \mu_1 = \text{upper valley mobility } \sim 400 \text{ cm}^2/\text{Vs} \]
\[ n = n_0 + n_1 \]

\[ \frac{di}{dt} = \frac{V_{tot}(t) - V(t)}{L_i} \]

\[ \frac{dn_1}{dt} = n_{1s}(V) - n_1(t) \]

\[ V(t) = \varepsilon A \]

\[ R_0 = \frac{w}{n_0 \mu_0 A} \]

\[ R_1 = \frac{w}{n_1 \mu_1 A} \]

\[ C_d = \frac{\varepsilon A}{w} \]

Velocity response to E-field steps of 5, 10 and 15 kV/cm

- Graph showing velocity response over time (ps) for various E-field steps.
Further work is still required!
Optimization of Size and Doping for 400 GHz Doubler

400 GHz Doubler, 300 K, 50 mW

400 GHz Doubler, 120 K, 50 mW
Reverse bias degradation over time is possibly due to trapping of positive charges in the passivation near the \( \text{Si}_3\text{N}_4/\text{GaAs} \) interface. Charges may be generated by impact ionization at high reverse fields.
Accumulation of positive charge near anode perimeter

Impact ionization from electrons accelerated in high field produces high energy holes and electrons that can be trapped near the nitride/GaAs interface.

\[ N_{\text{charge}} = N_{\text{traps}} [1 - \exp(-\sigma k I t)] \]

\( \sigma = \text{trap cross section}, \quad k = \text{constant} \)

\( I = \text{current}, \quad t = \text{time} \)
• The voltage waveform across the diode for a given input power is strongly dependent on matching and anode characteristics.

• The reverse and forward currents can be calculated via harmonic balance techniques but there is no easy way to measure them.

Calculated waveform for a single diode -2.5V / 25mW

Full device has 2x3 diodes -7.5V / 150mW

RF induced currents
Simulation of a 200 GHz doubler

Currents & Performance ($V_{br} = 10.4\, \text{V}$)

$P_{av} = 25\, \text{mW/diode}$, $I = \text{current at junction}$

- Efficiency (%)
- $V_{peak\,rev}$
- $|I_{peak\,rev}|$
- $I_{peak\,fwd}$
- $|I_{avg\,rev}|$
- $|I_{avg\,fwd}|$
- $|IV_{curve}|$

RF induced currents

Reverse current is over estimated in the diode model

Operating voltage per diode min. -2.5V
Safe RF operating conditions

• By plotting voltage vs. $\sqrt{P_{\text{coupled}}}$ we can extrapolate the ‘safe operating range’.

Note: This behavior is highly dependent on frequency and circuit design.
State-of-the-art Performance

190 GHz Doubler
- 6 anodes in balanced configuration
- $10^{17}$ cm$^{-3}$ doping for good power handling

375 GHz Doubler
- 4 anodes in balanced configuration
- $10^{17}$ cm$^{-3}$ doping for good power handling
190 GHz Doubler
- Measured power up to 90 mW at 120 K
- Measured 3 dB bandwidth > 13%

375 GHz Doubler
- Measured power up to 12 mW at 120 K
- Efficiency around 20%
- Nonlinear interaction between multipliers
- $P_{\text{out}}$ limited by power handling
Representative 150 & 300 GHz Doublers

150 GHz Doubler
- 6 anodes in balanced configuration
- $10^{17}$ cm$^{-3}$ doping for good power handling

300 GHz Doubler
- 4 anodes in balanced configuration
- $10^{17}$ cm$^{-3}$ doping for good power handling

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**Graph:**
- **Y-axis:** Output Power (mW)
- **X-axis:** Frequency (GHz)
- **Legend:**
  - Green triangles: P300 (mW)
  - Blue squares: P150 (mW)
  - Pink diamonds: Efficiency (%)

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**Data Points:**
- Frequency range: 280 GHz to 320 GHz
- Output Power and Efficiency vary across the frequency range.
x2x2x2 Chain to 800 GHz

- At 120K peak power of 2mW, 3dB BW of >6%

[Graph showing output power vs. frequency for two temperatures, 120K and 300K, with a peak power of 2mW at 120K and 3dB BW of >6% across a frequency range of 700 to 850 GHz.]

800D ES2 10210022- X1 SN001
LF2 4e17, 1p0x1p1-STM4 ~15 um thick IV#2301
Planar LO chain at 1200 GHz
1600 & 1900 Chips

1600 GHz doubler
2 anodes
3 micron thick substrate
Anodes placed in the input guide

1900 GHz Tripler
2 anodes
3 micron thick substrate
Input coupling via probe
1.1-1.9 THz Solid State Local Oscillators at 120 K

State-of-the-art
THz Power Measurement

• Several power meter technologies available
  – Golay cell, Keating meter, Erickson calorimeter, Bolometer
• Each meter brings specific calibration challenges
  – Impedance mismatch / standing waves
  – Waveguide losses
  – Optical losses / coupling
  – Atmospheric absorption
  – Drift
  – Sensitivity
  – Maximum power limits
• Factor of 2 discrepancies are common
• Agreement to 30% may be possible with care

→ The ultimate figure of merit is to pump a mixer.
Assumptions: 150 mW in at 92-106 GHz
120K operation, 5% bandwidth
Ref: Ward et. al. (IEEE-MTTS 2004 Symposium)
The measured data can be fit to…

\[ \eta(f) = \eta_0 \cdot e^{f/f_0} \]

\[ \eta(f) = \eta_0^N \cdot \exp \left[ \frac{f}{f_0} \cdot \sum_{i=0}^{N-1} 2^{-i} \right] \]

Single stage

Cascaded chain

<table>
<thead>
<tr>
<th>Description</th>
<th>( h_0 )</th>
<th>( f_0 ) (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doubler, 295 K, Peak</td>
<td>0.45</td>
<td>600</td>
</tr>
<tr>
<td>Doubler, 295 K, 5% B.W.</td>
<td>0.45</td>
<td>410</td>
</tr>
<tr>
<td>Doubler, 120 K, Peak</td>
<td>0.50</td>
<td>650</td>
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<tr>
<td>Doubler, 120 K, 5% B.W.</td>
<td>0.47</td>
<td>520</td>
</tr>
<tr>
<td>Tripler, 120 K, Peak</td>
<td>0.32</td>
<td>490</td>
</tr>
<tr>
<td>Tripler, 120 K, 5% B.W.</td>
<td>0.27</td>
<td>390</td>
</tr>
</tbody>
</table>
LO Chain efficiencies as function of temperature and bandwidth

<table>
<thead>
<tr>
<th>Design</th>
<th>Freq (GHz)</th>
<th>295 K</th>
<th>120 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>190 GHz doubler</td>
<td>190</td>
<td>30.6</td>
<td>32.8</td>
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<tr>
<td></td>
<td>185</td>
<td>33.5</td>
<td>39</td>
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<tr>
<td>200 GHz doubler</td>
<td>194</td>
<td>28.1</td>
<td>29.4</td>
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<tr>
<td></td>
<td>200</td>
<td>31.8</td>
<td>38.3</td>
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<td>375 GHz doubler</td>
<td>370</td>
<td>14.7</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>370</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>400 GHz doubler</td>
<td>385</td>
<td>14.9</td>
<td>18.3</td>
</tr>
<tr>
<td></td>
<td>370</td>
<td>18.3</td>
<td></td>
</tr>
<tr>
<td>750 GHz doubler</td>
<td>730</td>
<td>6.7</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>775</td>
<td>10.4</td>
<td>28</td>
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<tr>
<td>800 GHz doubler</td>
<td>775</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>1500 GHz doubler</td>
<td>1510</td>
<td>1.1</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>1510</td>
<td>3.5</td>
<td>5.2</td>
</tr>
<tr>
<td>600 GHz tripler</td>
<td>540</td>
<td>5.3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>580</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>1200 GHz tripler</td>
<td>1200</td>
<td>1.3</td>
<td>1.9</td>
</tr>
<tr>
<td>1800 GHz tripler</td>
<td>1740</td>
<td>a</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*Note: Values marked with 'a' are approximate.*
Output Power vs Block Temperature

- 1500 GHz
- 1200 GHz
- 800 GHz
- 400 GHz
- 200 GHz

Block Temperature, K

Power (mW)
Challenges

• More efficient higher freq power amps? InP, pHEMT
• Improve bandwidth—better designs, re-configurable
• Simplify chain construction—micro-machined blocks, increased integration
• Planar device/modeling—increase yield, increase throughput and uniformity, reduce time to completion
Challenge: increase output frequency

Planar Diode properties:
Membrane thickness: 3 micron
doping: $5 \times 10^{17}$ cm$^{-3}$
Anode dimensions: 0.14 x 0.6 um

Figure 1. Schematic of the all-solid-state source to 2500 GHz. Dashed outlined components are either commercially available or have already been demonstrated in our laboratory. Solid outlined components are to be developed under this proposal.
Challenge: multipixel receivers

- To increase output power
- Multiple frequency coverage
- Multiple pixel coverage

Components available, architecture, system issues need to be studied

Kim et al
1 mW at 600 GHz
Concluding Remarks

- Multiplier chains (200 to 1900 GHz) are now possible that are
  - Robust
  - Broadband (5 to 10 %)
  - Cool-able
  - Sufficient to pump SIS and HEBs
- Frequency range of 2-3 THz is attainable
- Wider bandwidths (>10%) are attainable
- Higher output power is possible with power combining techniques
- Leverage current technology for large format arrays