Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: *With InP HEMT, THz Dreams are Taking on a More Solid State*
Date Submitted: *14 July, 2011*
Source: *Stephen Sarkozy* Company *Northrop Grumman Aerospace Systems (NGAS)*
Address *One Space Park, Redondo Beach, 90278, California, United States of America*
Voice:*310-812-1106*, FAX: --, E-Mail: *stephen.sarkozy@ngc.com*

Re: [*N/A*]

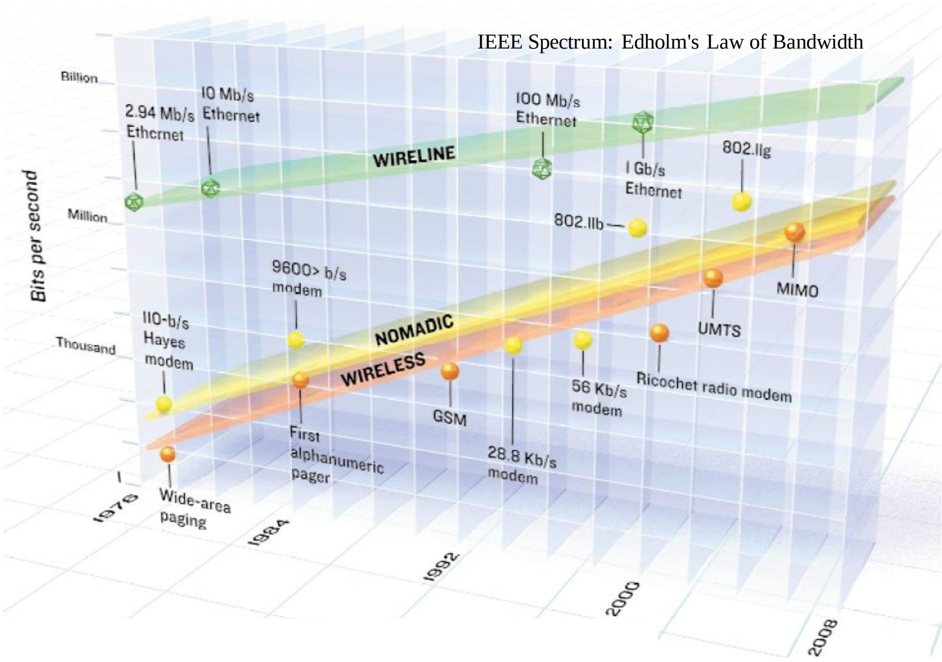
Abstract: This document contains some of the work done by NGAS with regards to advanced high frequency millimeter wave, sub-millimeter wave, and terahertz solid state technology.

Purpose: IEEE P802.15 may use this document to promote discussion at interest groups, including posting the document publically. This document is not meant to be a transfer of copyright of the information from NGAS to IEEE. Portions of this work were conducted under DARPA THz Electronics, DARPA HiFIVE, NASA GRIP, and JIEDDO LORPI, and material has been appropriately cleared for public release.

With InP HEMT, THz Dreams are Taking on a More Solid State

Stephen Sarkozy

Need for access to THz Spectrum



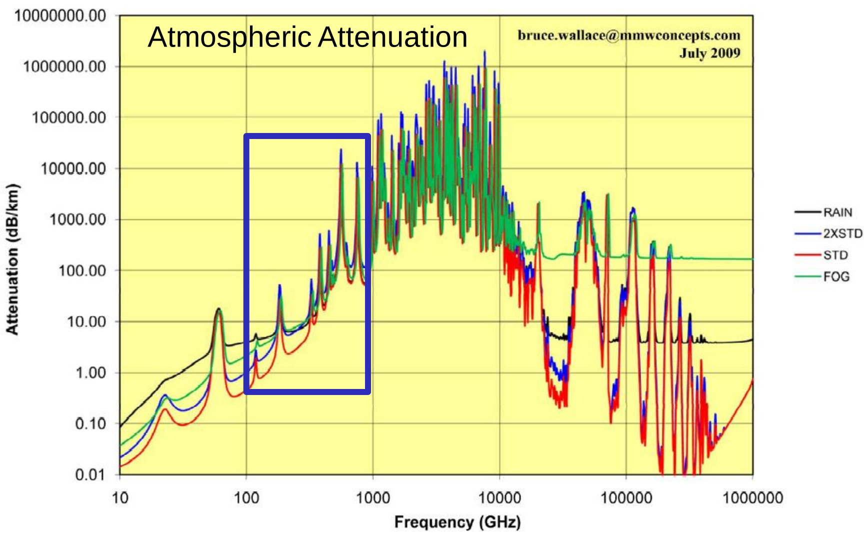
• Information driven society and consumers have shown an insatiable need for greater data rates spanning decades (Edholm's Law), and are showing no signs of subsiding

• Spectral reuse and trying to cram more bits/Hz is offering diminishing returns

• Need for access to a reservoir of untapped and reusable spectrum to satisfy next generation of data transfers needs (3D High Definition resolution, continual access to cloud computing, real time 360 awareness and projection

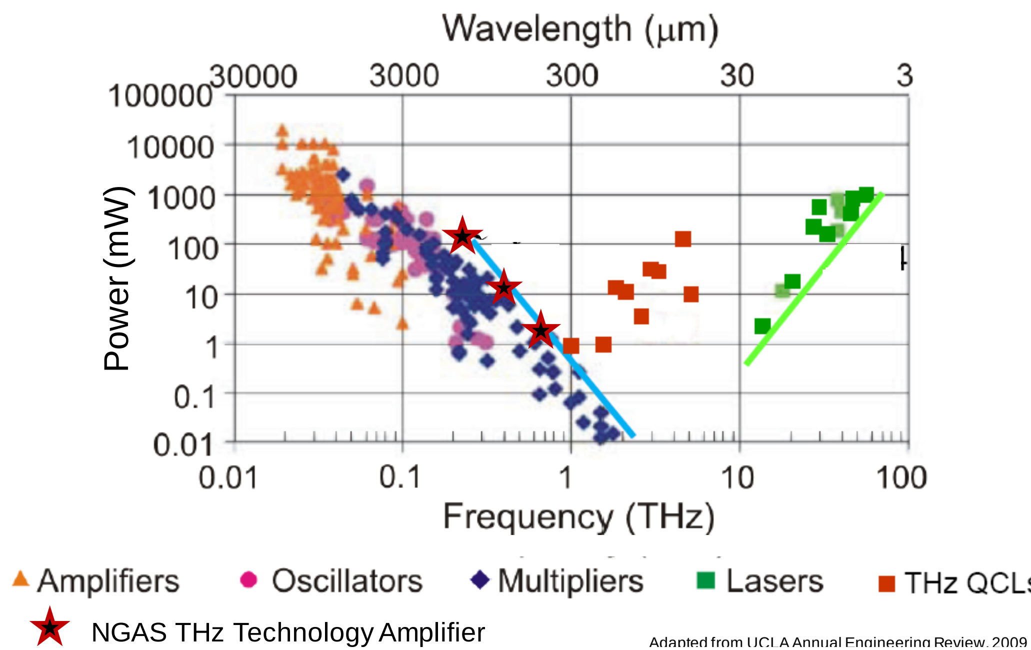
• THz frequency (0.1 to 1 THz) solid state electronics is the only solution which can meet the requirements of the consumer:

- Low Receiver Power consumption (battery life)
- Low cost (Batch Fabricated micro/nano electronics)
- High Reliability
- Selectable attenuation windows/bands to tailor point-to-point, point-to-multipoint, and other signal sharing operation concepts
- Evolutionary/Revolutionary Blend
  - Evolution – Consumer understands microchips, semiconductors - uses them in products today
  - Revolution – Game-changing capabilities with regards to integration, performance, and capabilities only tomorrow's generation can even imagine



Solid State Amplifiers for the THz Power Gap

- Fundamentally Room Temperature Operation
- Broadband operation
- Small form factor solution – often single chip
- Potential for low-cost, high volume production
- Low DC power consumption
- Amplifiers started operating in SMMW regime ~ 5 years – significant improvement to come.
- Mixers/multipliers operating ~ 3 decades, performance likely saturated



Solid State Amplification At Frequency is the Best Candidate Technology for Bringing THz Systems to Life

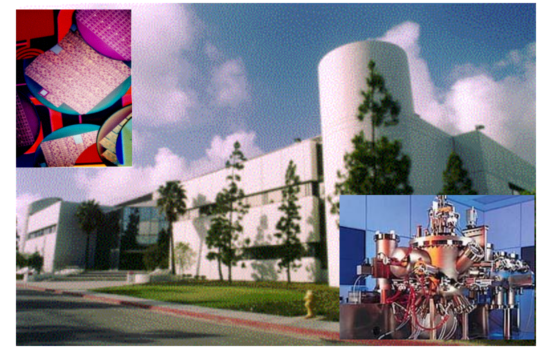
Space Systems Division

Strike and Surveillance Systems Division

Battle Management and Engagement Systems Division

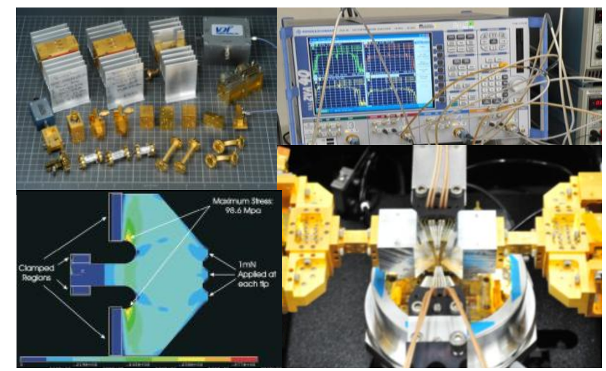
Advanced Programs and Technology Division

NGAS Terahertz Product Overview



Multi-use microelectronics foundry

- Flight-qualified, commercial, and R&D run on common fabrication line
- 100mm and 3” front side labs totaling 25,000 sq. ft.
- Multidisciplinary THz MIC “TMIC” team lead by NGAS Technology Fellow (Product, MBE, EBL, Process)



Dedicated high frequency design team

- Subject Matter Experts in mmW, smmW, and THz design
- Design experience in low noise amplifiers, power amplifiers, and frequency converting circuits

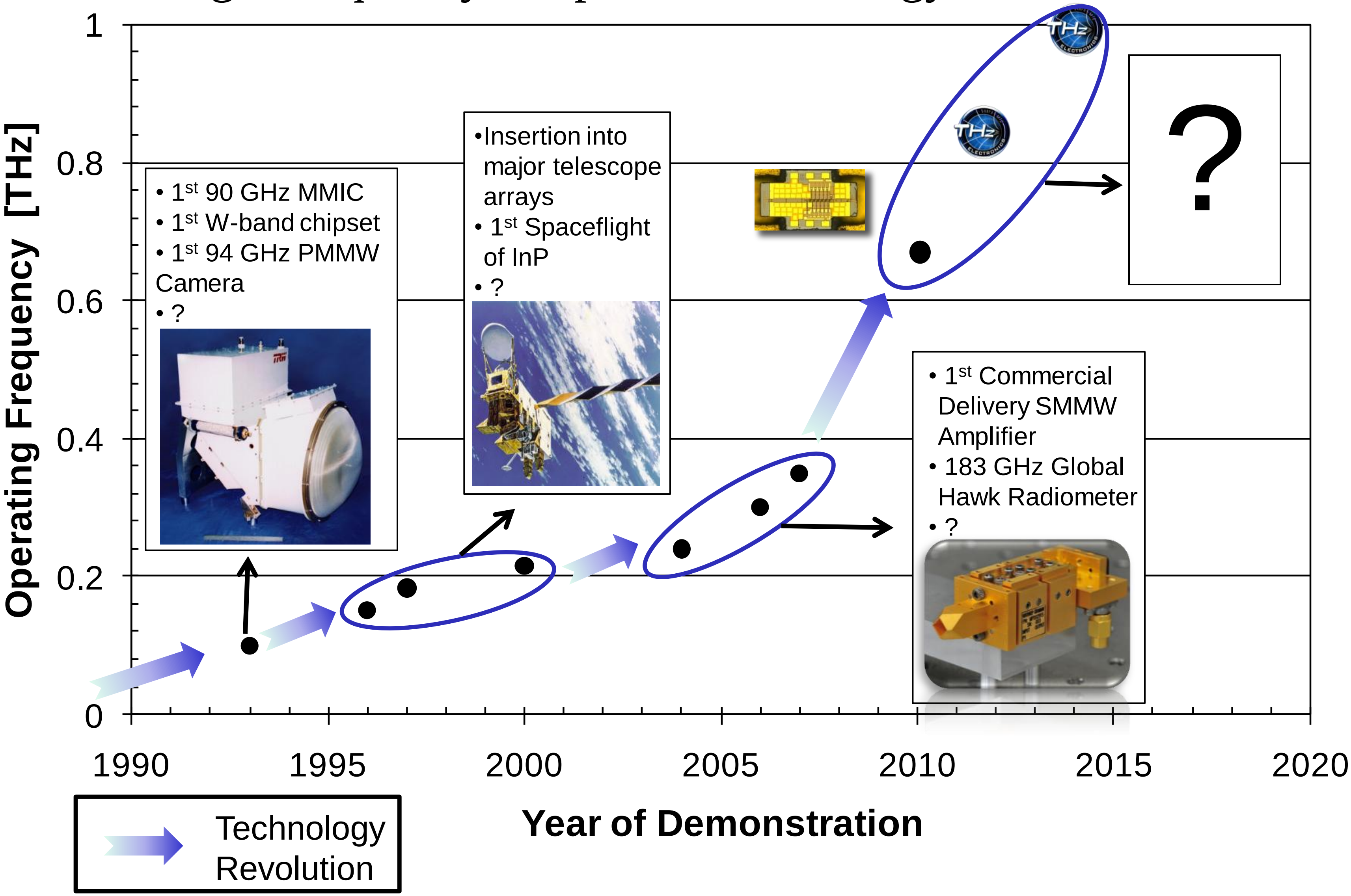
Dedicated THz Laboratory and state of art testing facilities

- On-wafer vector analysis to >700 GHz
- Power and noise figure measurements through 700 GHz
- Non-linear testing to 700 GHz
- Trained technicians in high frequency assembly and test
- Equipment and knowledge to build custom test setups
- Internal and external precision machine shops for THz frequency packages

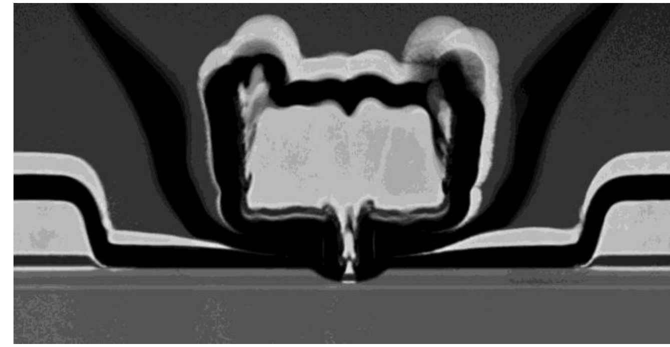
Extensive publication list, trade secrets, patents, and awards

- >100 papers and proceedings on smmW and THz results
- Trades secrets, patents, and pending patents on THz processes and technology
- Multiple records including Guinness World Record for Fastest Transistor
- DARPA MTO Coin #250

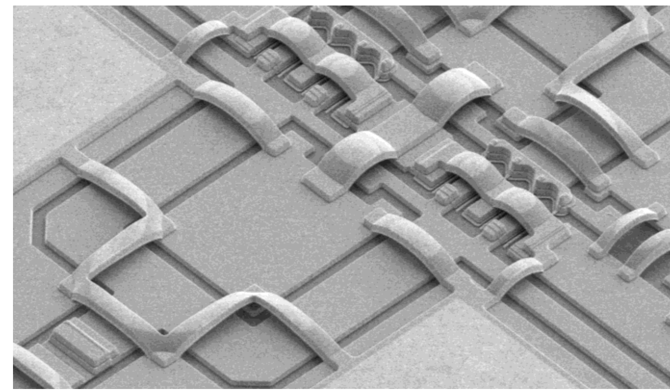
NGAS High Frequency Amplifier Technology



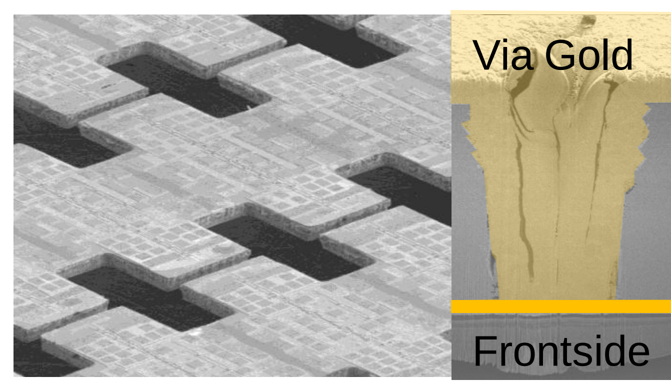
Sub-50nm InP HEMT Technology



Molecular Beam Epitaxy
- 3’’ wafers
- Indium Arsenide Composite Channel (IACC)
- μ > 14000 $cm^2/V \cdot s$, $n_s = 3.5 \times 10^{12}$ cm^{-2}
- Composite cap for tunnel Ohmic Contacts



IACC HEMT IC Features
- Non-alloyed Ohmic Contact
- sub-50nm T-gate
- 600 pF/mm Metal-Insulator-Metal Capacitors
- 20 and 100 Ω/ Thin Film Resistors
- Two layer metal interconnect with air bridges
- PECVD SiN passivation
- Substrate thinning to 25 -75 μm (frequency dependent)
- Scaled transmission lines and passive/active layouts

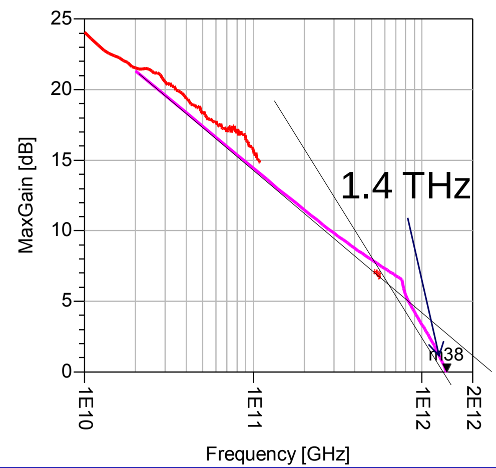


Process Commonality
- Same Fabrication Line for spaceflight, commercial, R&D
- Same MBE, EBL, and process for Low Noise Amplifiers, Power Amplifiers, and Frequency Conversion circuits
- High Frequency ICs small – multiple designs/circuit on a single wafer
- Macrocells and System-on-Chip Possibilities

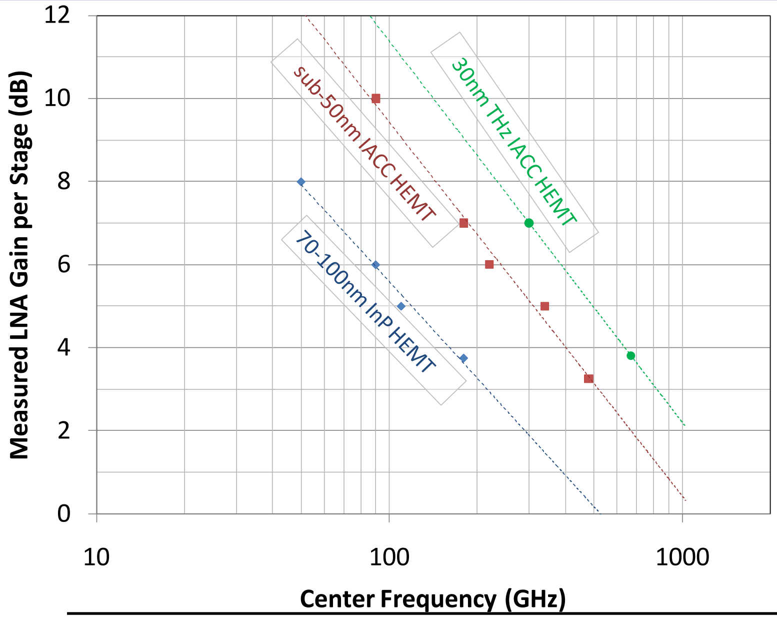
Terahertz Transistor Performance

- High f_{MAX} / f_T enable revolutionary circuit performance
- Highest Gain/Stage circuits to 670 GHz
- Gain, Threshold, and Phase uniformity
  - Power combining demonstrated up to 32 fingers in last stage
  - 10 stage LNA biased of single V_d and V_g voltages
  - High yield circuits and Macro-cells
- Single device profile for low noise amplification, high power amplification, and frequency conversion

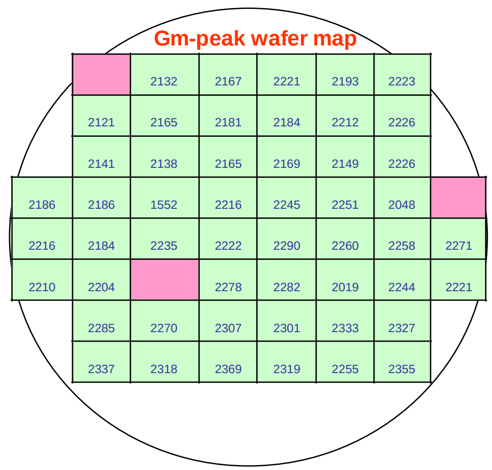
THz f_{MAX}

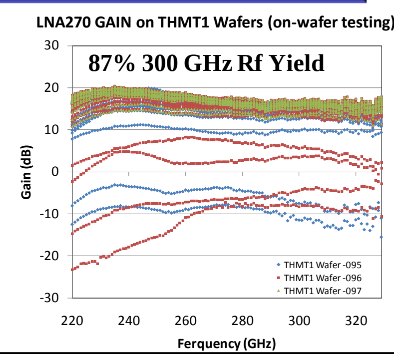


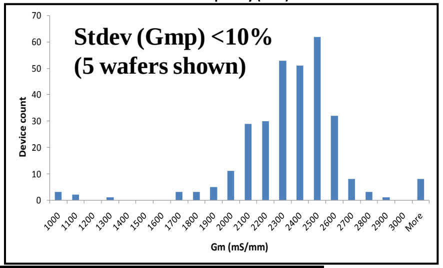
Gain per stage



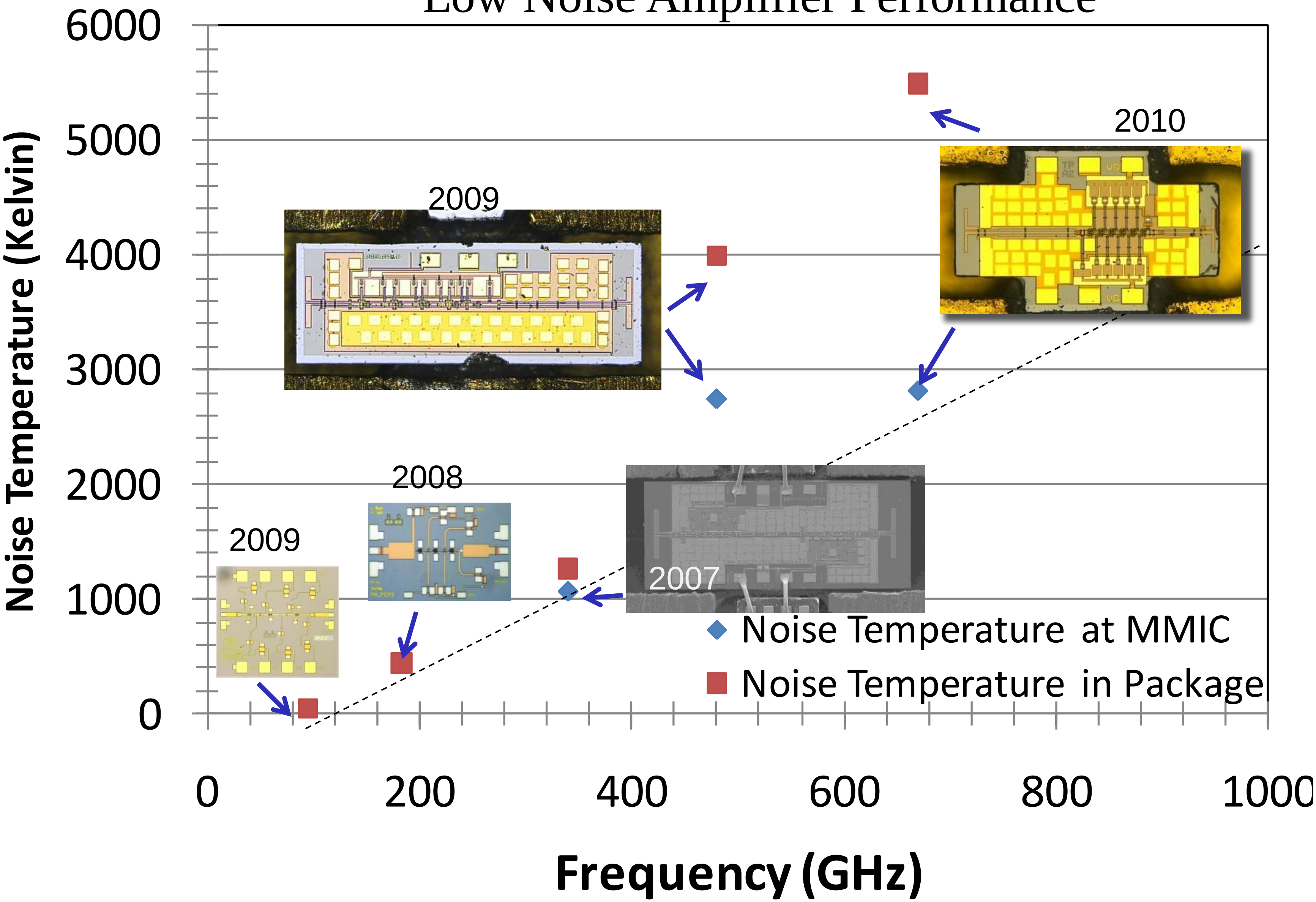
Uniformity



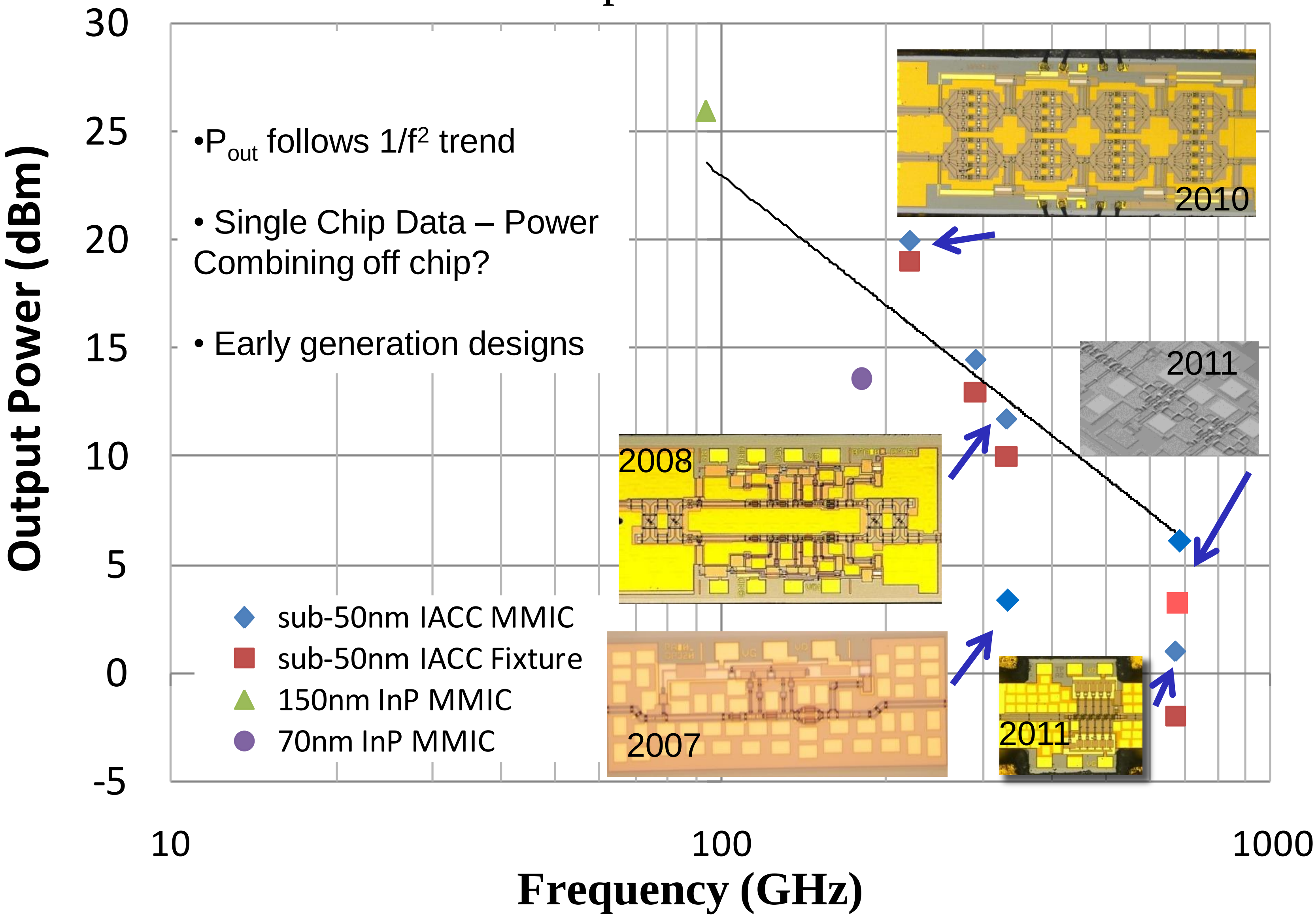




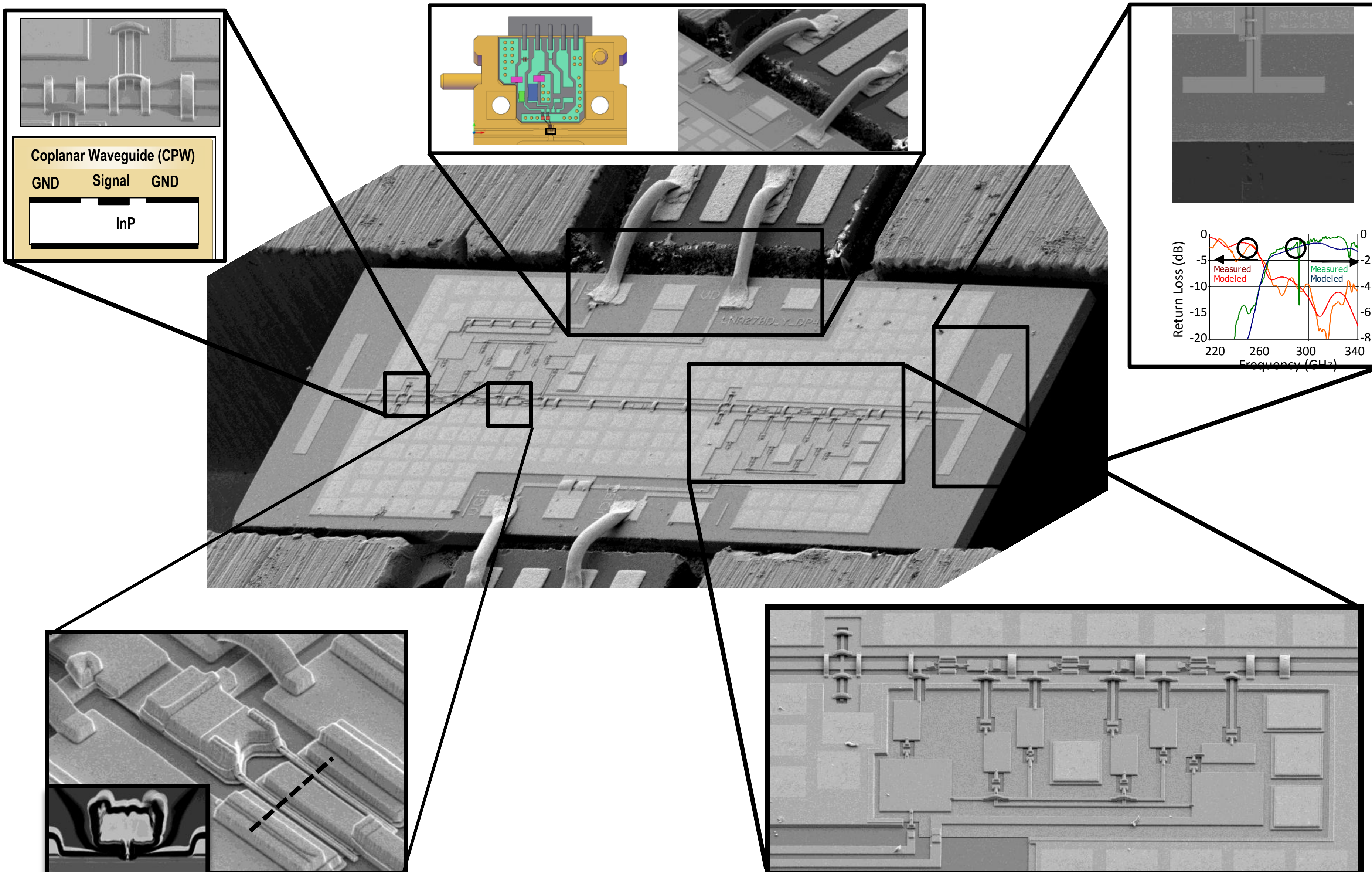
Low Noise Amplifier Performance



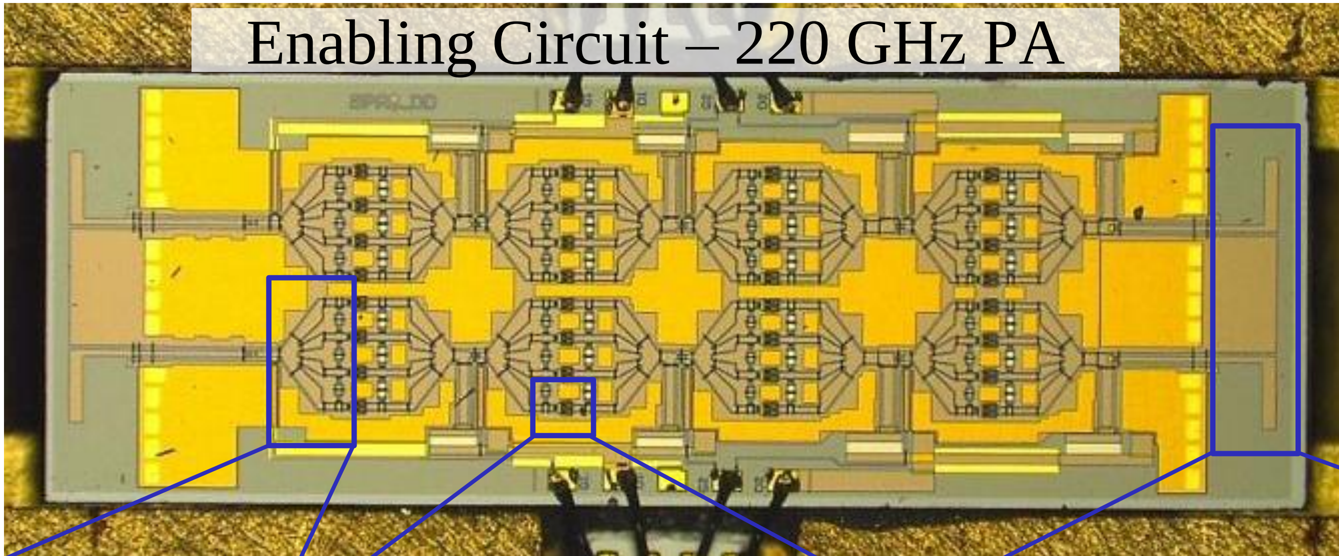
Power Amplifier Performance

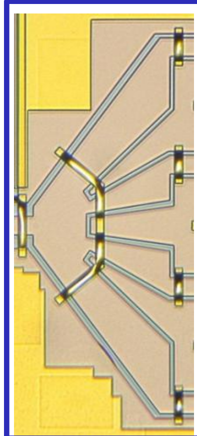


Enabling Circuit – 340 GHz LNA



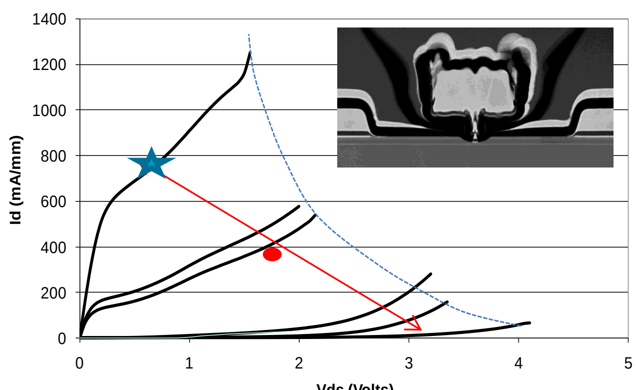
Enabling Circuit – 220 GHz PA



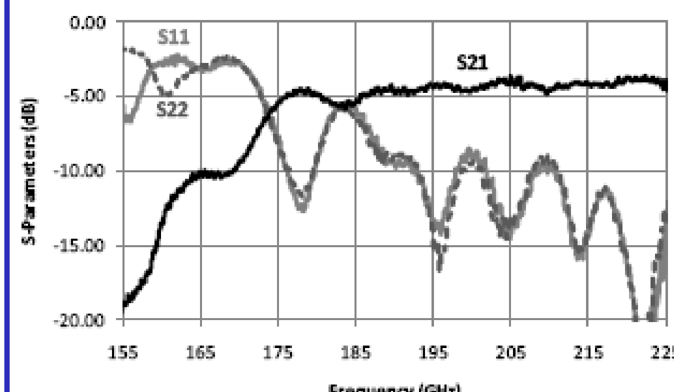


4-1 "fan" Combiner:
- Built in transformer absorbs matching networks
- 12.5-ohm input impedance
- 50-ohm output impedance
- Measured IL: < 2 dB

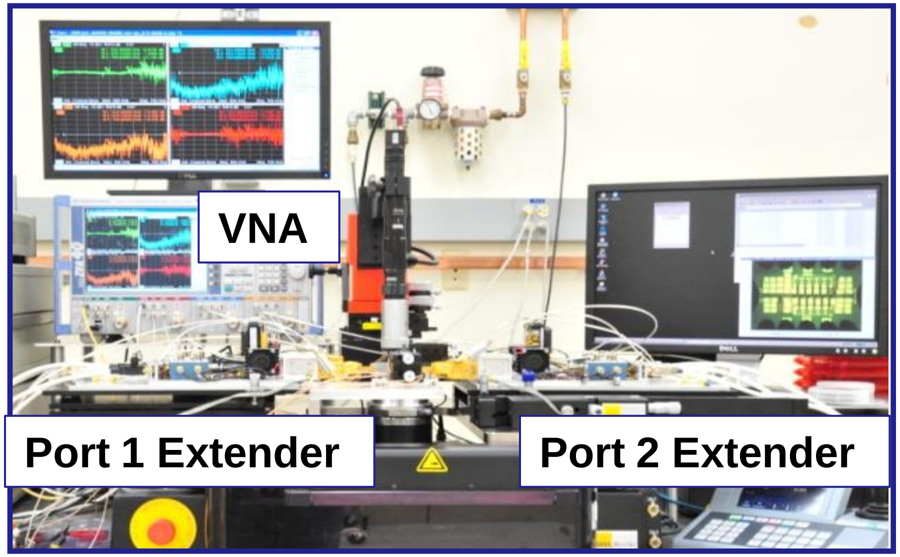
THz Transistor:
- Bias for high power and RF swing
- Can optimize Epitaxy for power device
- >1mm total gate periphery



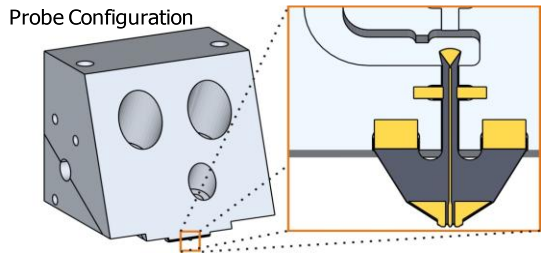
Low Loss Dual Dipole:
- Power Combining Transition to Waveguide
- Low Loss and excellent phase matching

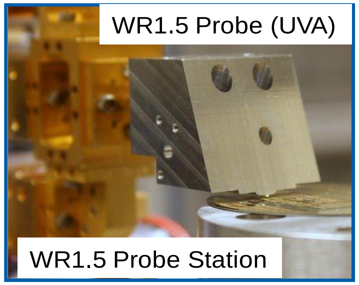


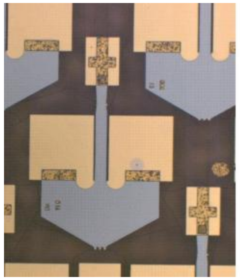
THz Measurement Capability

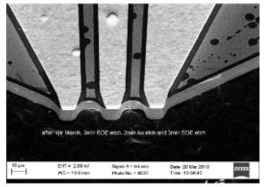


Images of WR-1.5 probe circuits and probe tip

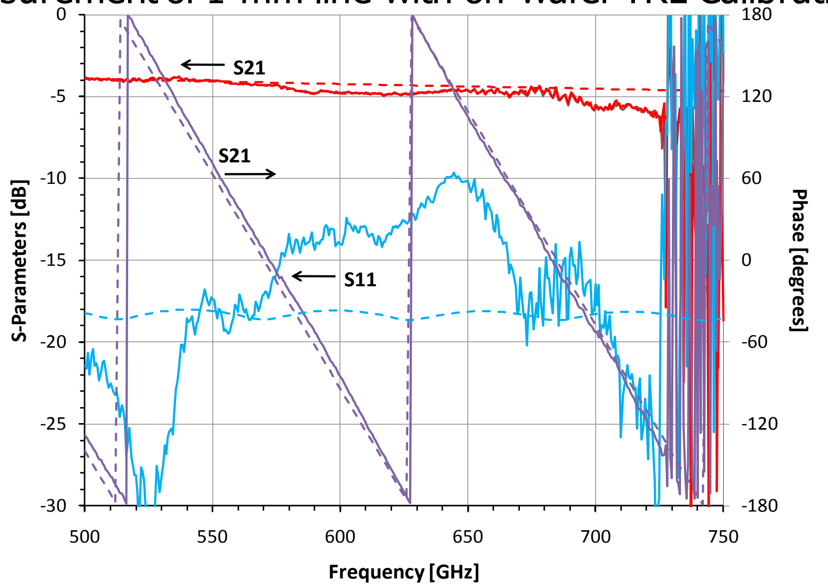








Measurement of 1-mm line with on-wafer TRL Calibration



THz Metrology Infrastructure “Needs”

- Method for evaluating large sample of designs
- Should be relatively low-cost (not packaged chips)

NGAS THz Metrology Infrastructure Capabilities

- On-Wafer Measurements from 140-950 GHz
- Waveguide Measurements from 70-1000 GHz
- Power Sensors from 70-1000 GHz
- Sources from 180-670 GHz
- Receiver from 180-1000 GHz

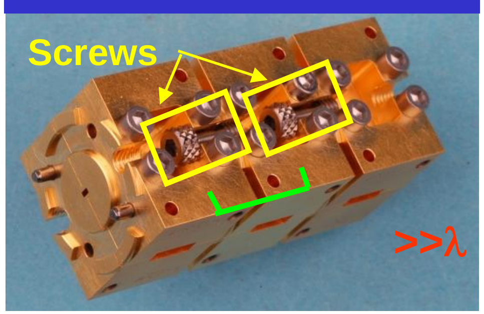
THz Collaboration

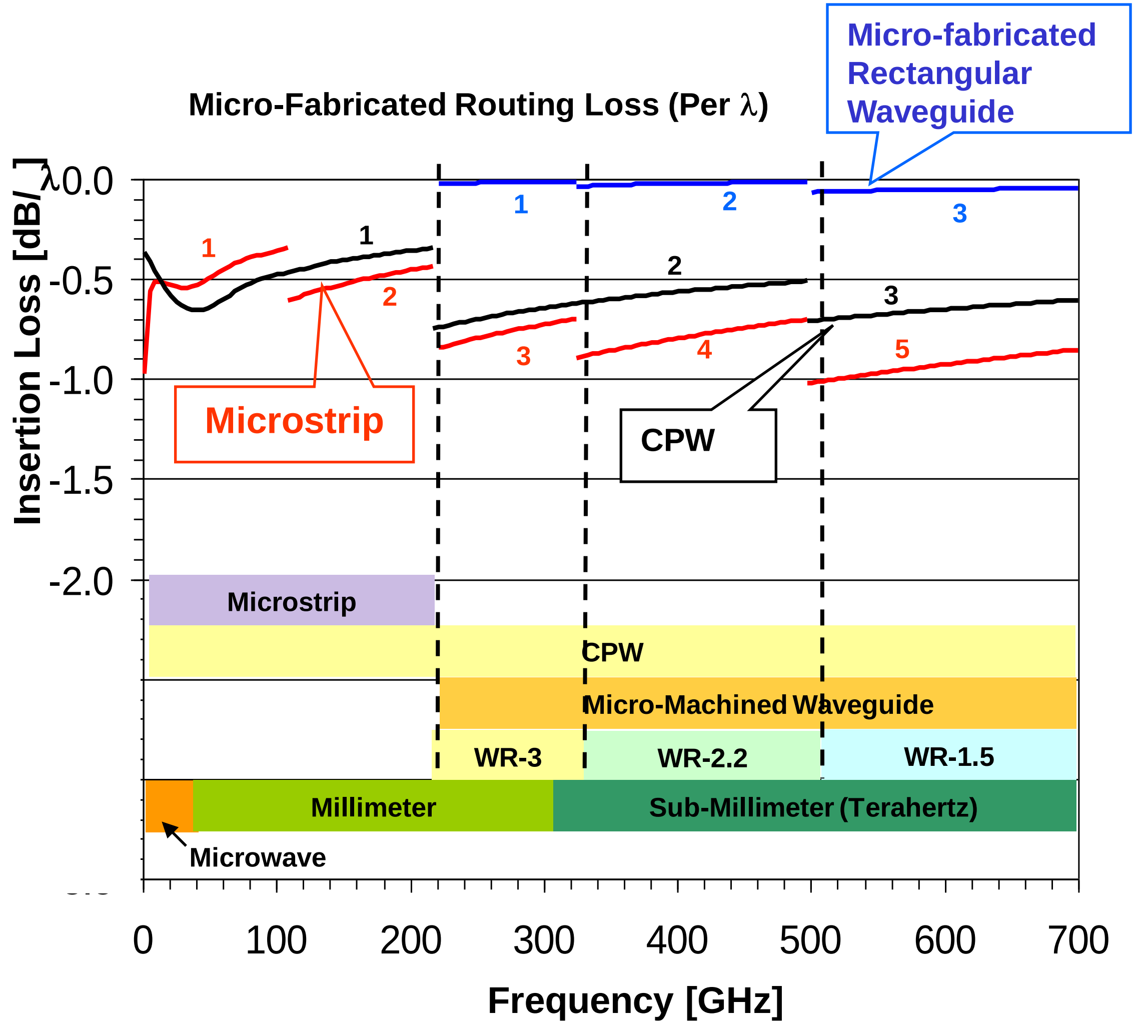
- Frequency Extenders developed by Virginia Diodes, Inc
- Probes developed by University of Virginia

SMMW Integration Limitations

- Physically scaling interconnect dimensions with wavelength virtually eliminates frequency dependence of the interconnect
- At SMMW (THz) frequencies, scaled interconnects requires micron-scale geometries

Machined Interconnects



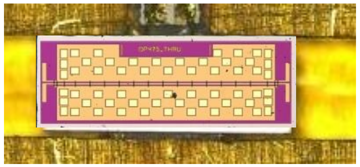


Micron-Scale Wavelengths Require Micron-Scale Interconnect Technologies

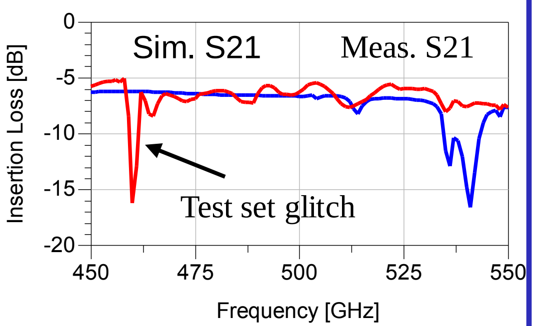
WR1.5 Fixture Evolution

WR2.2 Dipole Transition

320 µm



CPW thru chip in fixture

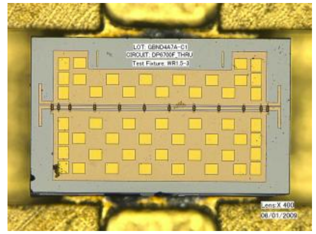


• Successful fabrication of 500 GHz transition on 1-mil InP

<u>Outcome:</u> Demonstration of 1 mil InP chip

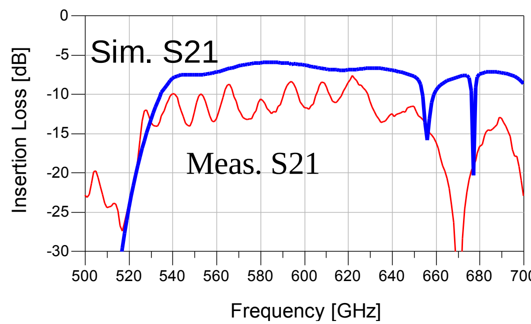
WR1.5 Dipole Transition v1

375 µm



Chip width set by circuit size

CPW thru chip in fixture



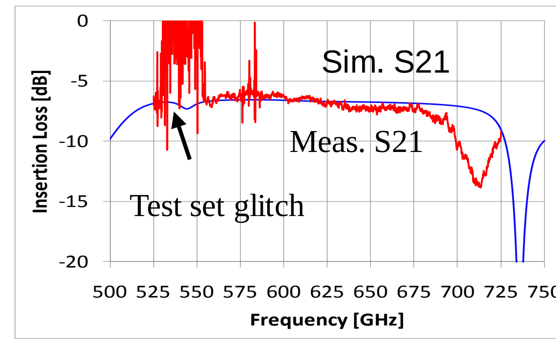
• Ripples in transmission measurement, due to low via density per wavelength, and orthogonal waveguide modes excited in wide chip fixture

<u>Outcome:</u> Need for more densely spaced vias and reduced chip width

Scaled chip width WR1.5 Transition

270 µm

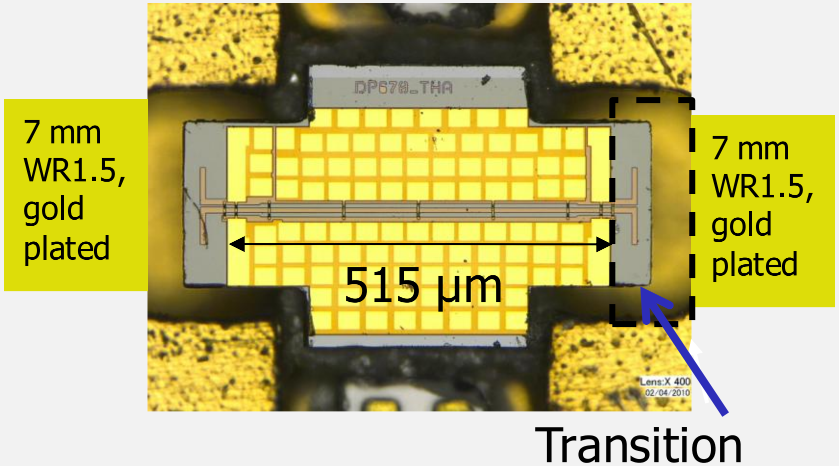
CPW thru chip in fixture

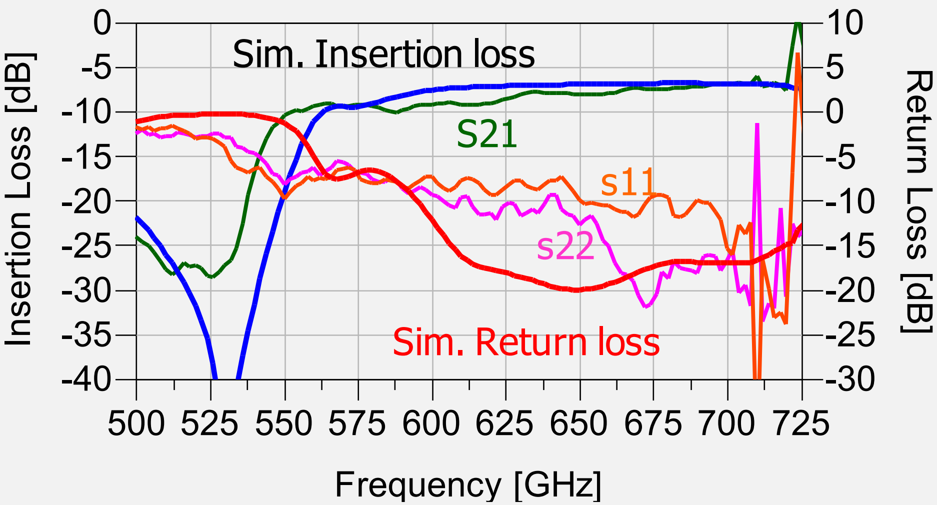


<u>Outcome:</u> Demonstration of dense vias, shows need for scaled chip width, but need more space for circuit

WR1.5 Fixture Evolution

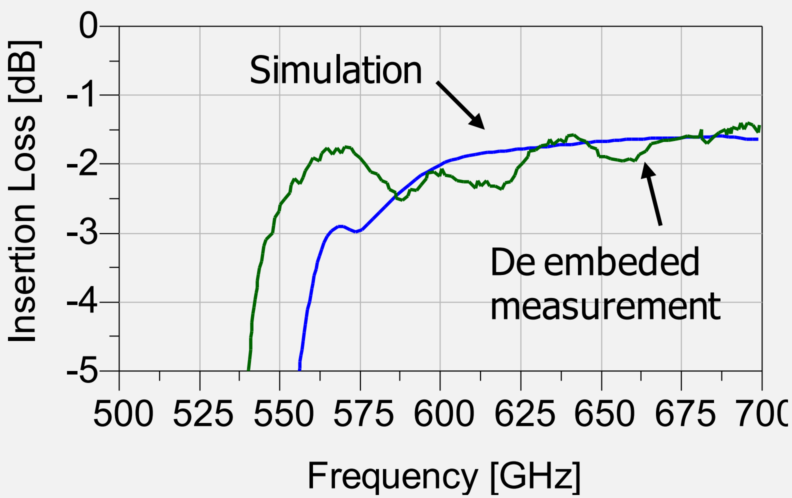
WR1.5 Integrated dipole probe with thru line





Loss mechanisms	Loss @ 670 GHz	Comments
Transition	~1.7 dB	Agrees with simulation, verify CPW loss
515 µm CPW	~2.25 dB	Based on W-band data (measure at 670 to verify)
7 mm WG	~0.75 dB	Based measured conductivity at 670 GHz
Total TMIC external loss (WGx2+DPx2)	~4.9 dB	Two transitions with waveguide loss

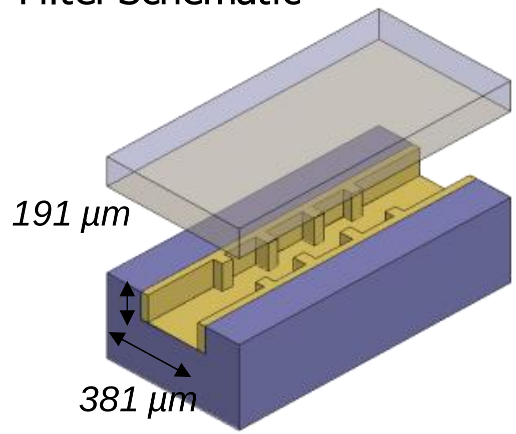
Single Dipole Insertion Loss



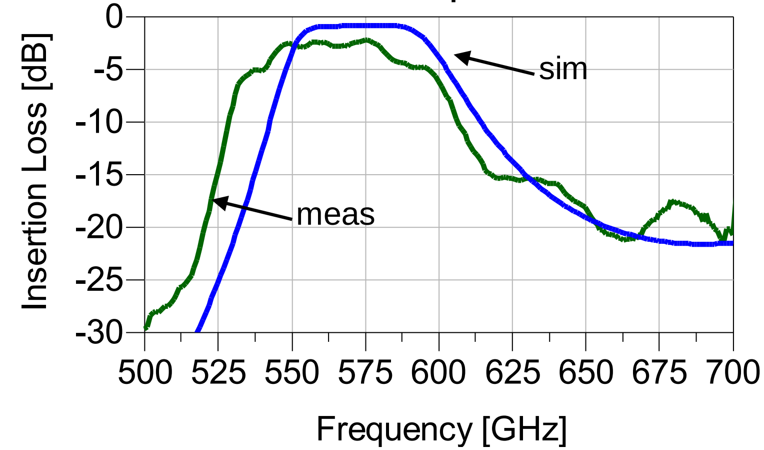
Future THz Integration

Direct integration of components with micromachined filters and waveguide will enable improved performance

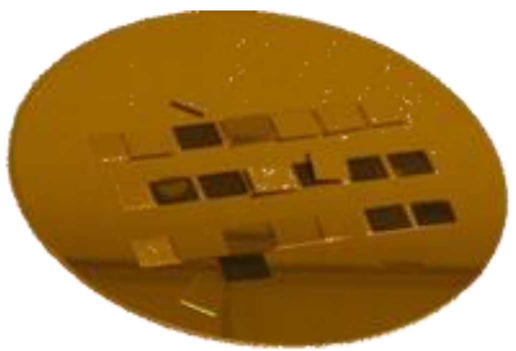
Filter Schematic



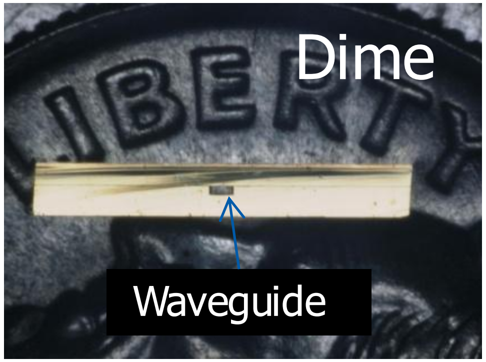
Filter Response



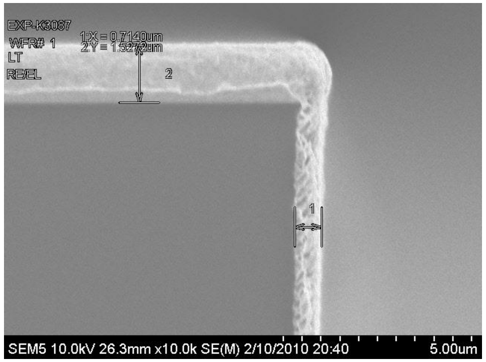
Batch-Fabricated Waveguide



Waveguide End-View



Waveguide Corner

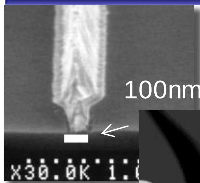


Low-Loss Batch Fabricated Integration and Waveguides

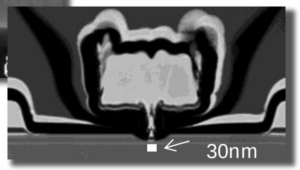
The Solid State Terahertz Solution

Fundamental Nanotech Components

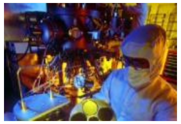
Electron Beam Lithography

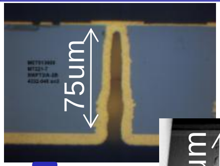


Dual-Develop Technology

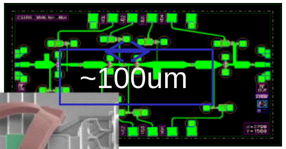


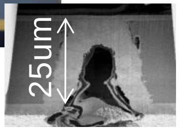
Advanced Layout and Processing

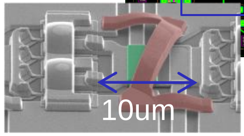




Scaled Material.
Scaled Wafers.
Scaled Layout.

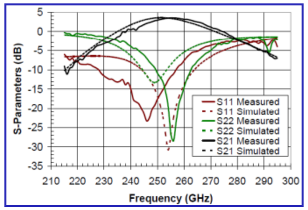




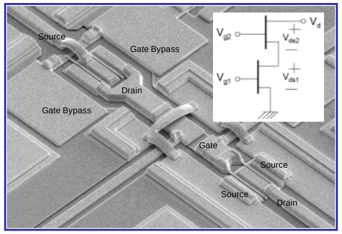


Leading THz Circuit Expertise

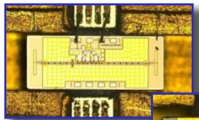
THz Modeling



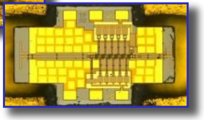
THz Design Techniques



Custom Shape



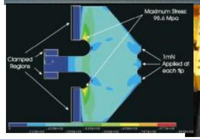
Suppress Substrate Modes

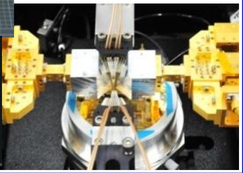


Understanding Terahertz Integration

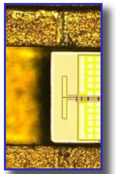
Metrology

THz Components.
THz Probes.
THz Stations.





Connectivity



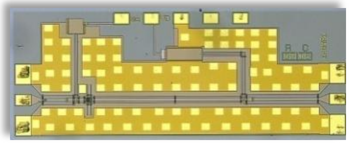
Electromagnetic Transition to Engineered Waveguide

Packaging

Micromachined Waveguide

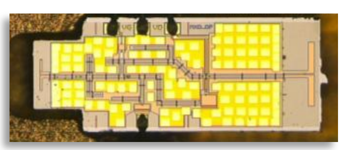
Terahertz Transceiver

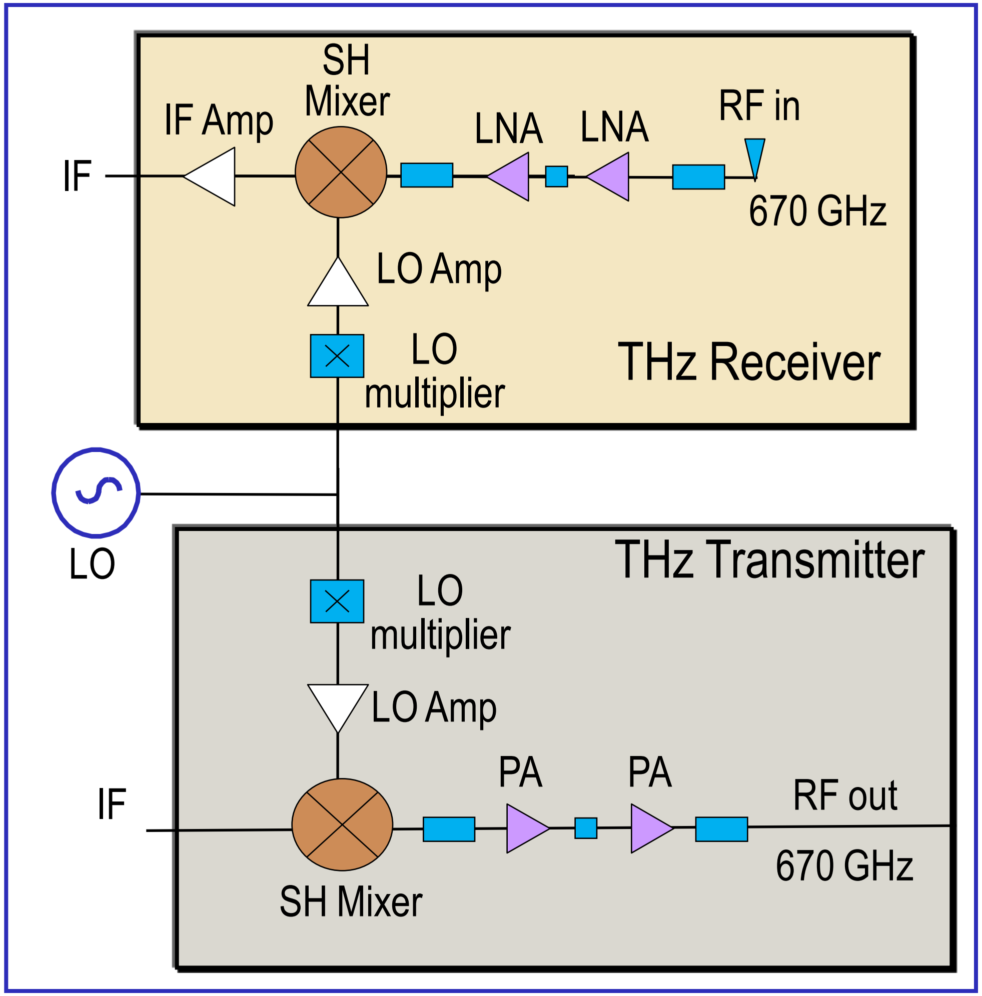
IF Amp



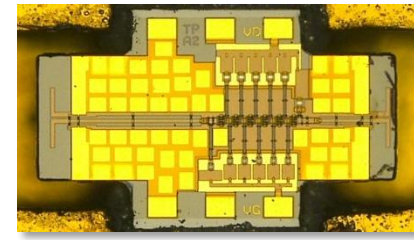
LO Amp

SH Mixer

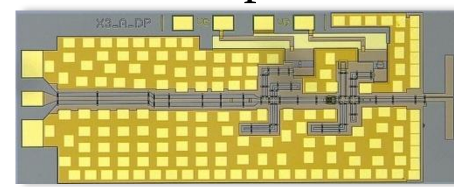




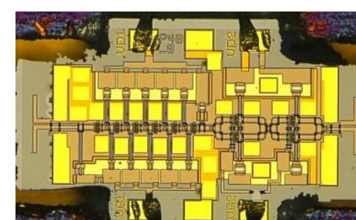
LNA TMIC



LO Multiplier



PA TMIC



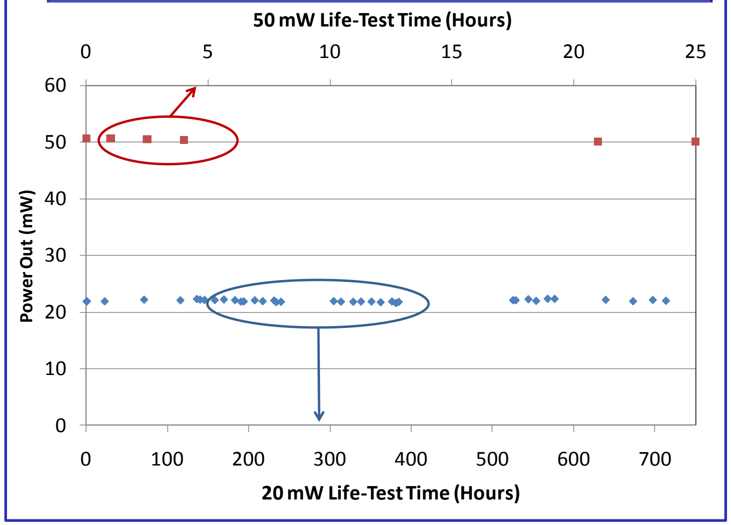
THz Transceivers are possible with THz amplifiers

Architecture of DARPA THz Electronics Program

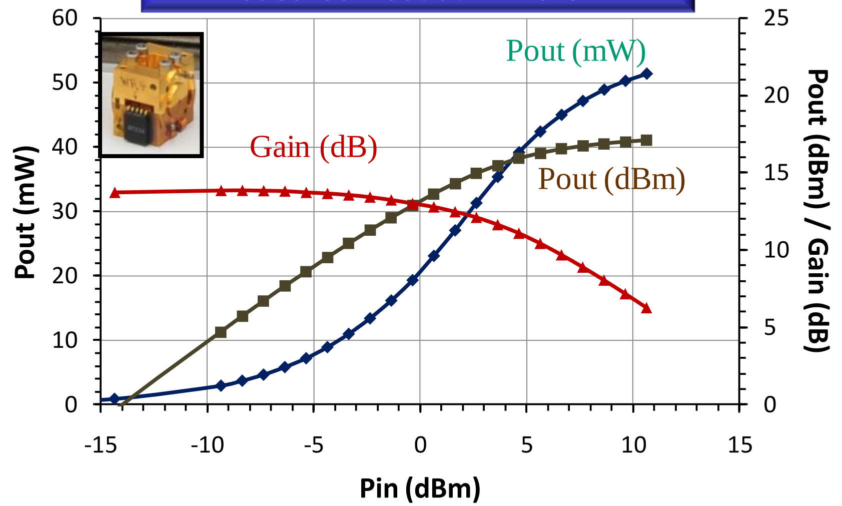
220 GHz PA

- Program Goal - microfabricate vacuum tube delivering ~5W output power centered at 220 GHz
- 50mW output power at waveguide flange
- Preliminary Life Test - no degradation with > 1 month continual operation at 20mW

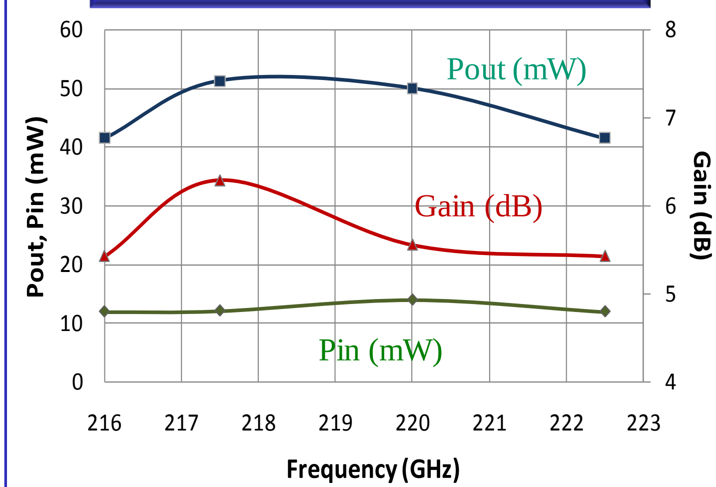
Preliminary Life Test



Measured Pout at 217.5 GHz



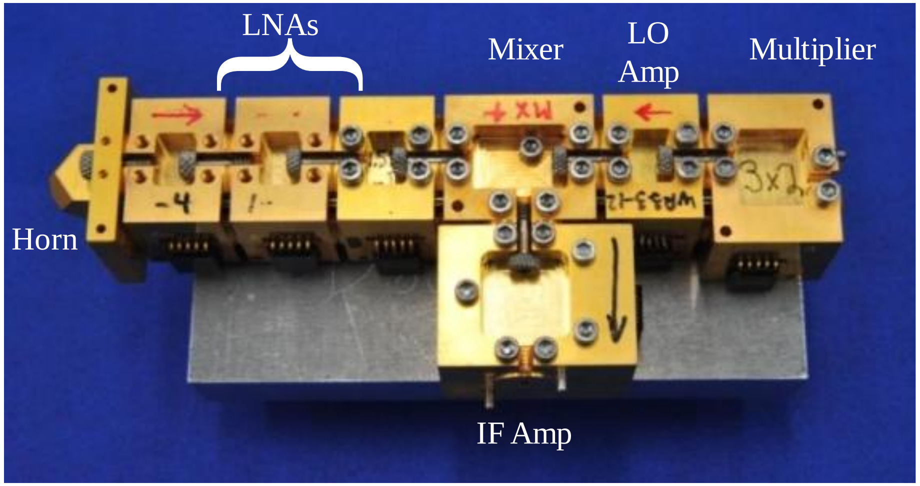
Measured Pout vs. Frequency

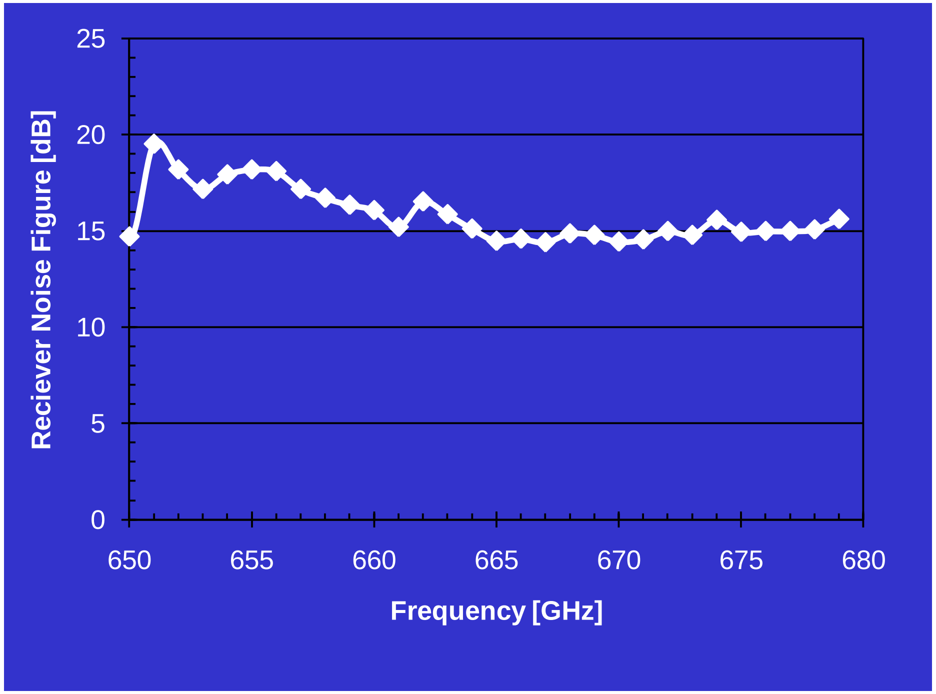


Results from DARPA HiFIVE program

Complete Terahertz Receiver

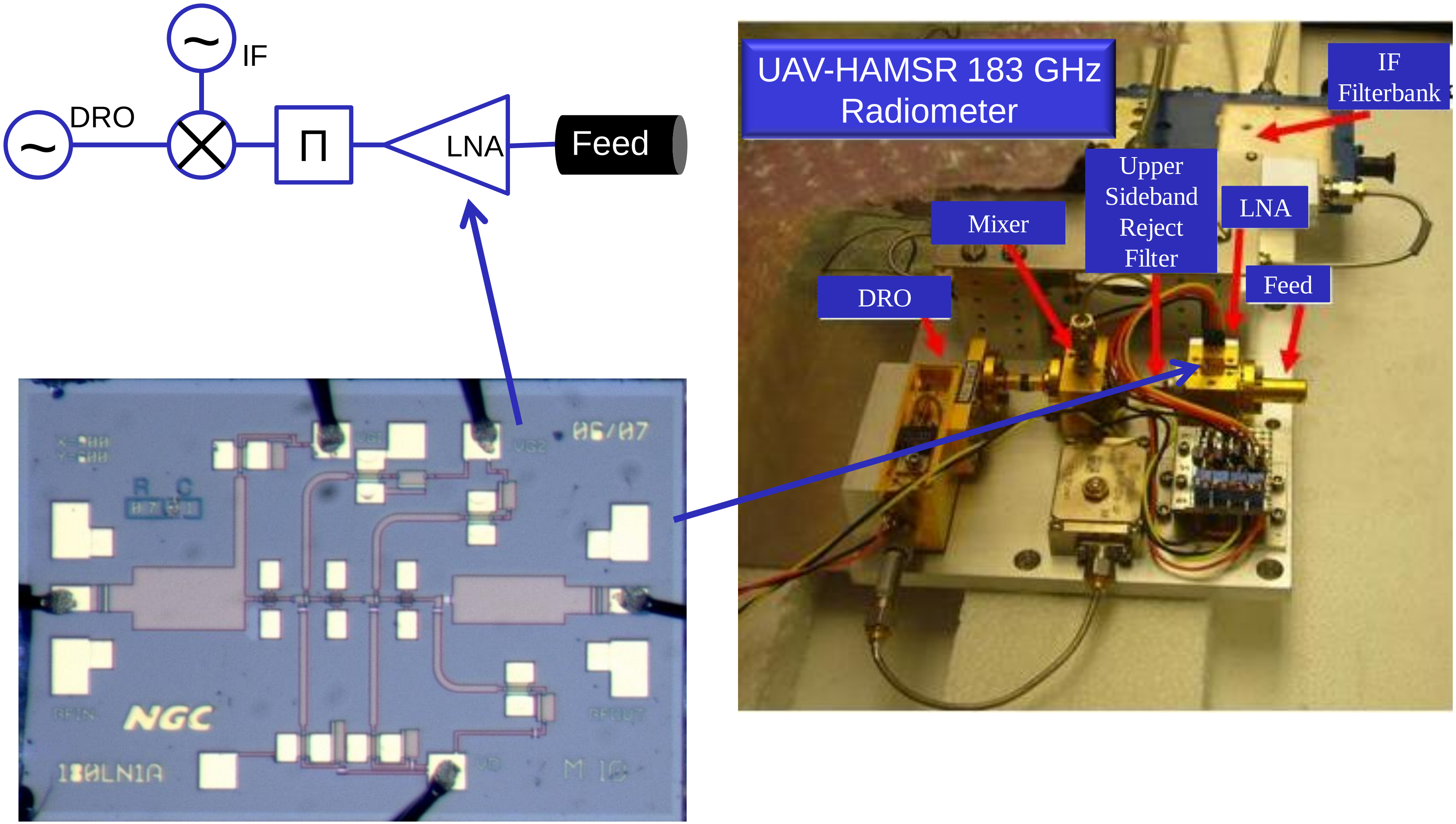
- First Demonstration of a THz Receiver, ~15dB Noise Figure from 660-680 GHz
- Room temperature performance roughly comparable to single-sideband Schottky mixers, cooling will increase performance significantly
- DC power consumption ~50x reduced in comparison to mixer/multiplier technology
- Realized completely in InP HEMT technology
  - IACC Molecular Beam Epitaxial Profile
  - Sub-50nm Gates
- Single technology allows for multiple functions integrated on a single chip to reduced losses and improve performance





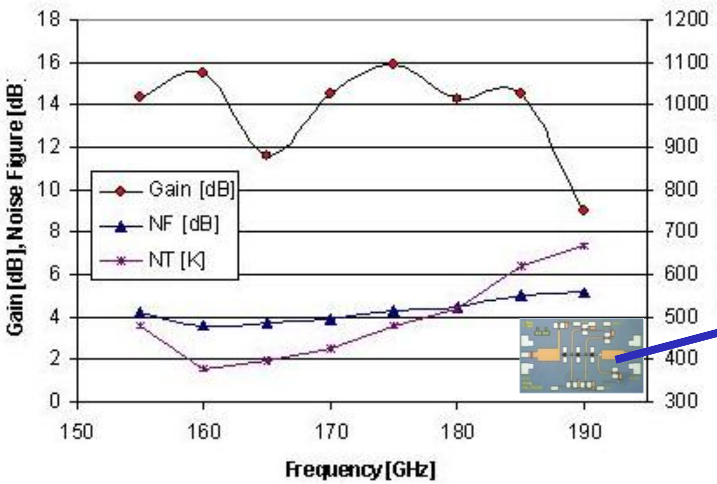
To be published in IEEE Terahertz Transactions, Inaugural Issue

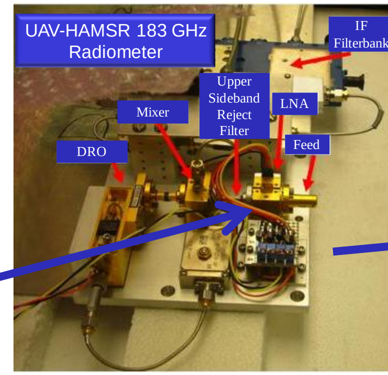
Global Hawk Radiometer

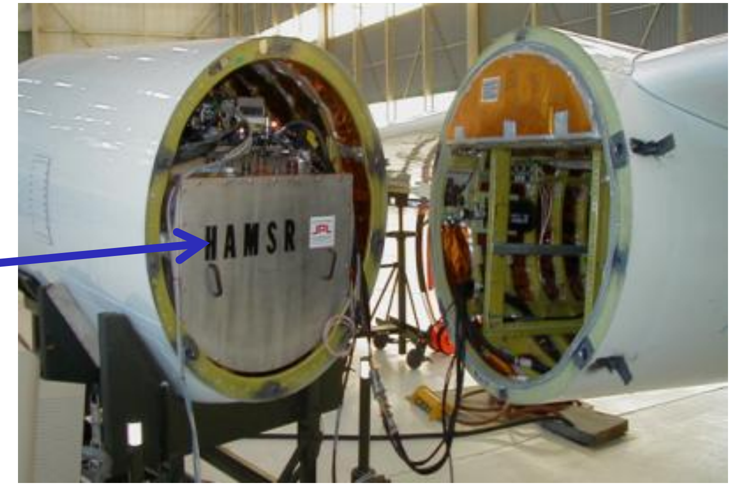


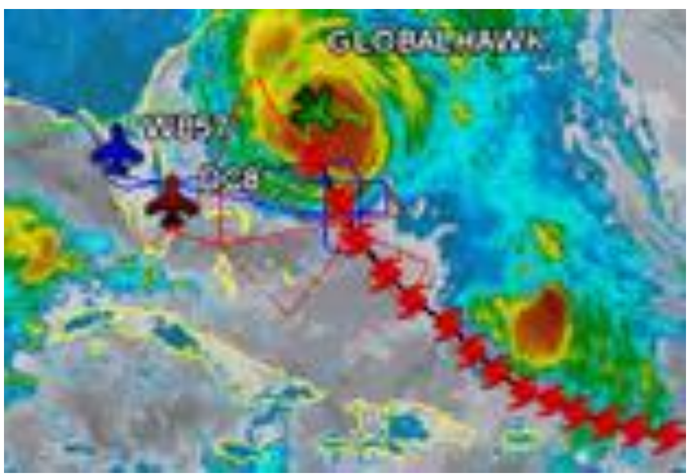
Images courtesy of NASA/JPL under GRIP (P Kangaslahti)

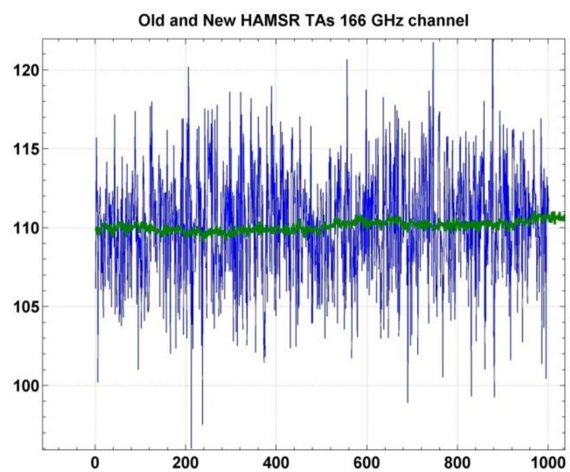
Global Hawk Radiometer







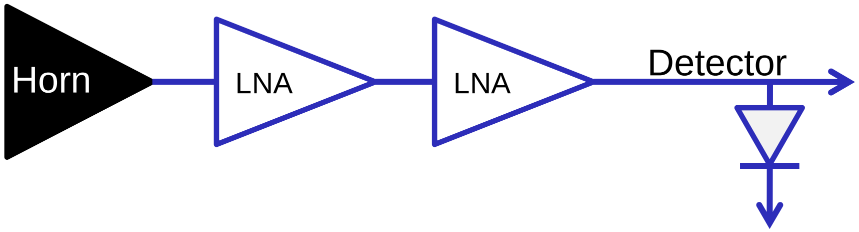


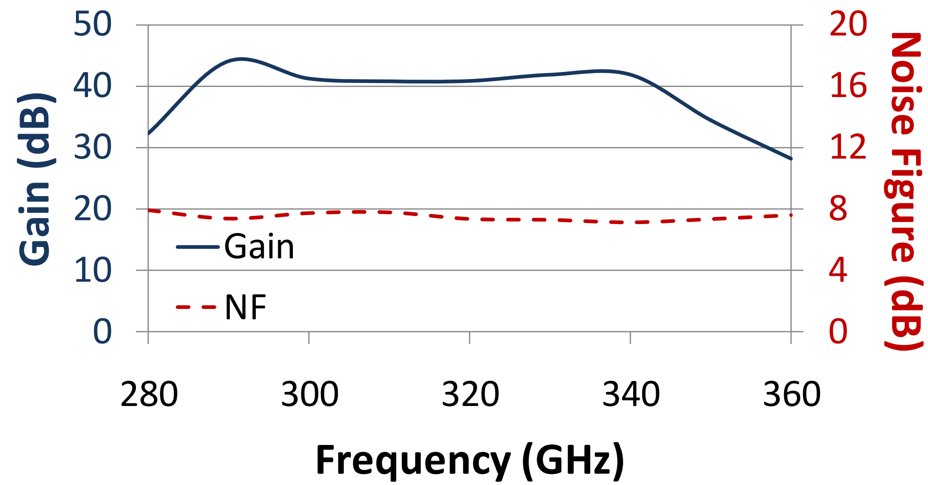


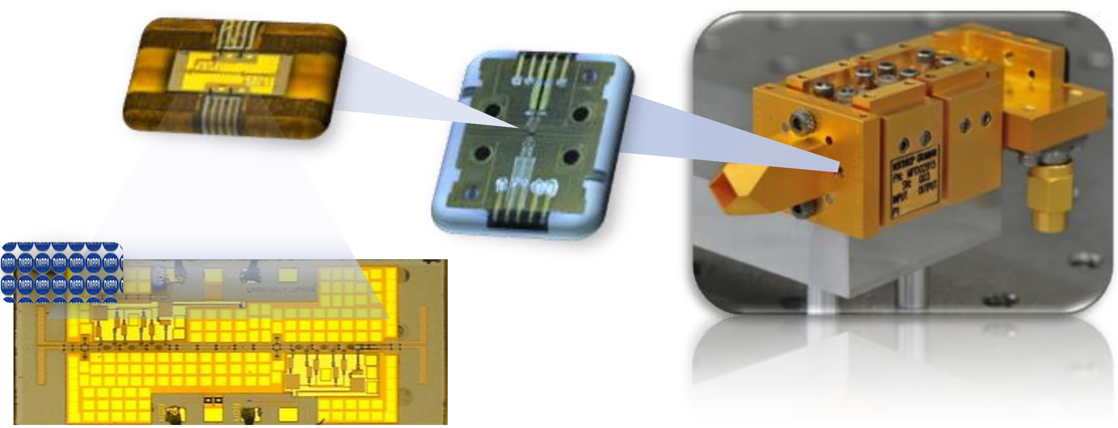
- 10x improvement in NEΔT
- >150 hours of flight time in open air housing
- Successful radiometry over multiple storms including Hurricane Earl

Images courtesy of NASA/JPL under GRIP

Sub-millimeter Wave Imaging Pixel

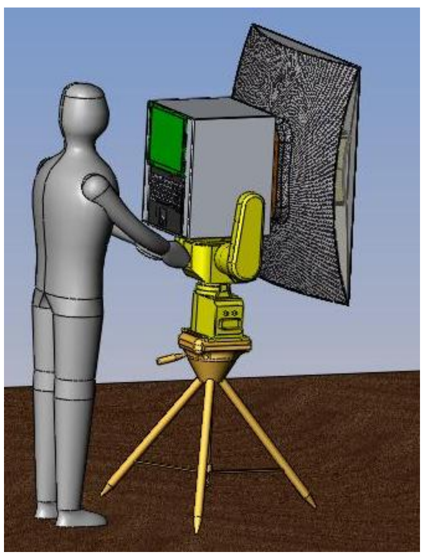


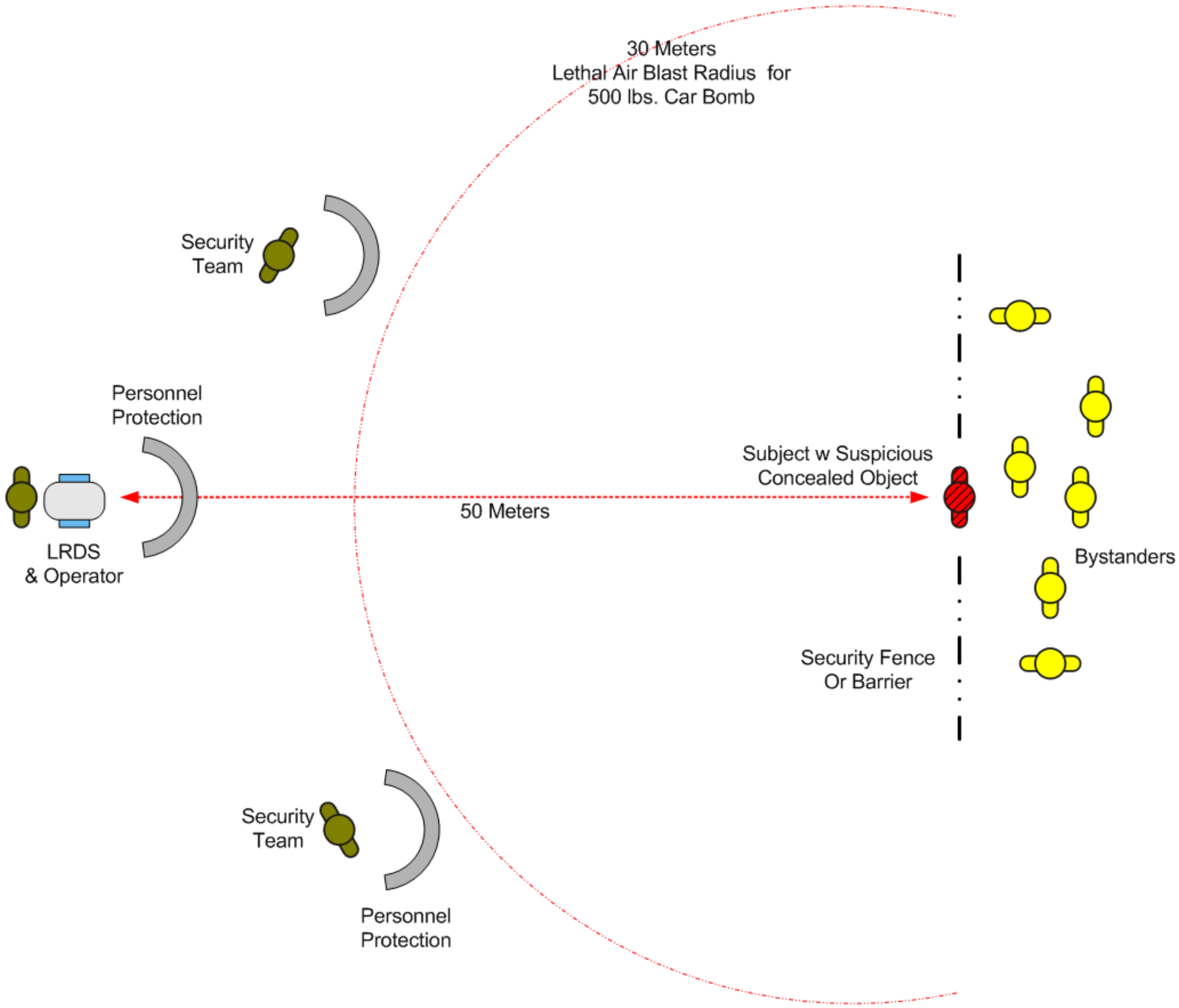




Part #	MPD02915
Bias Supply (V)	2.0
Bias Current (mA)	50-60
3dB – Bandwidth (GHz)	300-340
Gain (dB)	> 40
Noise Figure (dB)	< 8
RF Input / Output	WR3
Gain Blocks	2 or 3
Size (in) (l x w x h)	3x1x1¼

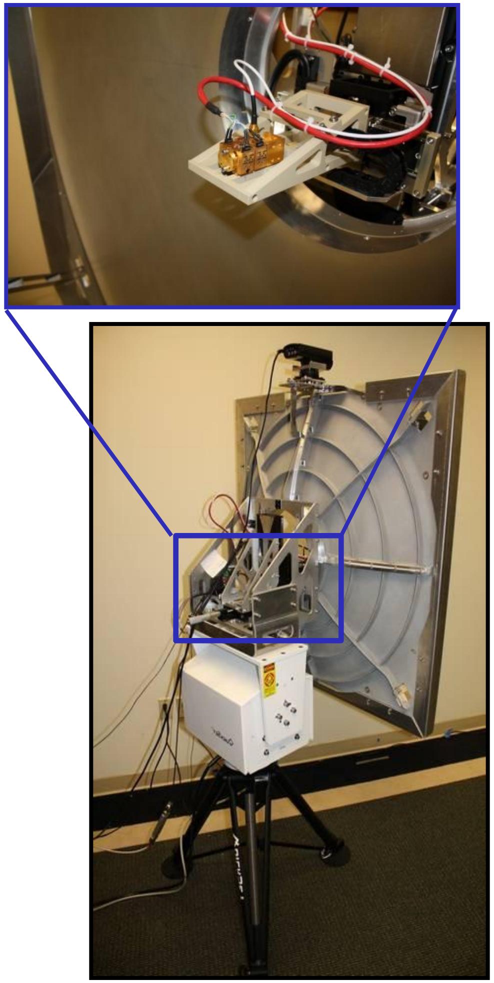
Sub-millimeter Wave Imaging Pixel

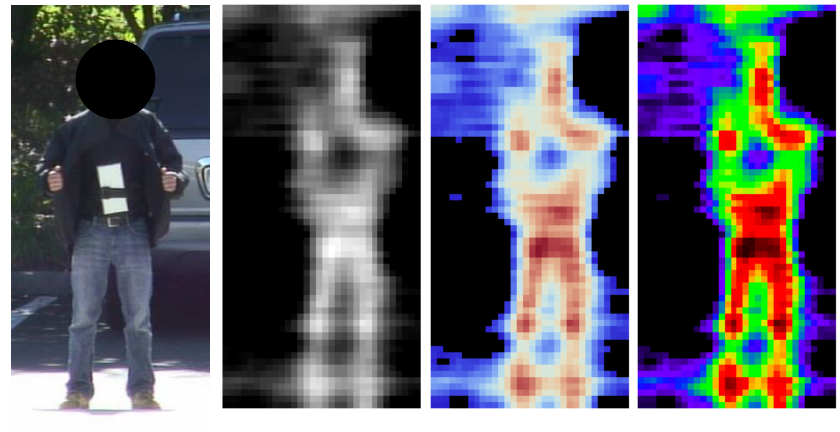




Images courtesy of Brijot Imaging Inc.

Sub-millimeter Wave Imaging Pixel

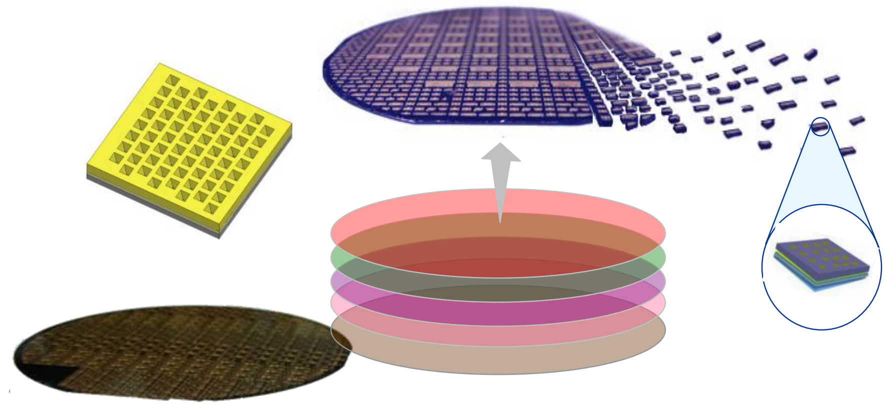




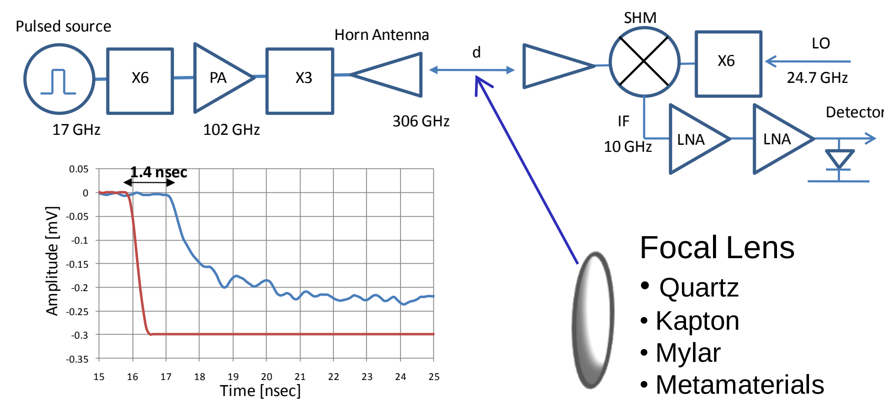
Images courtesy of Brijot Imaging Inc.

Dreams to Solid State Reality

Microintegration and Wafer Level Package for Array Scalability



Aperture Materials Evaluation and Enhancements



- POC Solid State THz Hardware is performing in the field today, and demonstrating system value
- Drivers for advancing technology for immediate future seem to continue to be military and scientific missions
- Transition to commercial world will require a paradigm shift
  - Compaction
  - Cost/Ease of Use
  - Propagation Understanding

THz technology pieces exist, is there a player willing to put them together?