THz Integrated Electronics

MICROSYSTEMS TECHNOLOGY OFFICE

Mark Rosker

2008 SURA Terahertz Applications Symposium

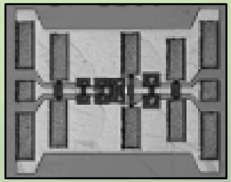
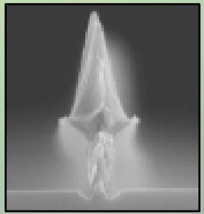
4 June 2008

BRIDGING THE GAP DARPA 1958 2008 50 YEARS POWERED BY IDEAS

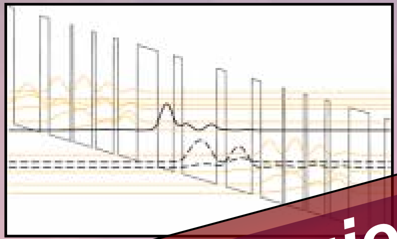
(Some) THz Source Approaches

Electronic → ← **Photonic**

Transistors

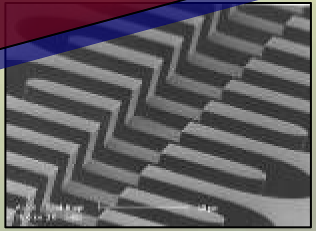
Lasers



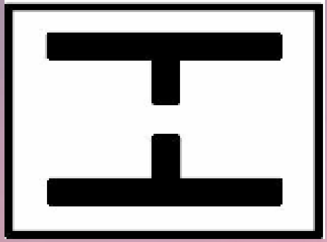
Diodes


These are not just different technologies; they are different communities

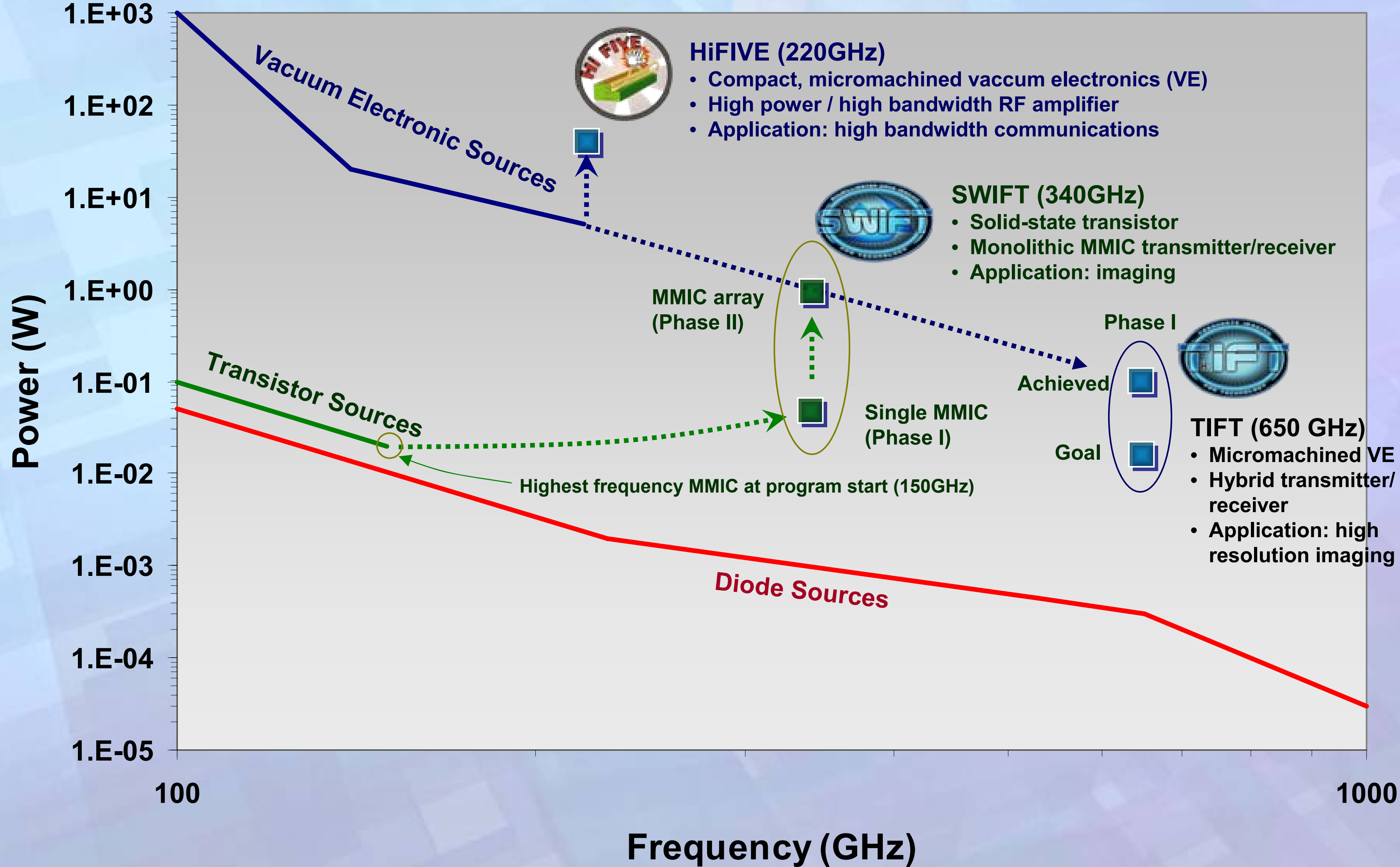
Vacuum Electronics




Photoconductive



Electronic Sources Above 100GHz



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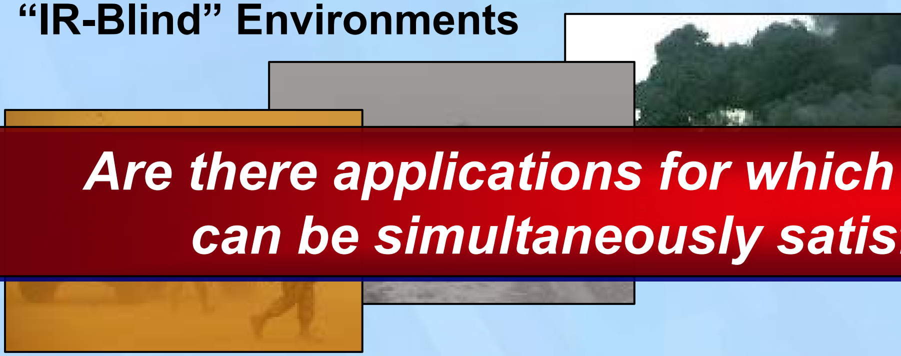
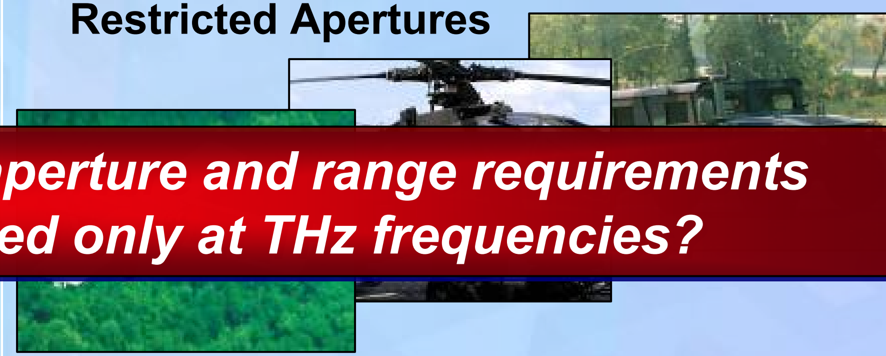
Terahertz Imaging Focal-Plane Technology (TIFT)

THz Imaging: Why Bother?

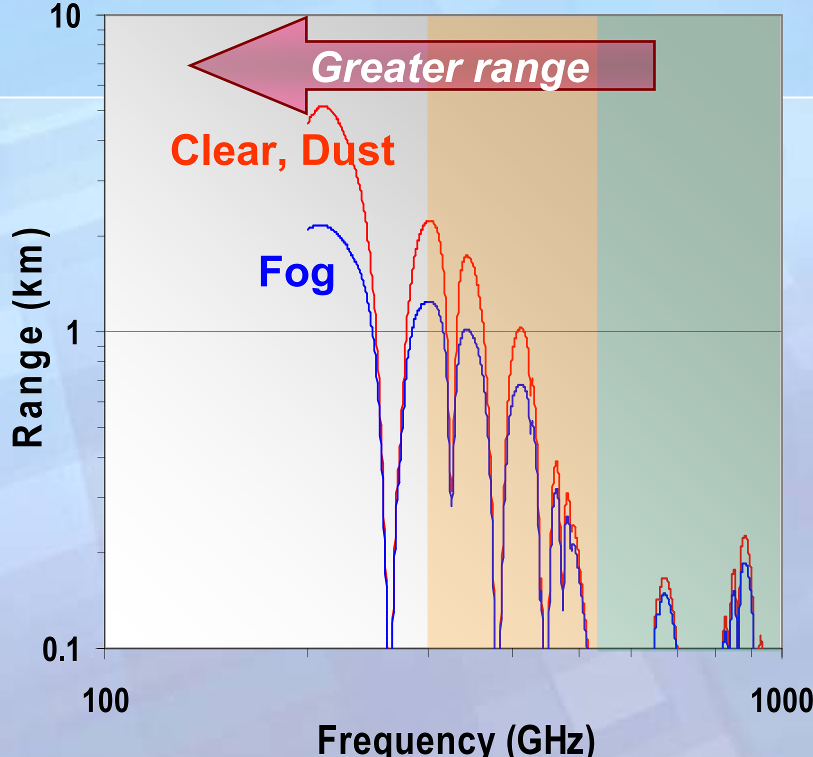
"IR-Blind" Environments

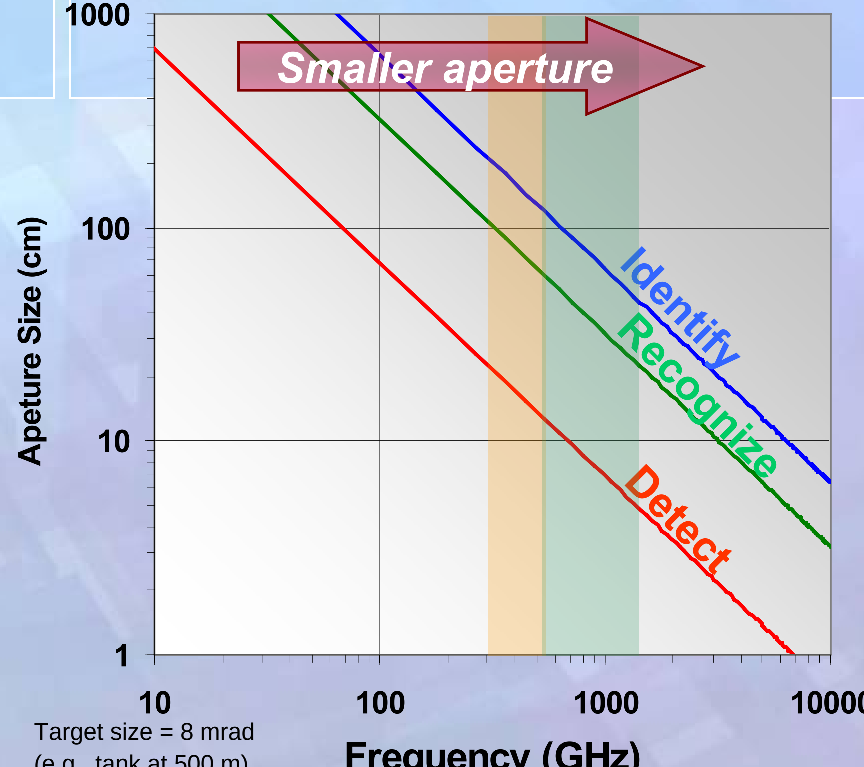


Restricted Apertures



Are there applications for which aperture and range requirements can be simultaneously satisfied only at THz frequencies?





Target size = 8 mrad
(e.g., tank at 500 m)

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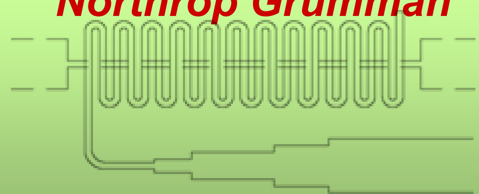
Technical Goals

Sources
- Increase available sub-MMW power to 10mW, with a path to 100mW (10 to 100X increase*)
- Achieve 1% wallplug efficiency (nearly 100X increase*)

Detectors
- Implement an array-integrable approach achieving NEP′ of $1x10^{-12}$ W/√Hz (> 100X improvement*)

Micromachined Vacuum Electronics‡

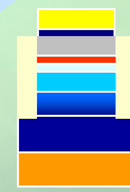
Northrop Grumman



Regenerative Amplifier

Direct Detectors

UC Santa Barbara



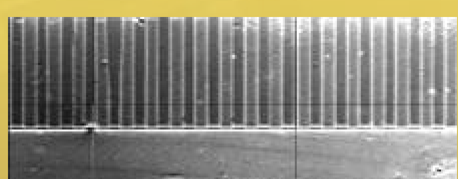
ErAs Diodes

‡ *Work on diamond BWO by GENVAC Aerospace also supported by SBIR funding*

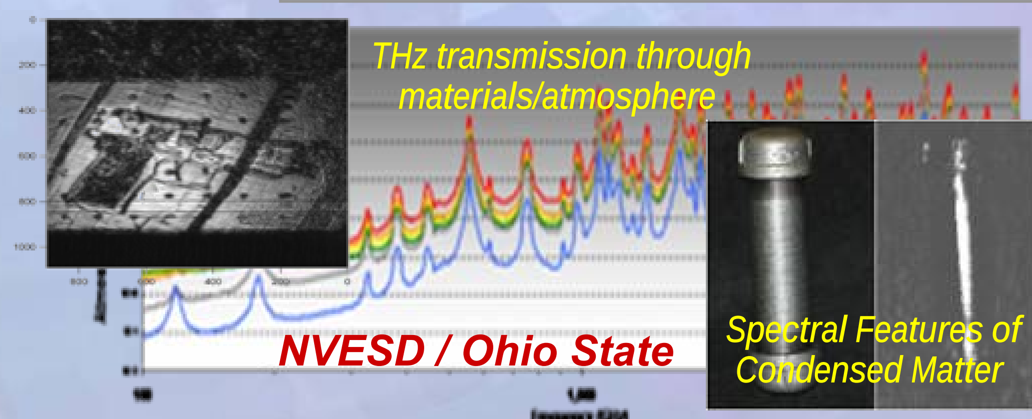
Phenomenology & System Model
- Define FPA requirements for TIFT imaging through IR-blind conditions

Photonic Downconversion

Stanford



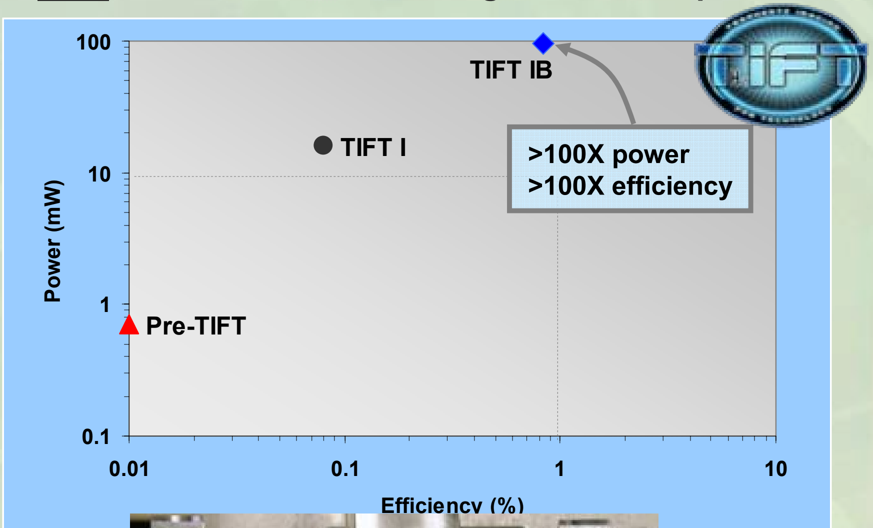
Cascaded OPO



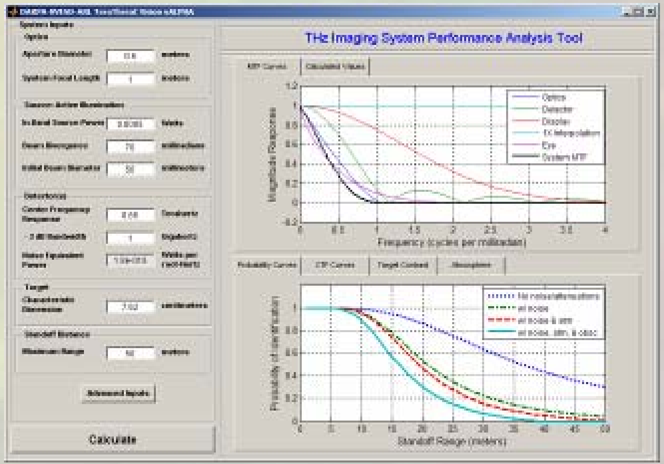
***Comparisons referenced to 0.65THz**

TIFT Performers

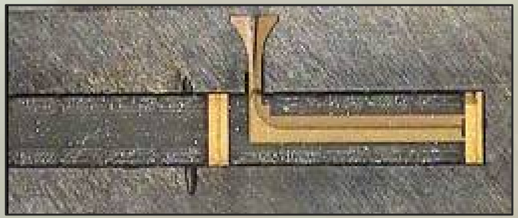
NGC: Micromachined TWT regenerative amplifier



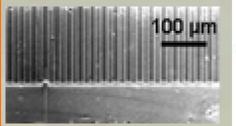
NVESD: THz Imaging Phenomenology & System Performance Model

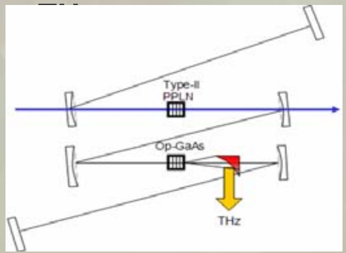


Genvac: Wafer scale manufacturing of diamond and gold BWOs

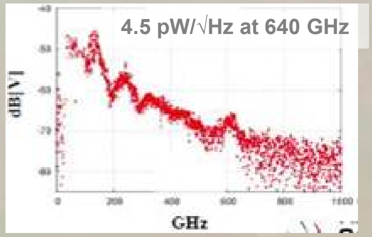


Stanford: Cascaded optical down-conversion based source at 1.5





UCSB: Single-crystal ErAs:InGaAlAs rectifier based direct detectors



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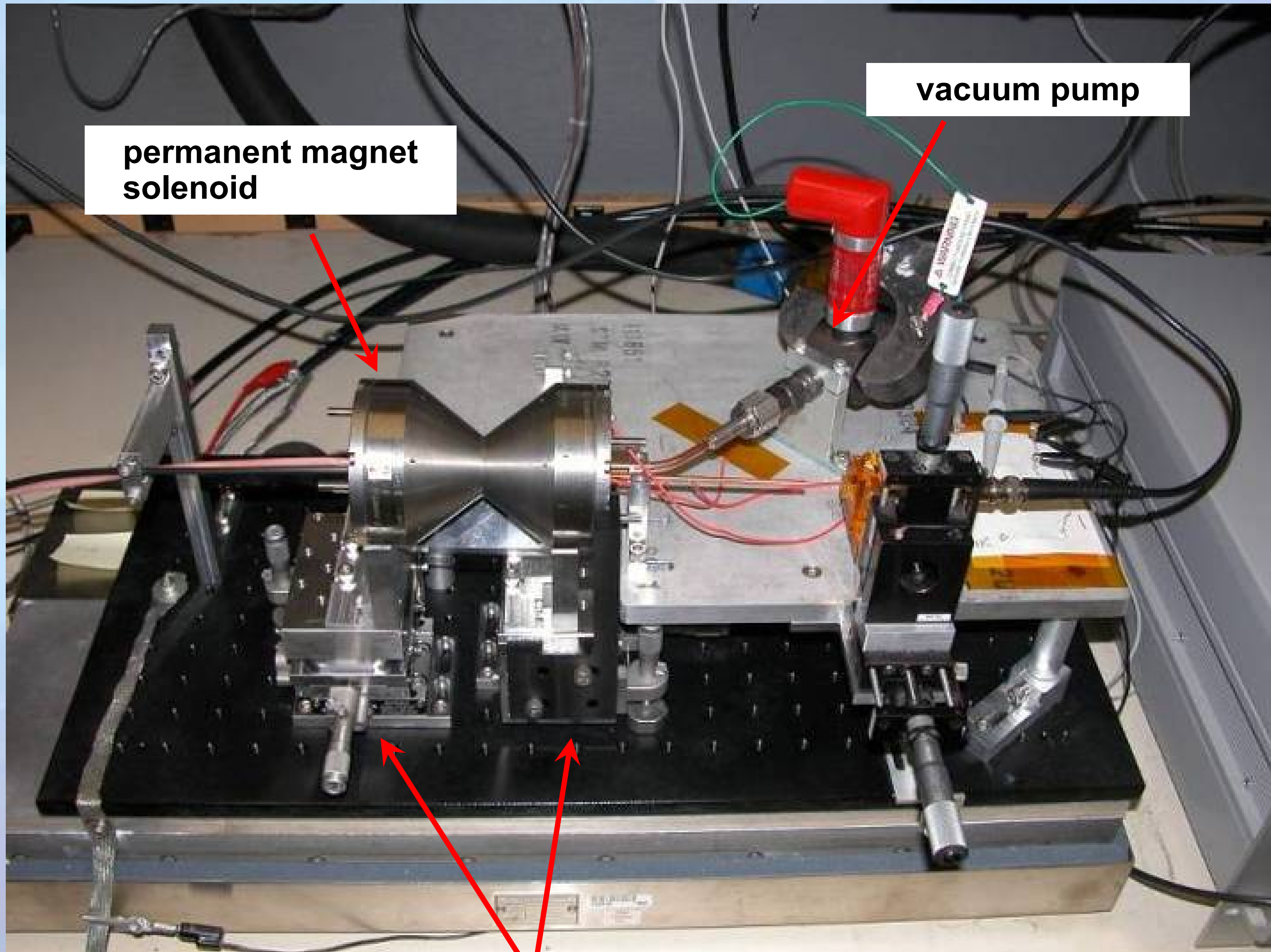
TIFT 1A – Source 1 on Test



magnet aligners

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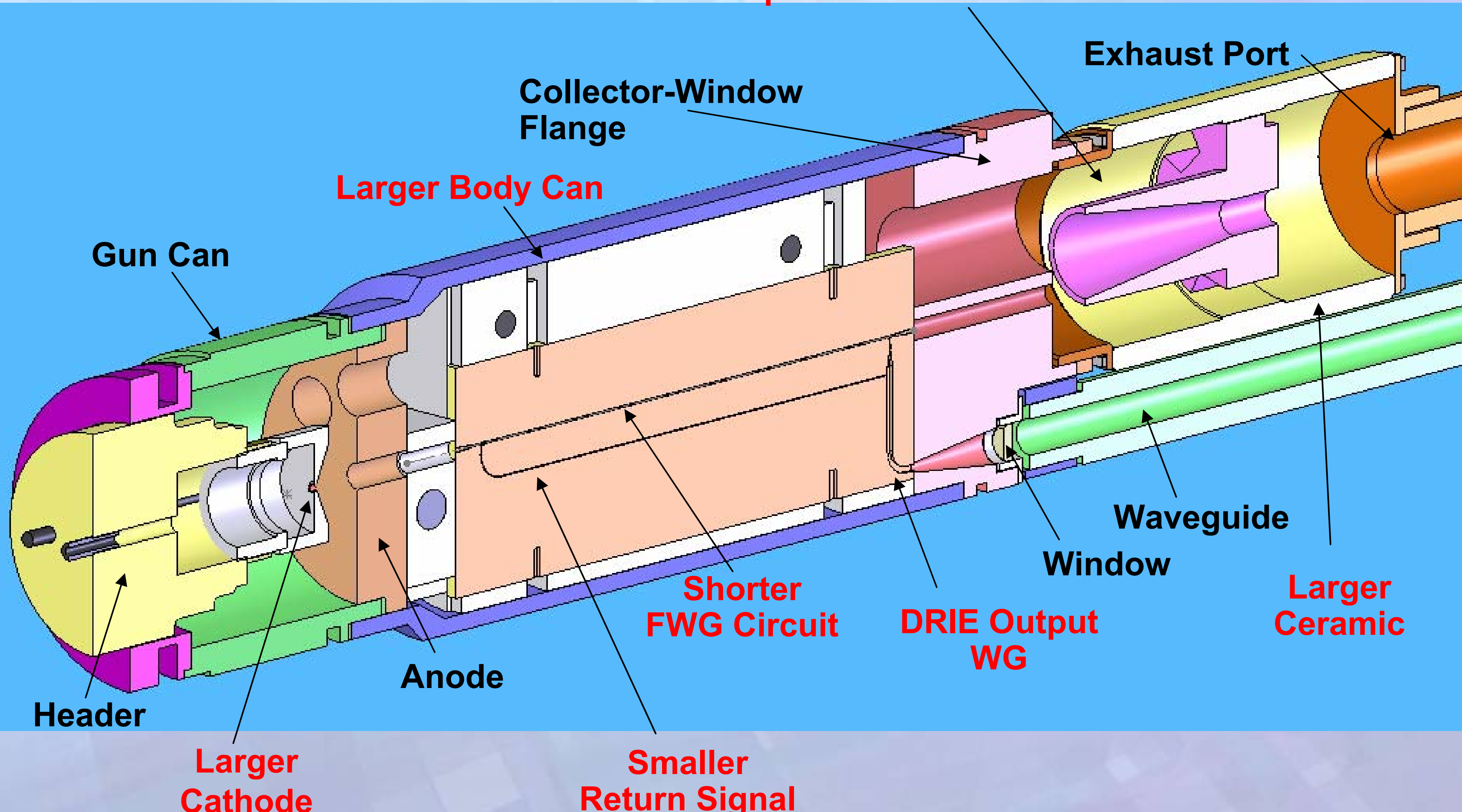
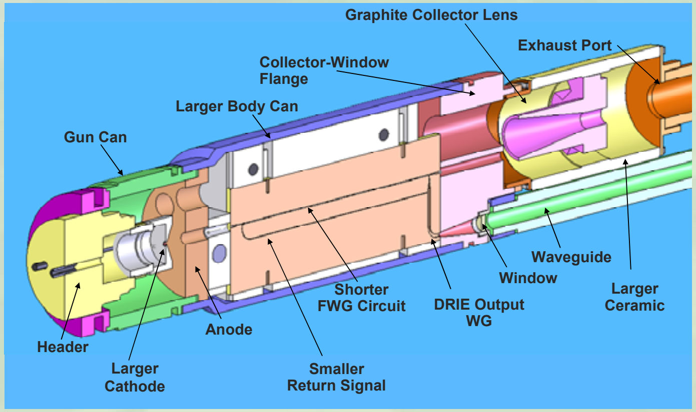
Improvements in Phase IB

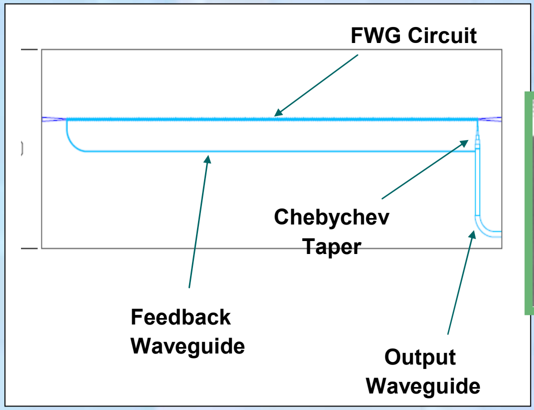
Changes in Red



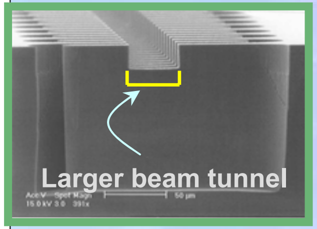
NGC Phase IB Accomplishments

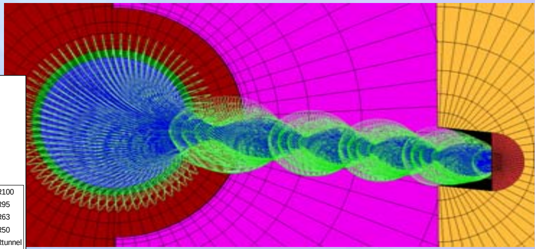
Micromachined TWT

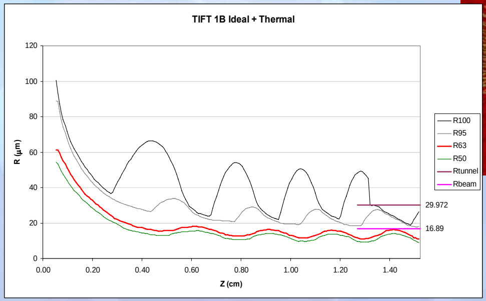




Circuit redesign for higher current operation

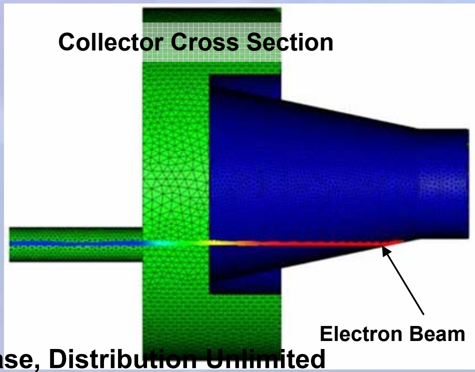






Increase beam transmission from 39% to 79% by reduced edge emission, beam deflection

	unit	Goal	Achieved
Power	mW	16	98
Efficiency	%	1.0	0.83
Operating frequency	GHz	>557	595
Duty cycle	%	50	3
Bandwidth	GHz	15	61*



Collector efficiency: 92.4 %

Sub-millimeter Wave Imaging Focal-Plane Technology (SWIFT)

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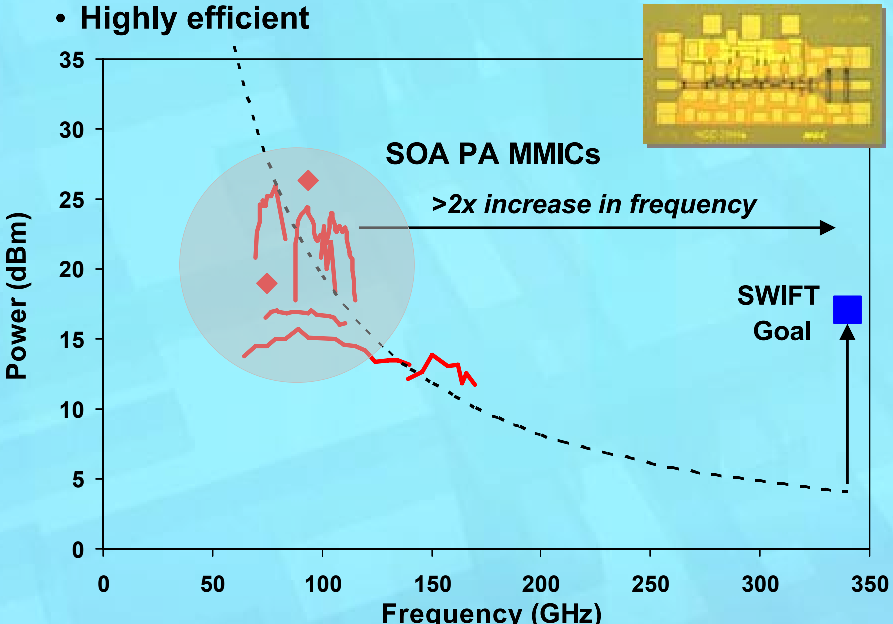
SWIFT Technical Challenges

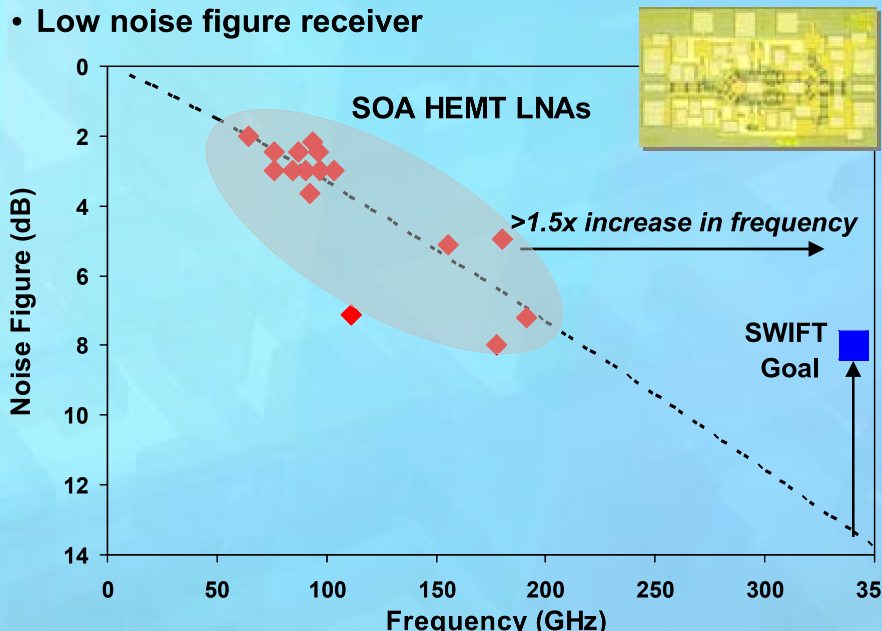
Sub-MMW Sources

- Ultrafast power amplifier MMICs
- Highly efficient



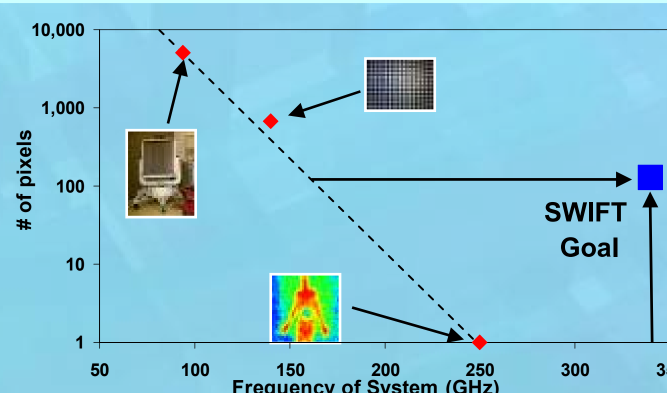
Sub-MMW Receivers

- Ultrafast LNA MMICs and mixers
- Low noise figure receiver



Imaging Array Architecture

- Minimization of LO power
- Low loss interconnects



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SWIFT Accomplishments

World's Fastest MMICs

35nm InP HEMT Devices

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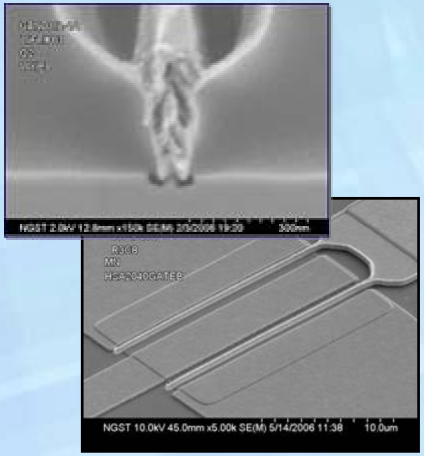
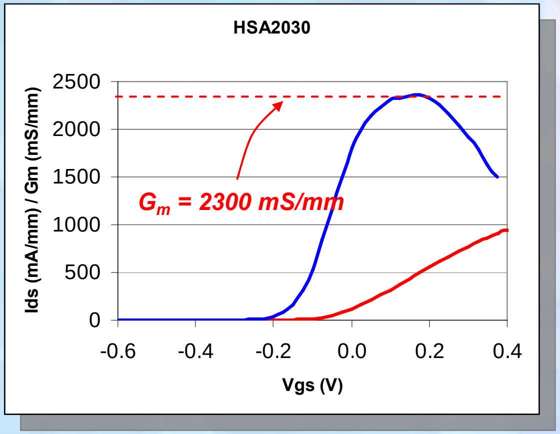
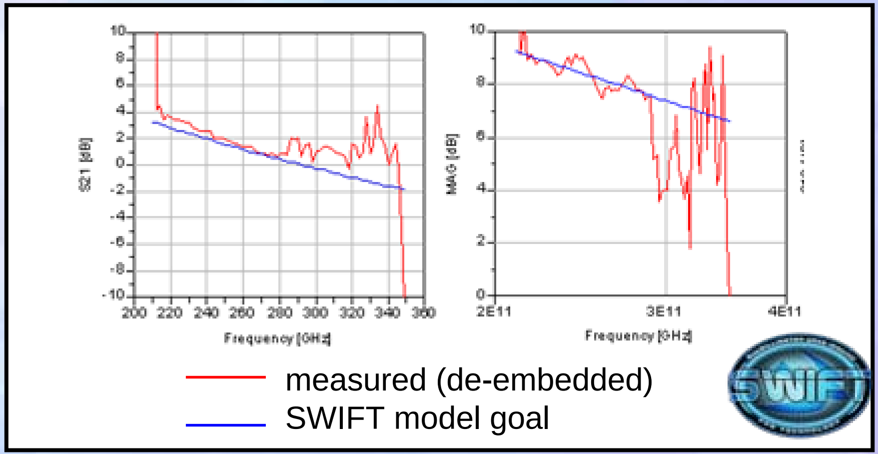
35nm gate of InP HEMT with record Gm = 2300mS/mm



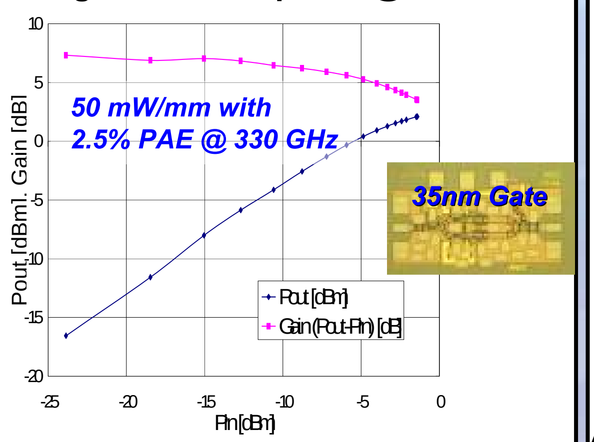


MAG@340 GHz > 6 dB for both model & measured results

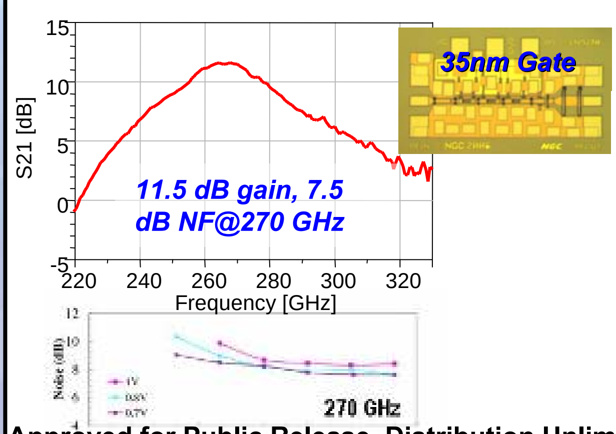


World Record Sub-MMW MMICs ("s-MMIC")

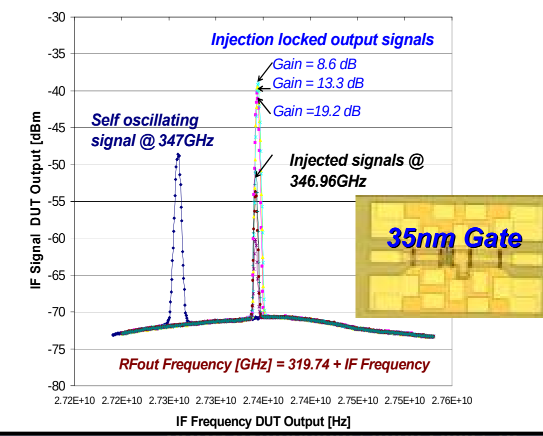
3-stage Power Amplifier @ 330 GHz



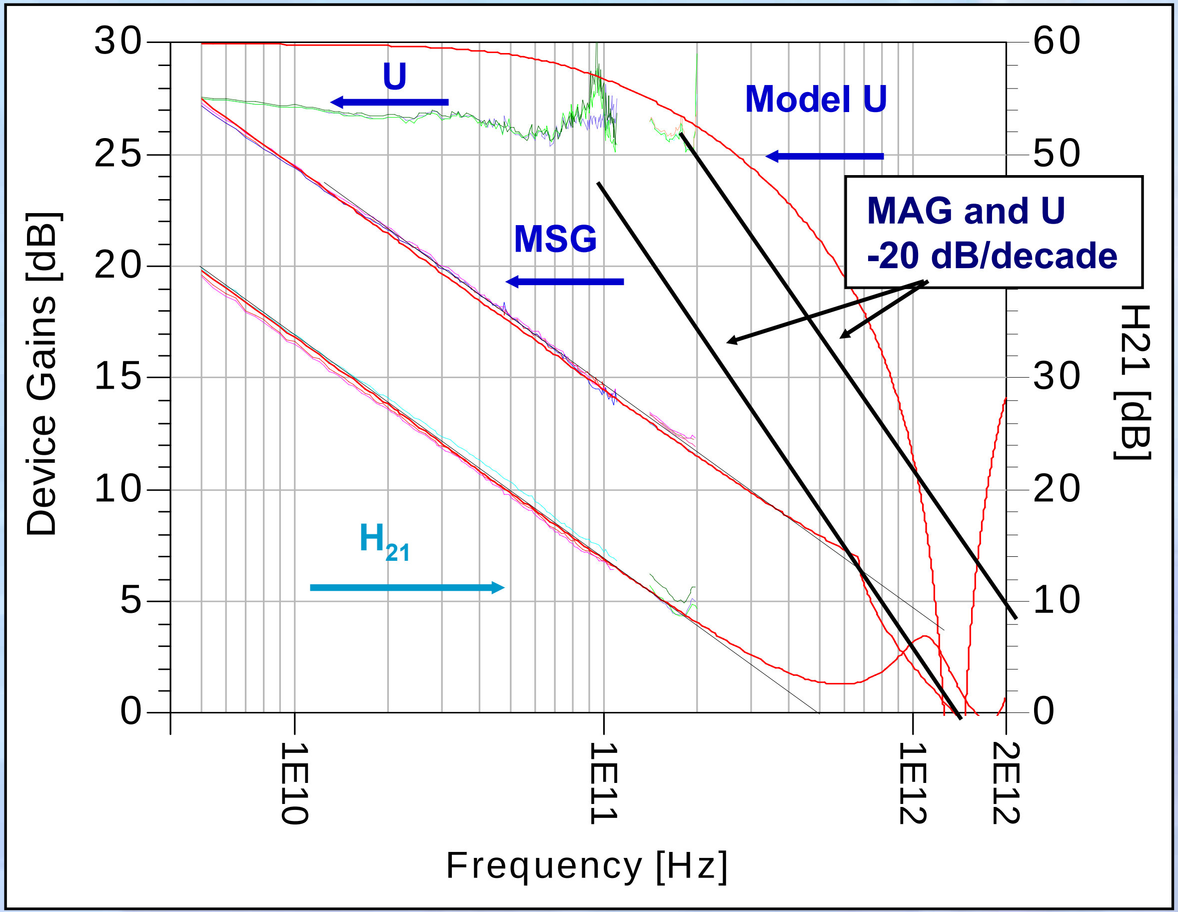
3-stage Low Noise Amplifier @270 GHz



First s-MMIC: a 347GHz HEMT VCO



HEMT with > 1 THz f_{max}



- 4 finger 60 um device
  - 1-110 GHz; 140-220 GHz
- TRL cal structure used
  - Better 140-220 GHz measurement accuracy
- U follows predicted model
- MSG follows both trend & predicted model
- H21 follows both trend & predicted model

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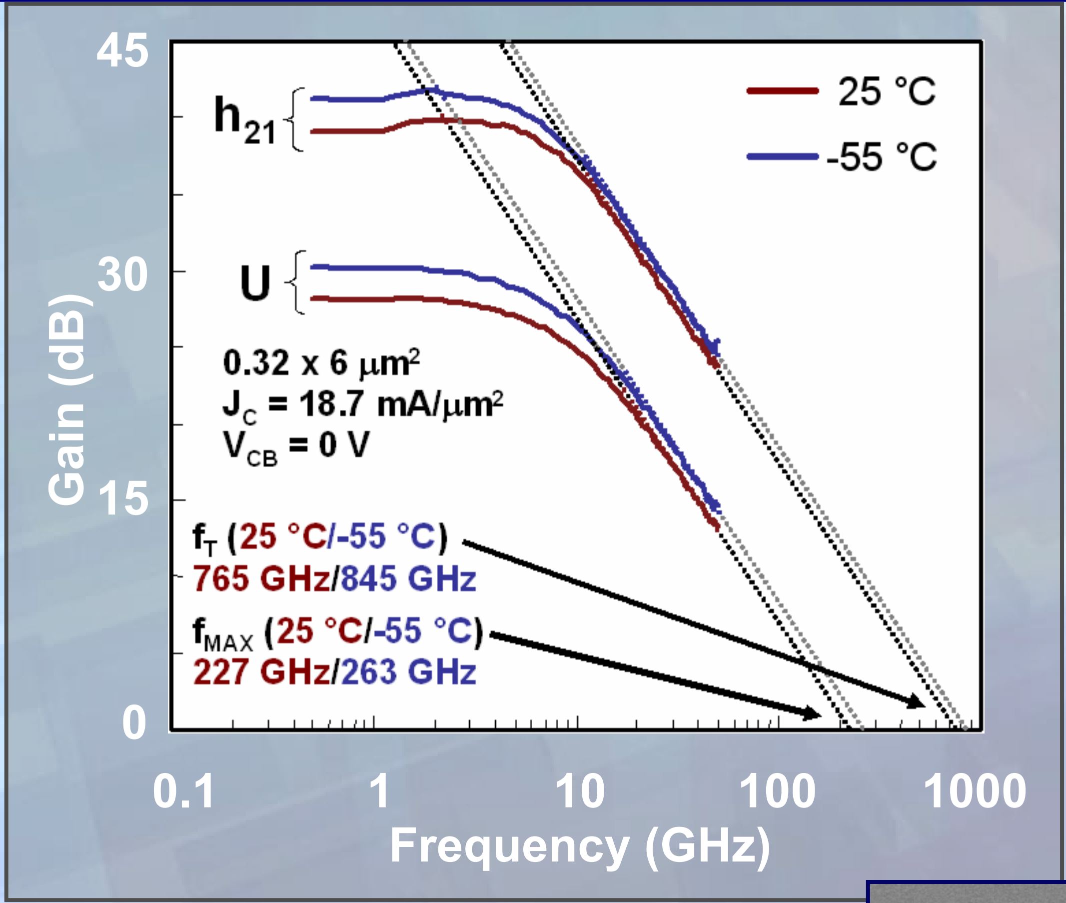
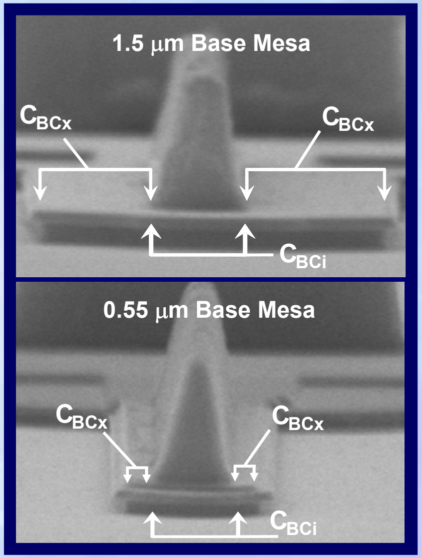
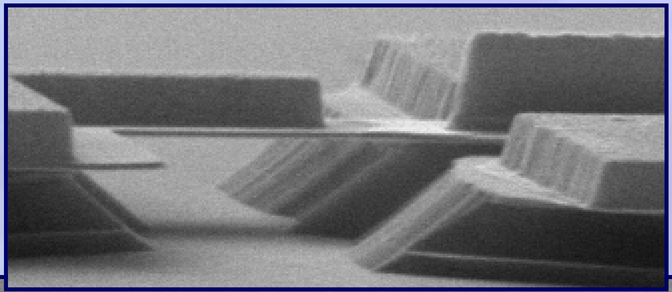
- f_{max} ~ 1.2 THz; f_T ~ 500 GHz
- Measurements extended to 200 GHz follow gain and H21 trends

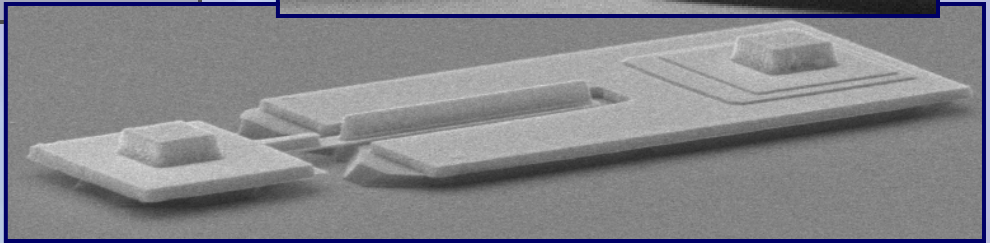
World's Fastest HBT Transistor





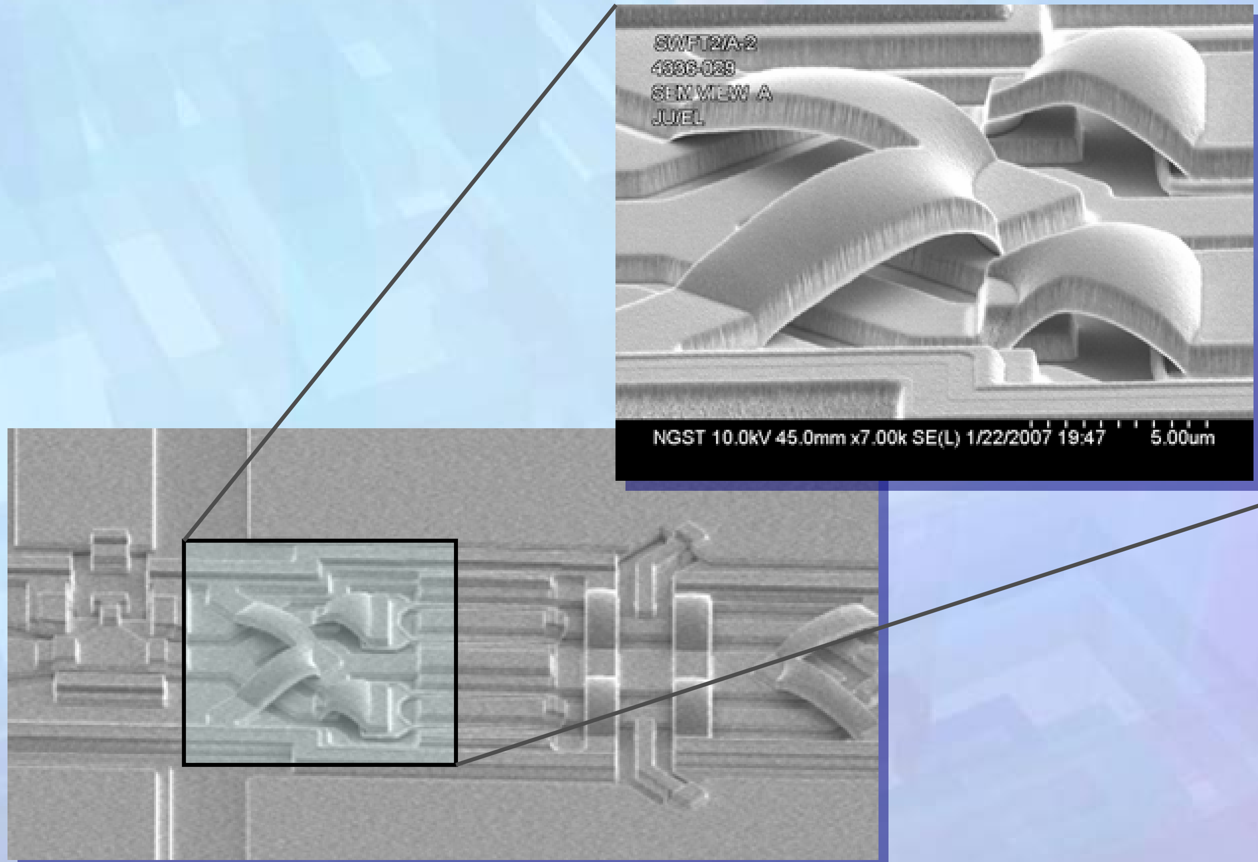
Reduce base contact junction area





μ-bridge Base Contact

What Does an s-MMIC Look Like?



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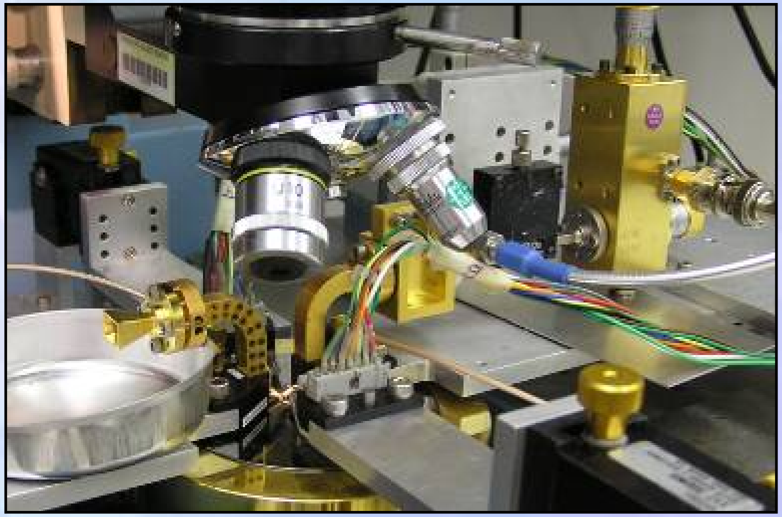
Compact.

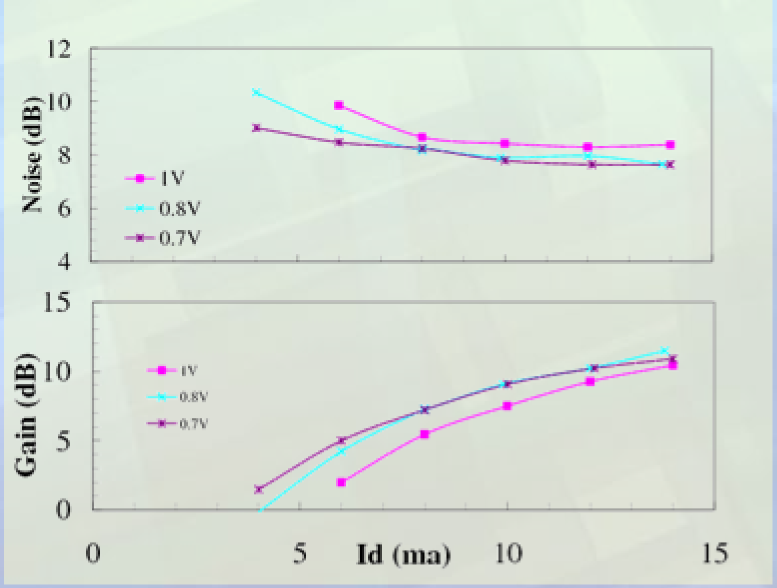
Sub-MMW Metrology: Another DARPA-Hard Challenge

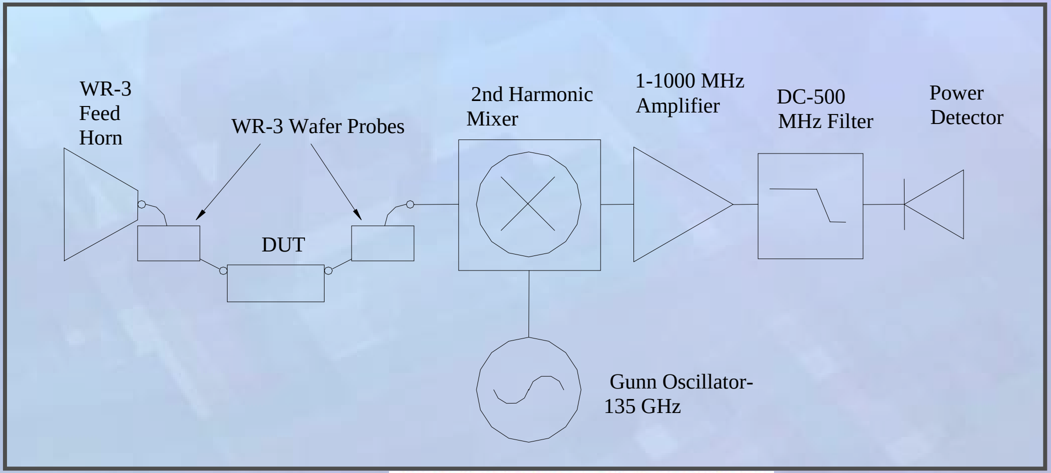
Things that don't exist at 340 GHz…

- Isolators
  - Impedance control for power and noise measurements
- Rotary vane attenuators
  - Calibrated loss
- Low loss couplers
  - In-situ power calibrations
- Low loss probes
  - De-embedding noise measurements
- Power amplifiers
  - Input power margin in power measurement
- Impedance tuners
  - Noise/load pull measurement



330 GHz Noise Figure Test Set





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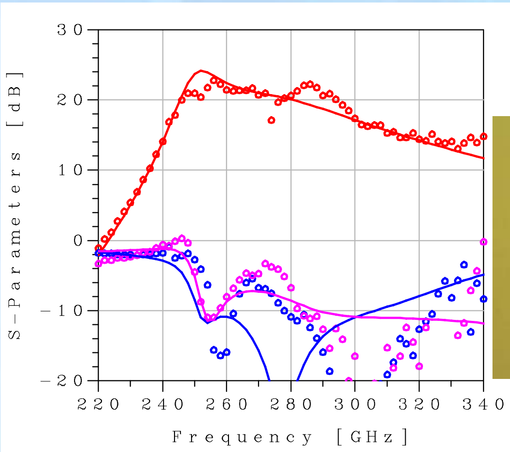
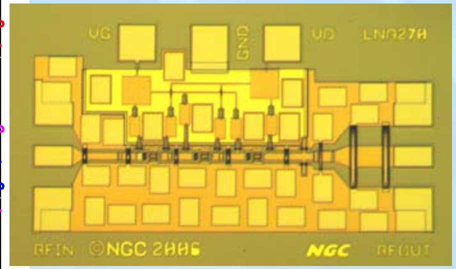
JPL

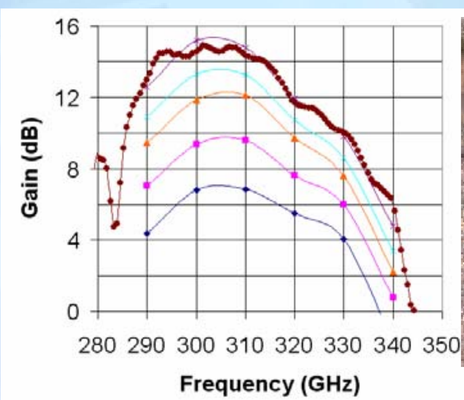
Highest Frequency Circuits

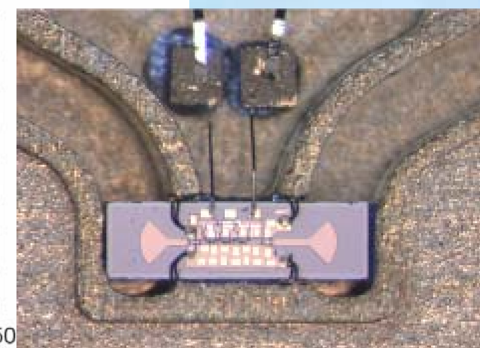




Features

- Sub 50 nm gate InP HEMT
- 2-mil InP thickness with compact vias
- 3-stage MMIC LNA (2f 20 um per stage)
  - 21 dB gain @280 GHz (7 dB/stage)
  - 17 dB gain @300 GHz (5.7 dB/stage)
  - 15 dB gain @340 GHz (5 dB/stage)
  - Some LNAs show 18 dB gain@340 GHz
- JPL designed integrated radial probes & WR3 fixture (cutoff < 285 GHz & > 340 GHz)
- Amplifier fixture measurements taken and referenced to waveguide flange
  - 4-6 dB loss due to transitions & waveguide
  - fixture & on-wafer measurement data matches from 290 – 330 GHz





- **Highest frequency MMIC amplifier ever demonstrated**
- **Excellent match to simulation validates model**
- **Fixtured amplifier validates measurement**
- **Validates THz fmax Transistor claim**

High Frequency Integrated Vacuum Electronics (HiFIVE)

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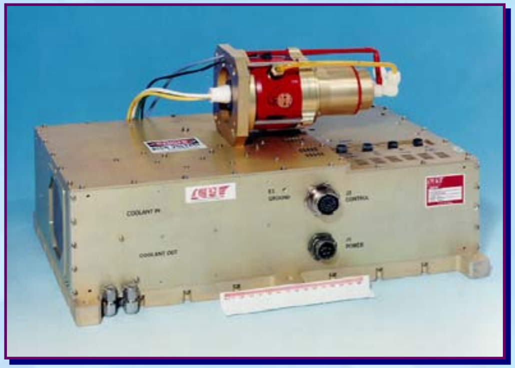
HIgh Frequency Integrated Vacuum Electronics (HIFIVE)



EIK, CPI Canada

SOA Today
- 220 GHz
- 5 W*
- Not integrated

* In development

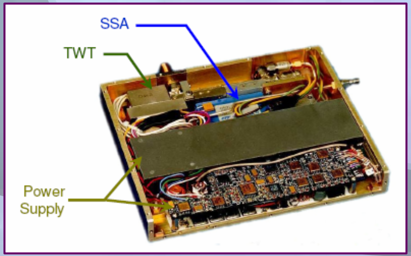
Today:
High frequency sources are large, expensive, and performance-limited

Objective
Develop the first all-integrated (“chip-scale”) vacuum electronic devices for high-power millimeter-wave sources

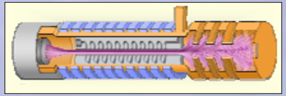
Technologies
- Si micromachining
- High aspect-ratio interaction structures
- Integrated, high current density cathodes

Impact
- High bandwidth, LPI communication systems
- High-resolution radar
- Manufacturable vacuum electronics process based on standard MEMS rather than custom & expert machining

HIFIVE Phase II
- 220 GHz
- 50 W
- “MPM” level of integration (compact module)*
- 250 W-GHz Power bandwidth product



HIFIVE Phase III
- 220 GHz
- 50 W
- Fully integrated*
- 500 W-GHz Power Bandwidth product



* Cathode, gun, interaction structure, collector, driver, HV source

HiFIVE: Small, high power-bandwidth source

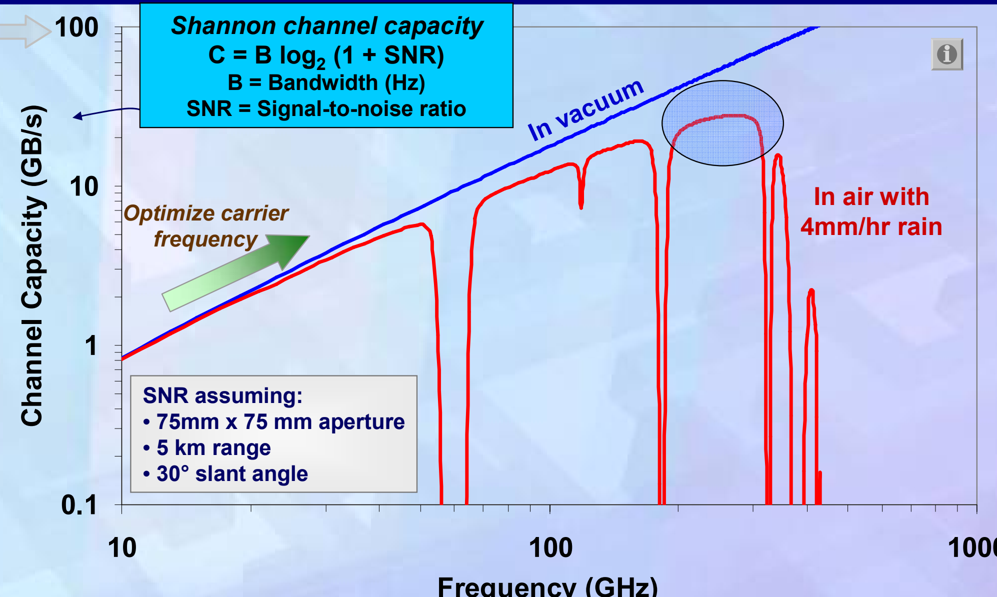
*MPM = Microwave Power Module

Program Impact

Source for high bandwidth datalinks

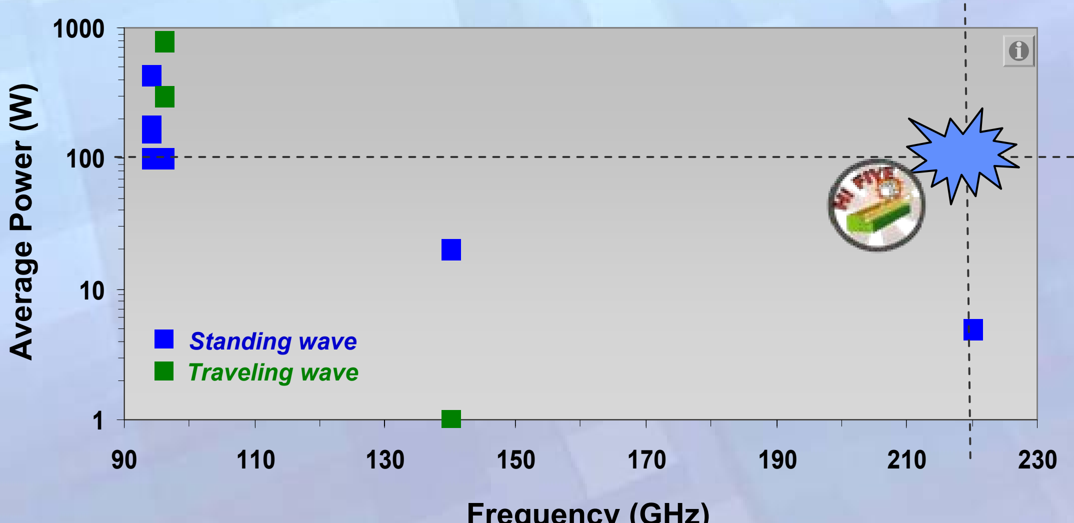
- Offers ~10x higher Shannon capacity than Ku-band (for same antenna area), or
- Offers ~100X smaller antenna area than Ku-band (for same Shannon capacity)

Today: UAVs use Ku- band MPMs for tactical comms



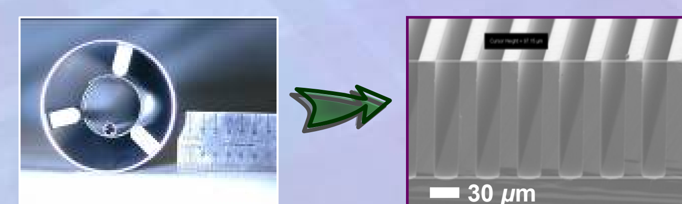
First high power source above 200GHz

- Power density / power-bandwidth product at 220GHz comparable to the best available at any frequency



Micromachined TWT process

- End reliance on custom machining
- Extensible to wide range of frequencies



Tactical communications

- Commercial sources and receivers currently are virtually unknown at 220GHz

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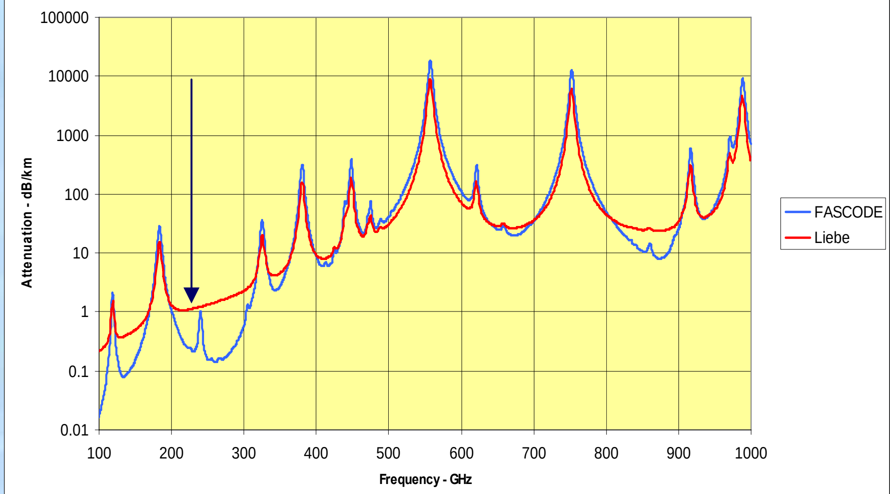
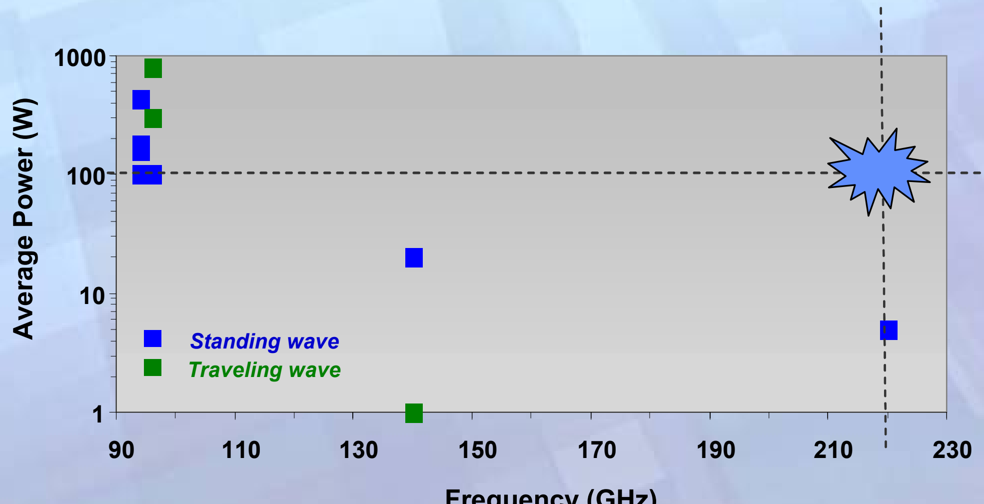
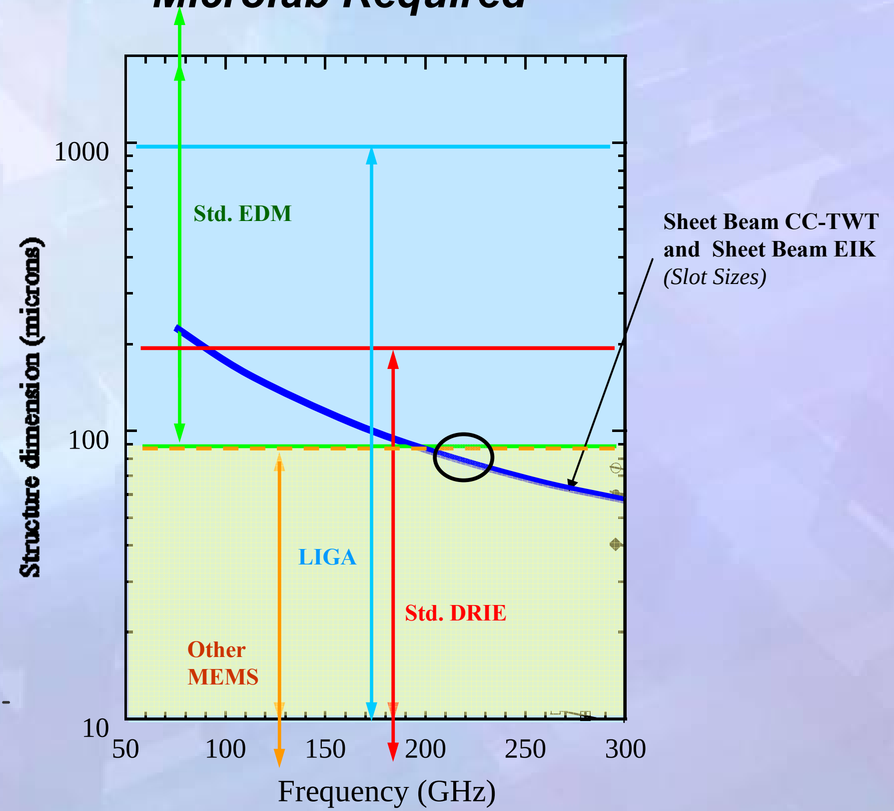
Why 220GHz?

Unexploited atmospheric window



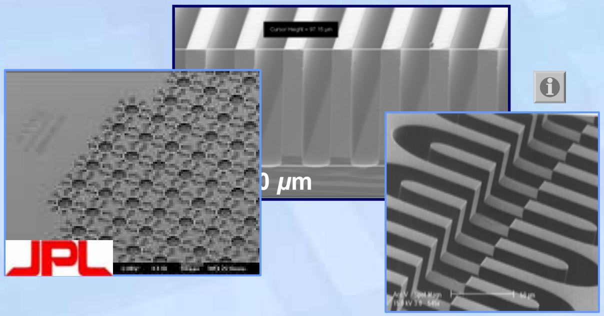


Microfab Required



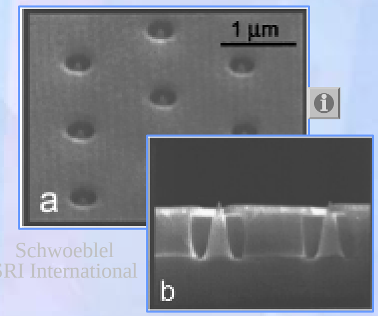
Why Now? HIFIVE Enablers

Micromachining Approaches Achieving Fine Surface Smoothness and High Aspect Ratio

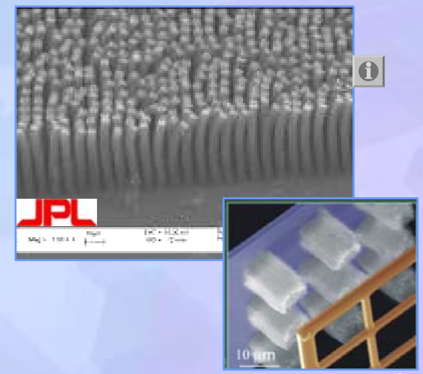


- *High precision machining of interaction structures*
- *Structures susceptible to outgassing adsorption*
- *Depth of structure difficult for many techniques*

Novel Field Emitter Array Cathodes with Improved Current Density



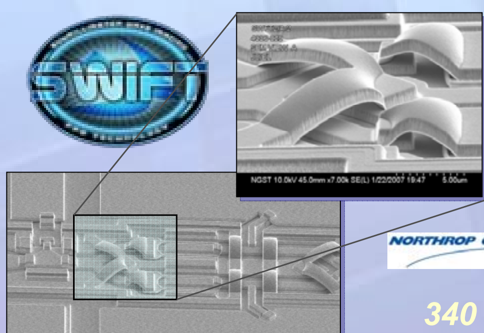
Schwoeblel
SRI International



Wei Zhu
Agere Systems

- *Compact and efficient*
- *Very short lifetimes*
- *Further increase in current densities needed*

High Frequency MMIC Process

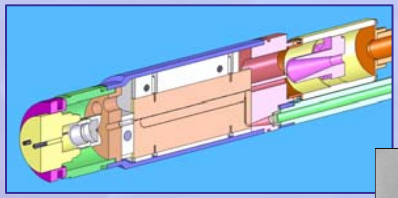


NORTHROP GRUMMAN

340 GHz MMIC

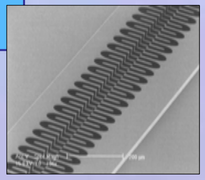
- *Frequency of operation now well beyond 220GHz*
- *Need to increase power*
- *Integrating the device is difficult (~6dB loss)*

THz Frequency TWTA Demo



1st THz frequency (0.65THz) vacuum device

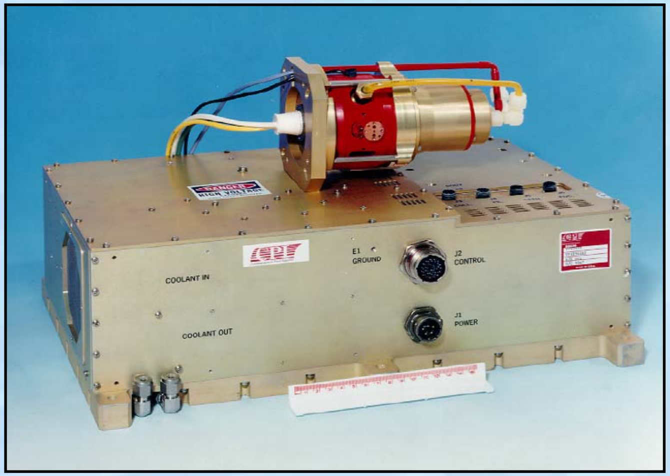
NORTHROP GRUMMAN



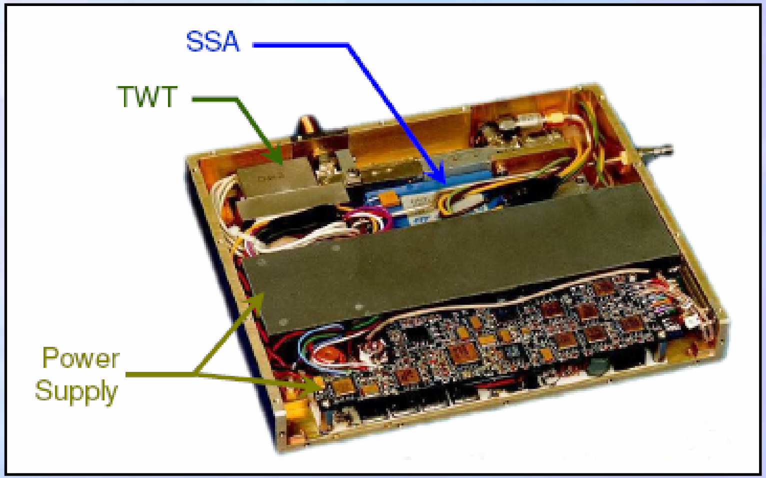
- *High precision machining at frequency*
- *Round beam*
- *Lower frequency structure more difficult*

What Is Compact?

PA size can be dominated by the high voltage power supply



Substantial engineering has miniaturized & flight qualified HV power supplies to ~20kV



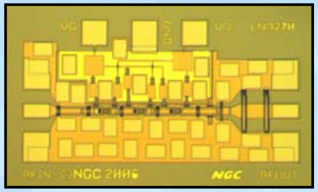
Fixed upper limit on circuit magnetic field B_{max} due to permanent magnet technology (~ 11 kG)

Practical upper limit on beam voltage ~ 20 kV

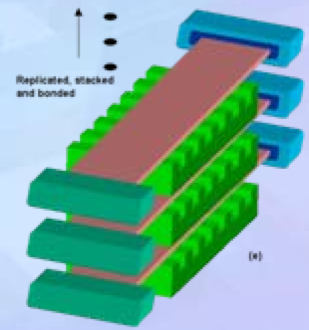
In HiFIVE, we expect V < 20kV and B_{max} < 11kG

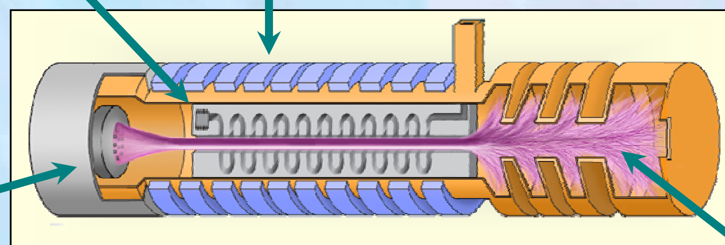
Technical Challenges

High Power MMIC Driver
- Accommodate relatively low VE gain at 220 GHz



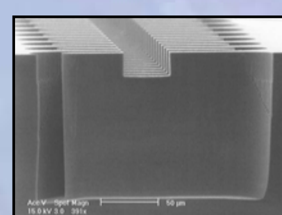
High Aspect-Ratio Devices
- High efficiency interaction structures
- Single vs. multi-beam topologies
- Magnetic compression to achieve high aspect ratio beam (N~100)
- Mitigation of parasitic oscillations



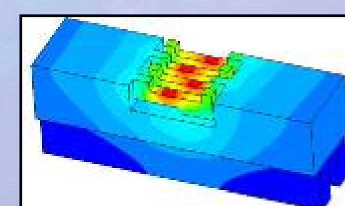


High Current Density, Long Life Cathodes
- High unfocused current density (~100A/cm^2)
- Life > 10^4 hrs

High Precision Micromachined Fabrication and Integration
- Achieve required smoothness & aspect ratio
- Material/technology/process compatibility
- Heterogeneous integration
- Maintain high vacuum



High Efficiency Thermal Management
- Mode confinement / reduction of beam interception
- Aggressive thermal management (mat'ls and structures)



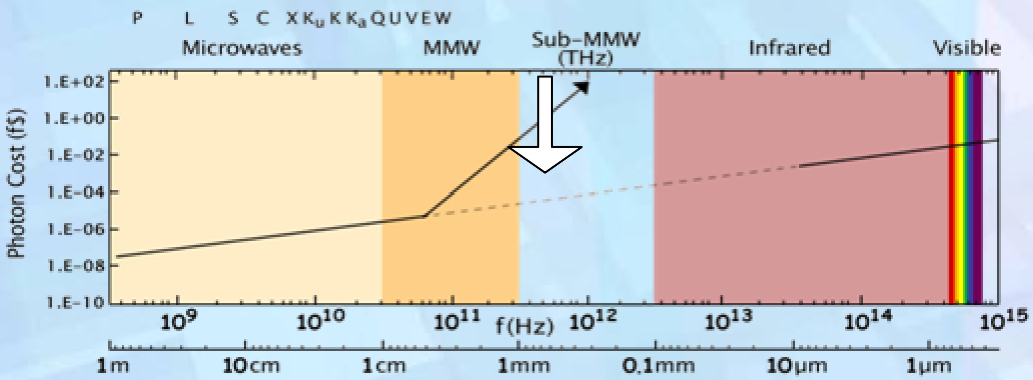
THz Integrated Electronics

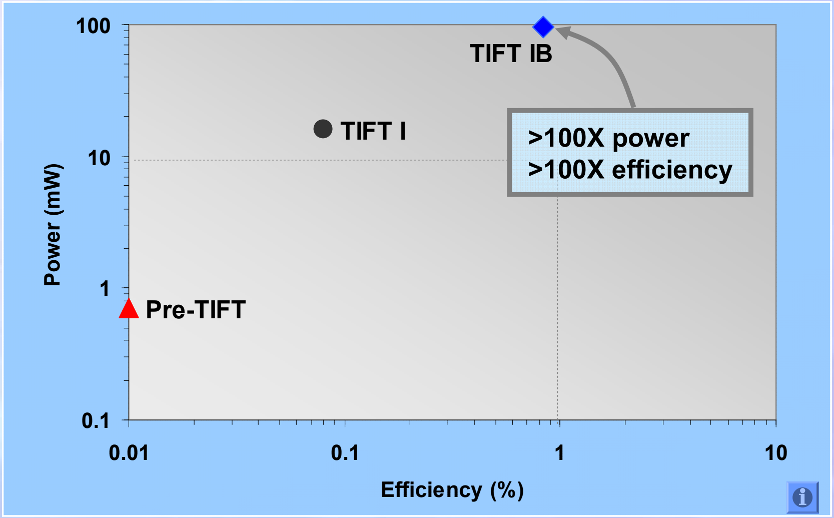
MICROSYSTEMS TECHNOLOGY OFFICE

What Has Changed

1. "Cheap" THz sources becoming available

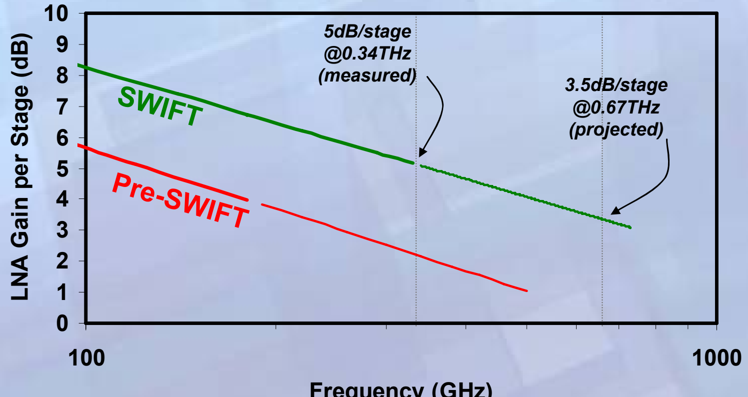
- Essential for transmitters
- Enabling for heterodyne receivers

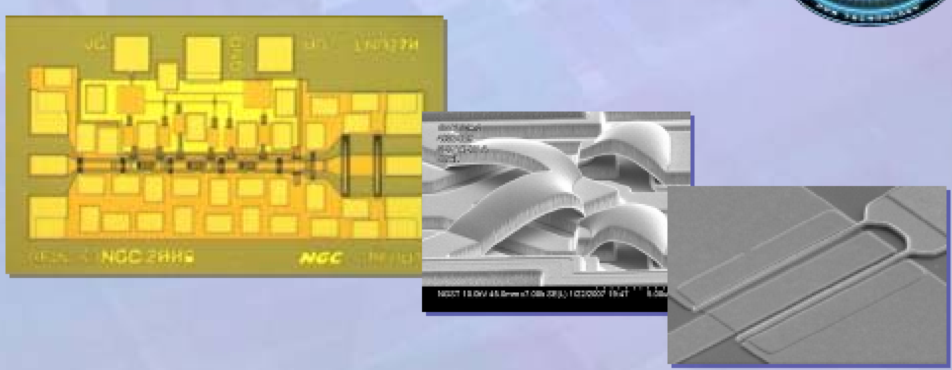




2. THz processing electronics now possible

- Existing devices have substantial THz gain
- High-yield MMIC process at 340GHz





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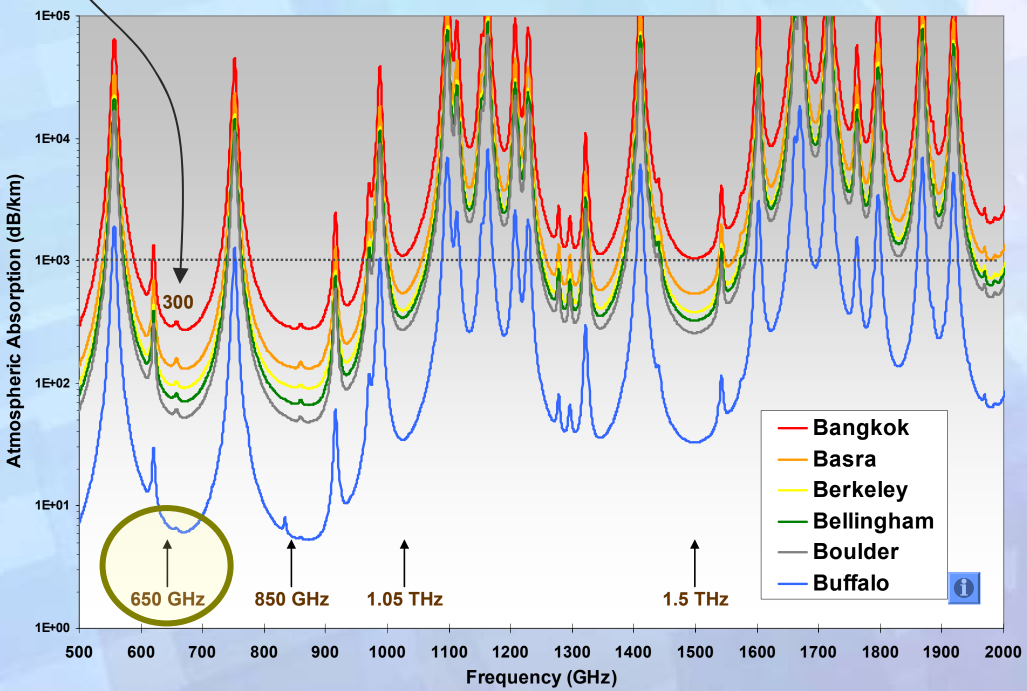
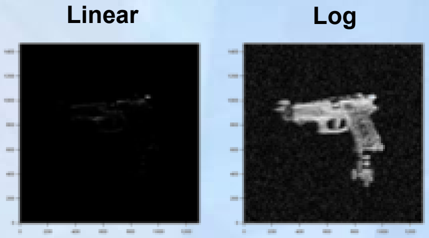
What Hasn't Changed: "For THz, SNR is King"

Attenuation of Signal by Atmosphere

Losses in "worst case" environment ≥ 300 dB/km



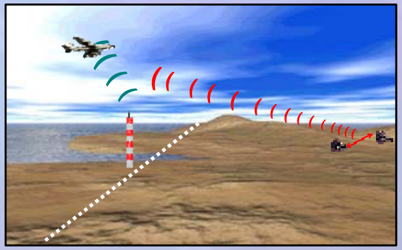
Dynamic Range Needed for Applications



Signal processing

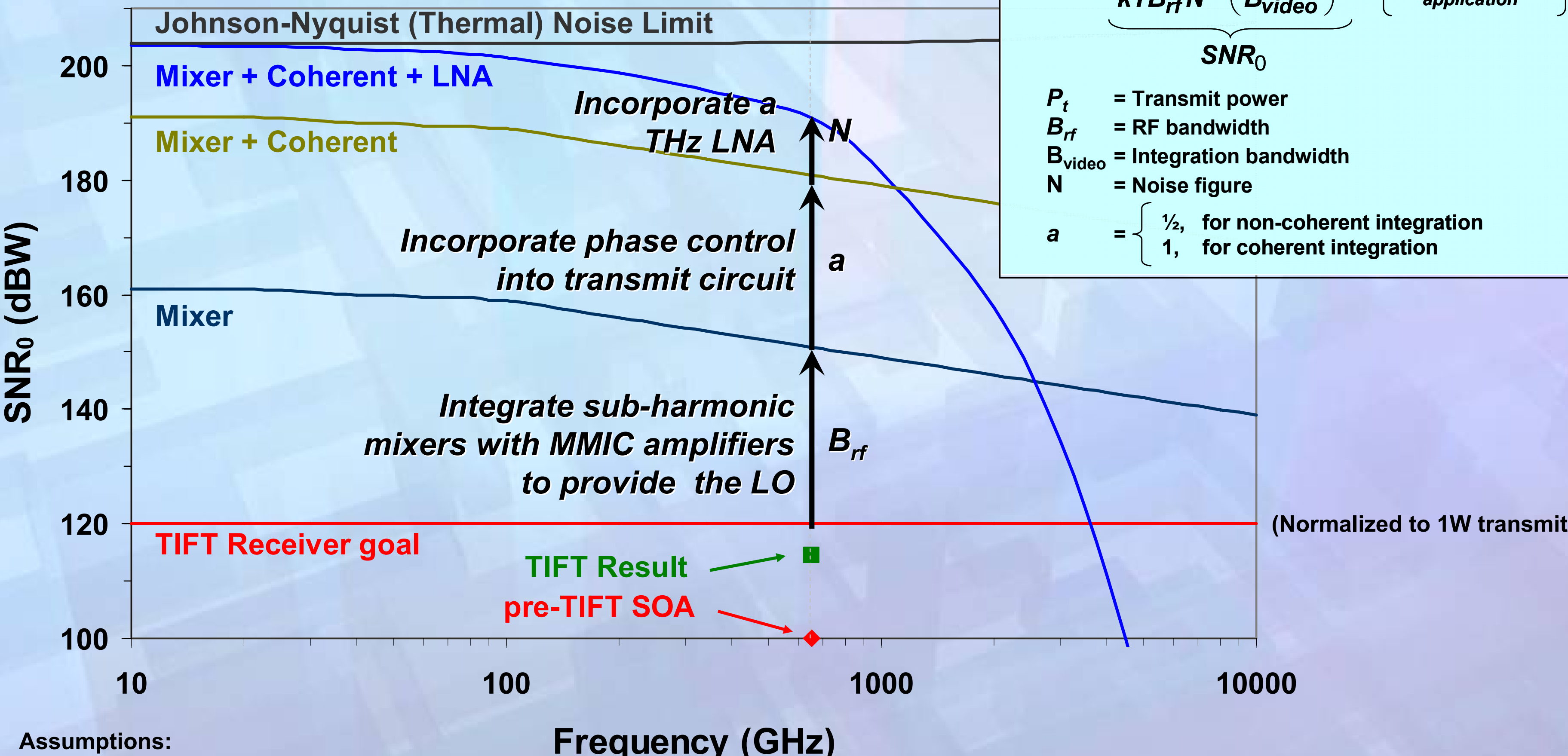
Bit error rate / channel capacity

Interfering signals



Any terrestrial THz front-end will be severely challenged to achieve the highest possible SNR

The Next THz Challenge: Achieve Enormous Gains in Receiver Sensitivity



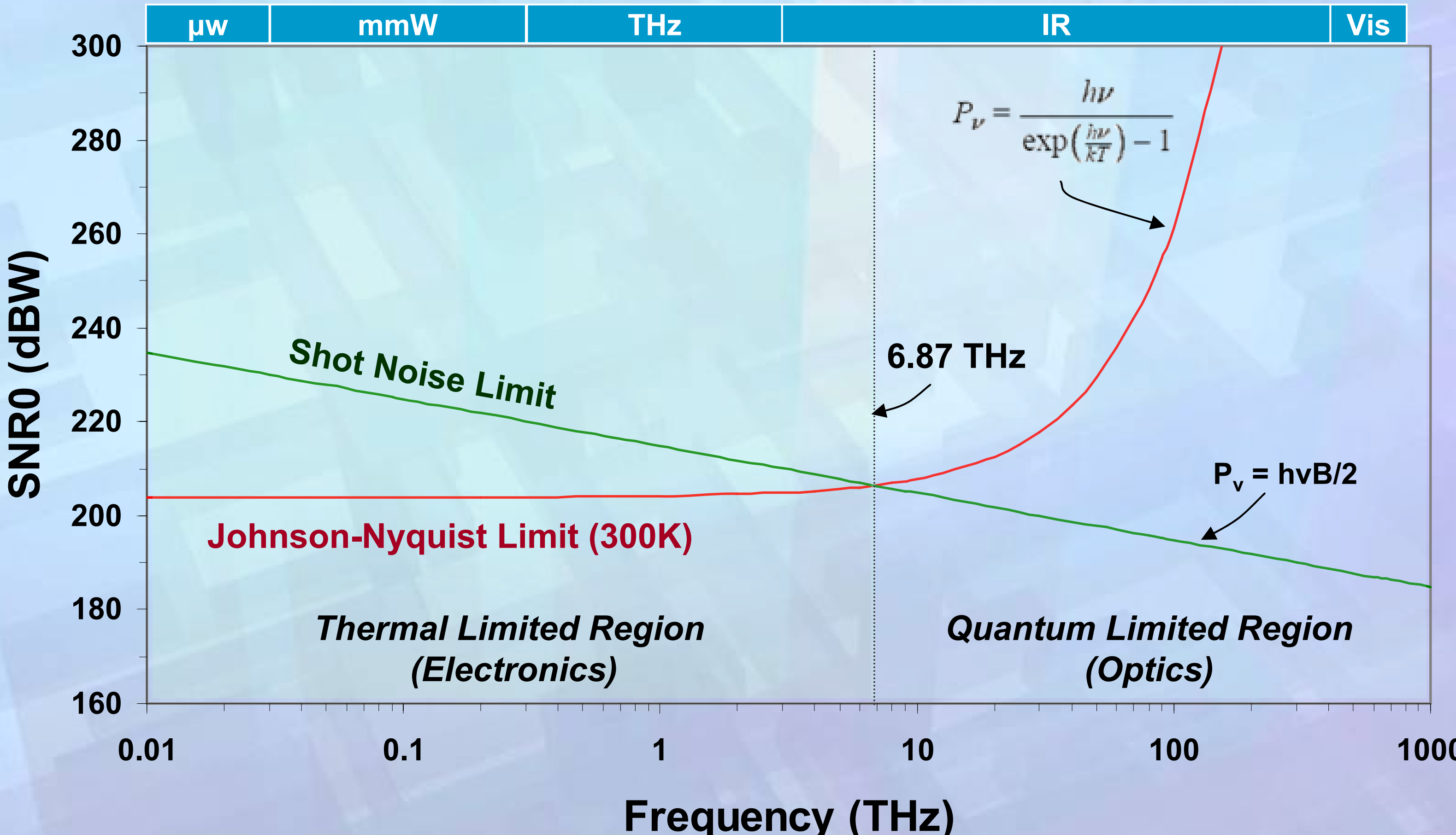
$$SNR = \underbrace{\frac{P_t}{kTB_{rf}N} \times \left(\frac{B_{rf}}{B_{video}}\right)^a}_{SNR_0} \times \left\{ \begin{array}{c} \text{Terms that depend} \\ \text{on the specific} \\ \text{application} \end{array} \right\}$$

- P_t = Transmit power
- B_{rf} = RF bandwidth
- B_{video} = Integration bandwidth
- N = Noise figure
- $a = \begin{cases} ½, & \text{for non-coherent integration} \\ 1, & \text{for coherent integration} \end{cases}$

Assumptions:
B_{video} = 1 Hz, P_t = 1W

Through integration, huge increase in SNR is achievable; ~70dB compared to direct detection, ~40dB compared to SSB mixer

Frequency and Noise Limits



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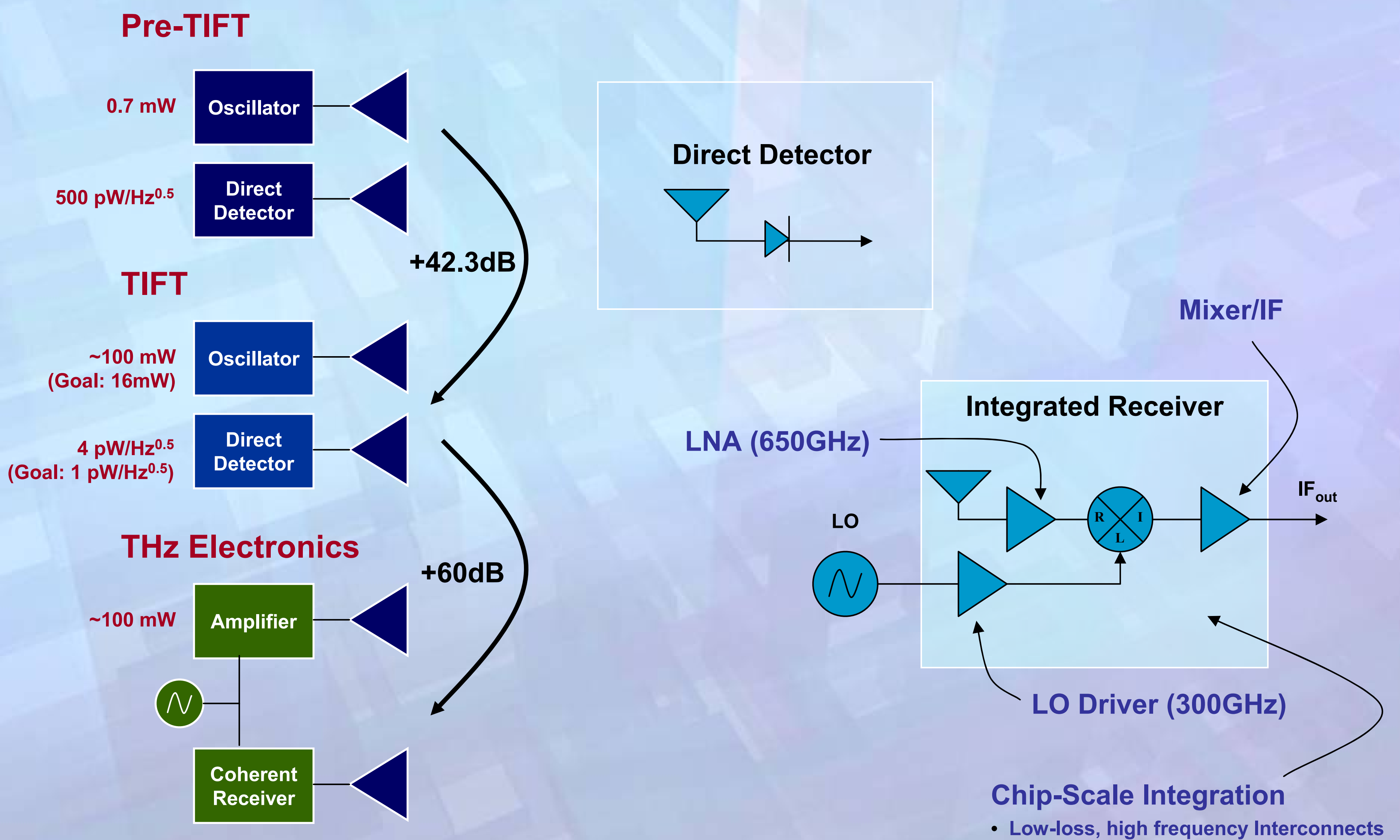
THz Integrated Electronics



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THz Integration Allows Huge Potential SNR and SWaP Gains

LO Driver	SOA*	TIE
Power dissipation (mW)	500	<100

*Multiplier chain

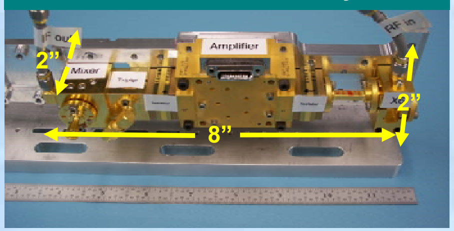
650 GHz LNA	SOA	TIE
NF (dB)	N/A	10 ?
Gain (dB)	N/A	25 ?

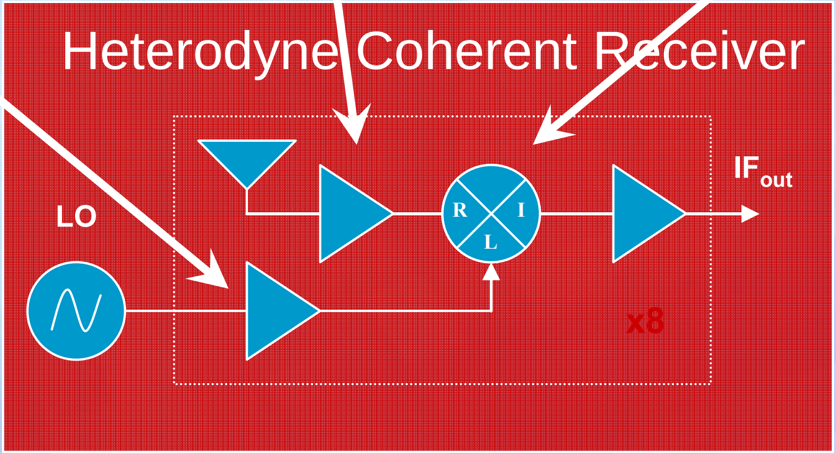
Mixer/IF	SOA*	TIE
Bandwidth (GHz)	6	50 ?
Noise figure (dB)	14	12 ?

*SSB mixer

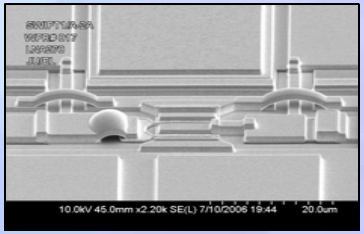
State-of-the-Art (SOA)

Conventional 650 GHz Sub-System





THz Integrated Electronics



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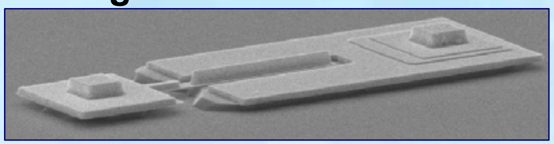
Receiver	SOA	TIE
NF (dB)	24.3	12 ?
Gain (dB)	– 4.3	> 20
Volume (mm^3)	5 x 10^5	5 ?

Technical Challenges to Realizing a THz Integrated Circuit

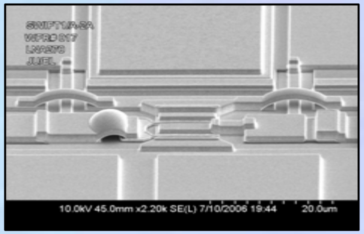
Terahertz Transistors

- Size scaling
- Mitigation of parasitic impedances
- Thermal management



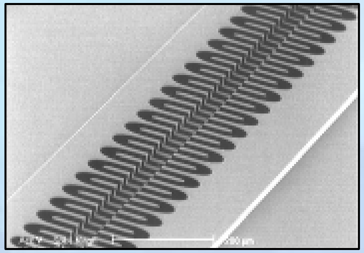
THz Monolithic Integrated Circuits (TMIC)

- Low-loss HF interconnects
- Integration of mixer diodes with transistors
- Extrapolation of device models to THz frequencies



THz High Power Amplifier

- High gain amplification
- Increase P_{out} despite inclusion of filter & antenna into interaction structure
- Wide bandwidth

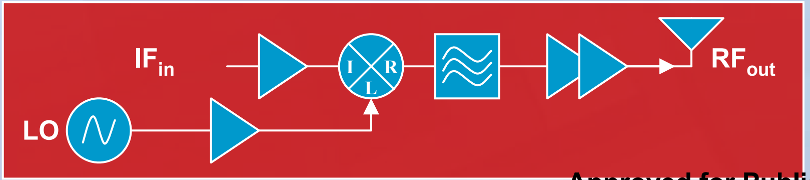


THz Test

- Low-loss fixtures and transitions @ THz
- Traceability / validation
- Turnaround time / cost due to lack of automated test equipment

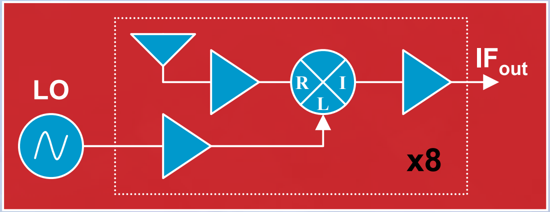
Transmitter Module Integration

- Integration of solid-state RF with HPA
- Low-loss high frequency interconnects
- Yield/uniformity of components



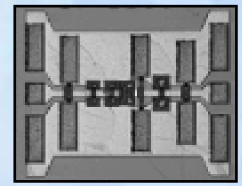
Receiver Array Integration

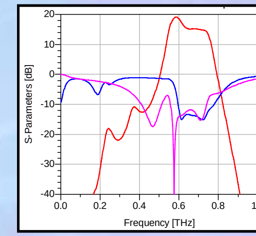
- Low-loss distribution of high-frequency signals
- Precise alignment & interconnect tolerances
- Yield/uniformity of components

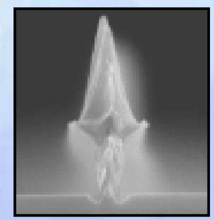


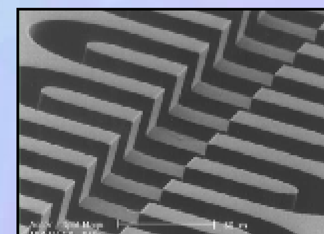
Summary

- A more sophisticated view is emerging of what is required to enable practical THz systems
  - THz devices → THz circuits
    - Not just sources!
    - Much higher level of integration
    - Increased functionality
  - Huge gain in size/weight/power/cost
  - Huge gains in performance
    - Low noise amplifiers *at frequency*
    - Coherent processing
- THz *Electronics*
  - Compact THz vacuum electronics established
  - THz transistors are now here
    - Limits to speed incompletely understood
    - Substantial room for improvement
  - THz integrated circuits aren't far behind









Through integration, huge increase in system SNR is achievable

Questions?