Vacuum Electronics and the World Above 100 GHz

Mark Rosker, DARPA/MTO

International Vacuum Electronics Conference

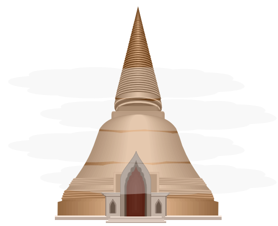
Monterey, CA

22 April 2008

A THz Atlas: The 6 B's

Increasing THz Absorption

Bangkok



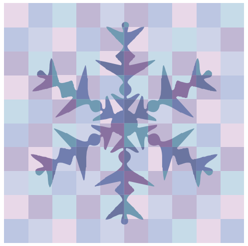
Basra

Berkeley

Bellingham

Boulder

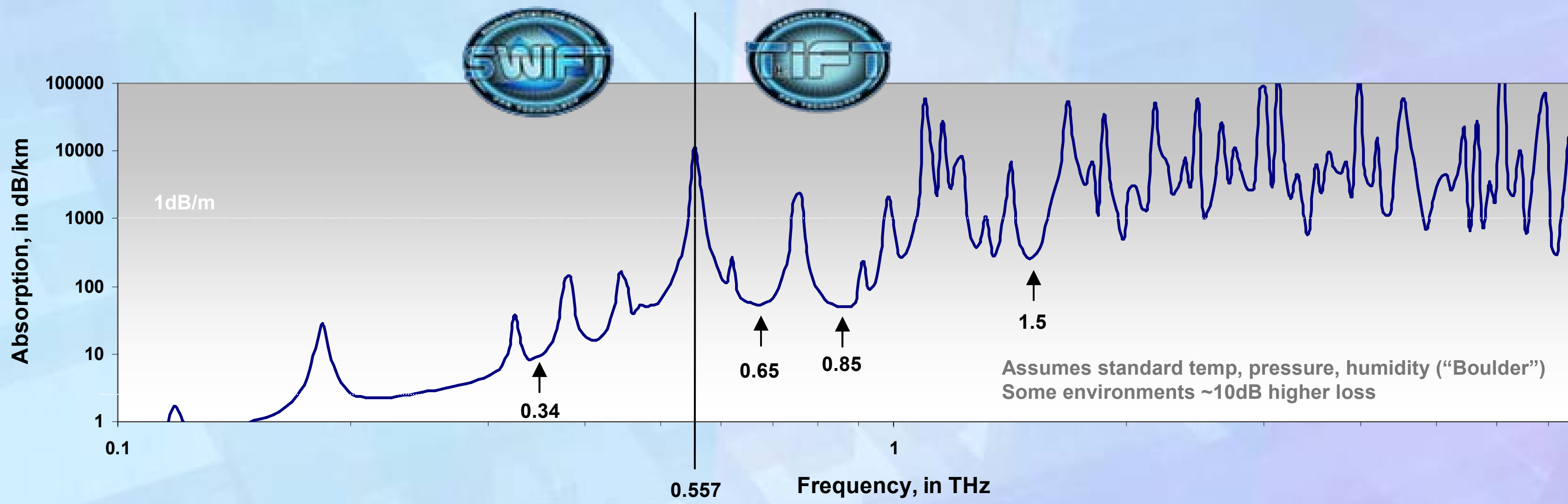
Buffalo



Decreasing THz Absorption

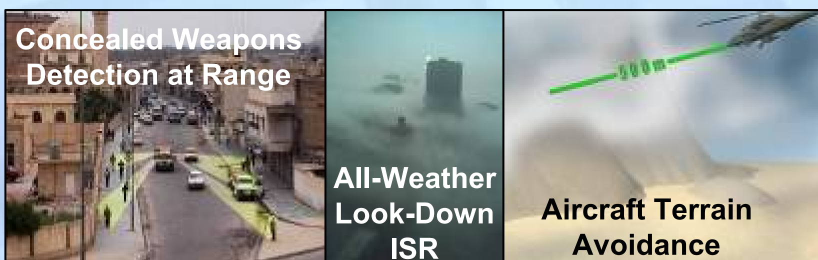
MTO's THz Programs

Phenomenology



Applications

Ranges up to 1 km

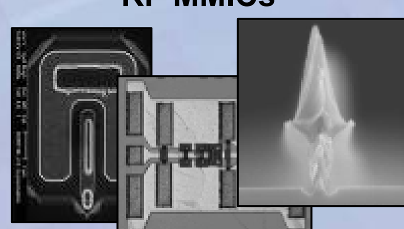


Ranges < 100m

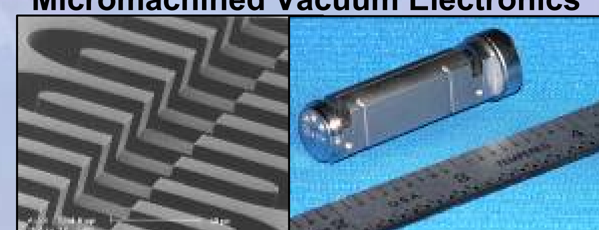
Technologies

Electronic Upconversion

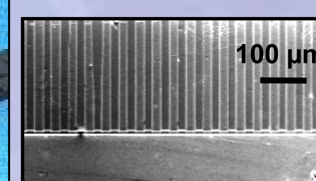
RF MMICs



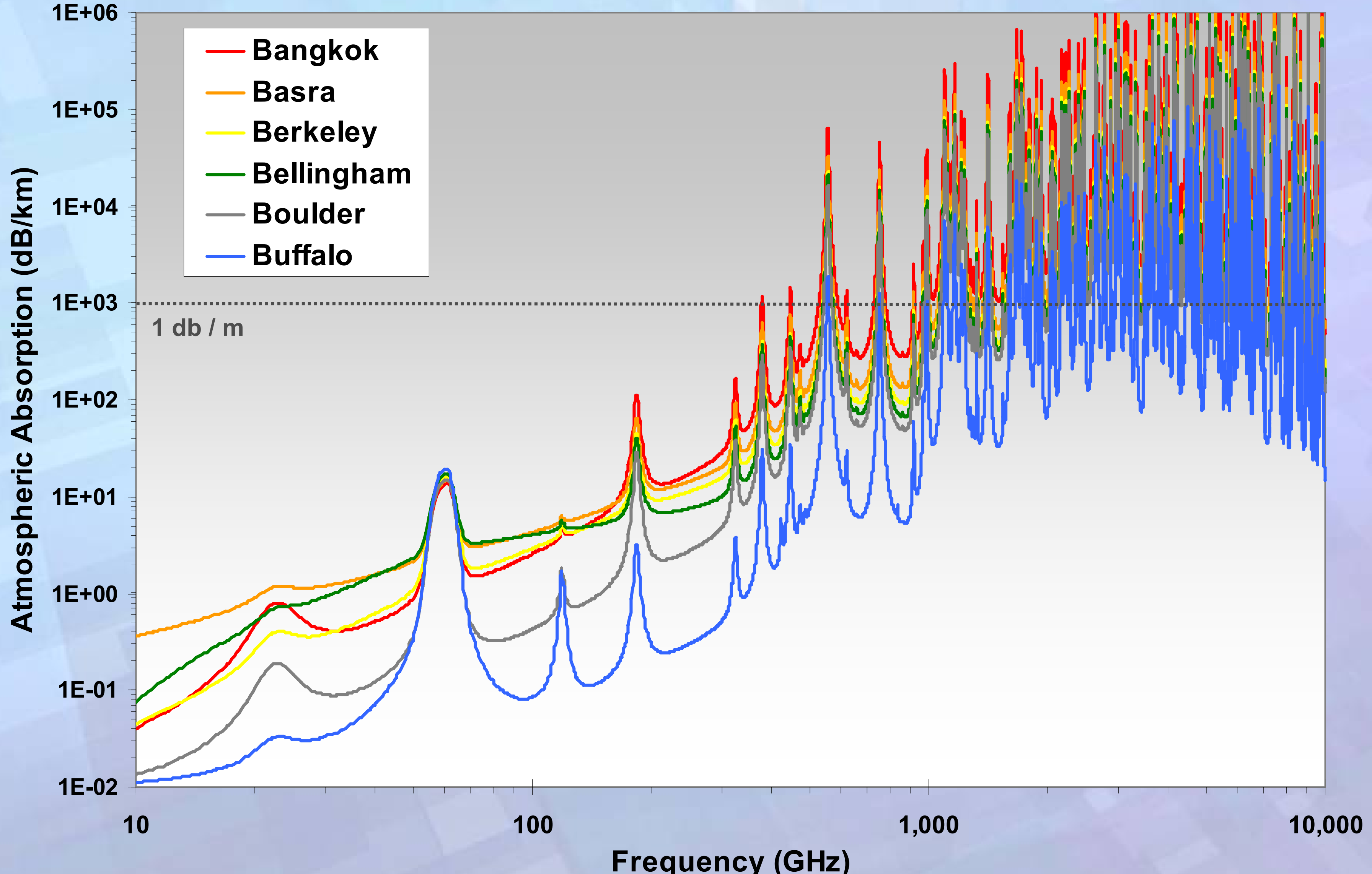
Micromachined Vacuum Electronics



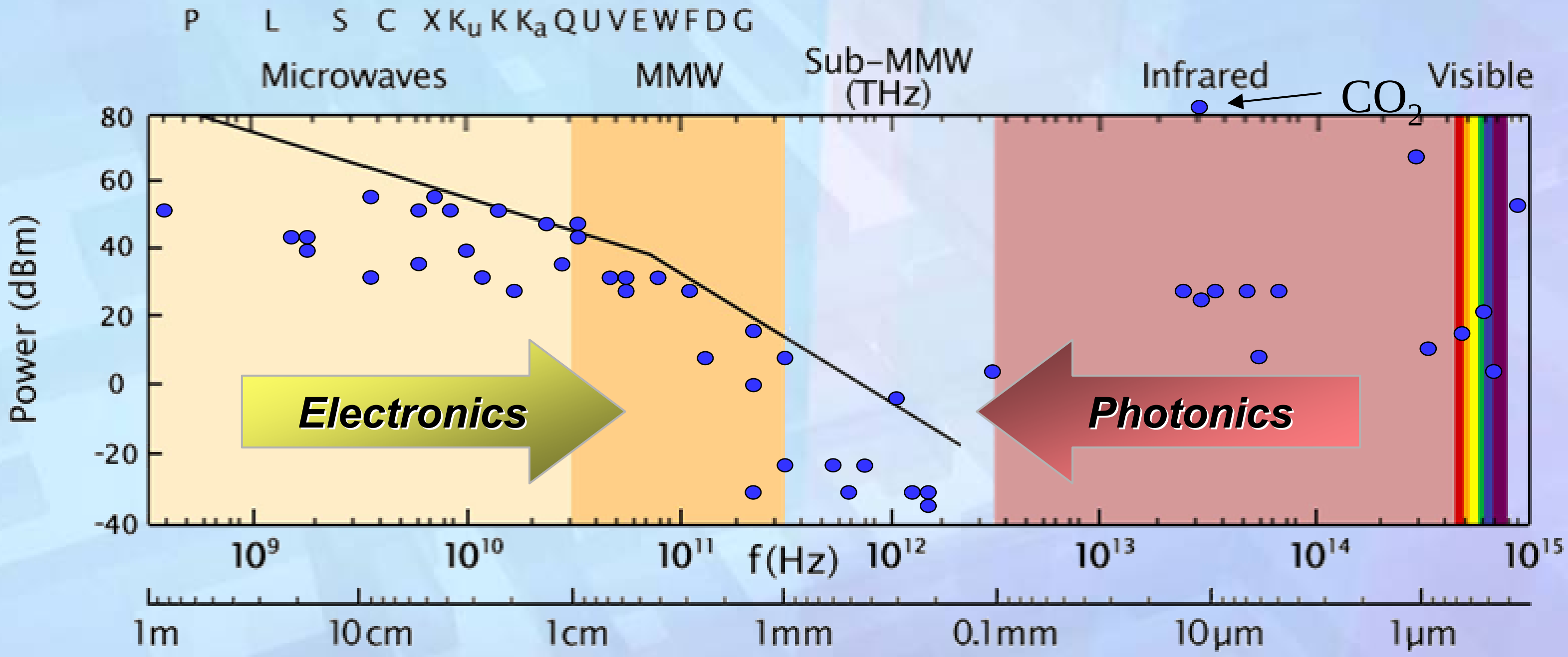
Photonic Downconversion



Compiled Atmospheric Models



The "THz Gap"



Electronics

- Classical region (hv << kT)
- Critical dimensions << λ
- Atmosphere transparent
- Sources readily available

THz / Sub MMW

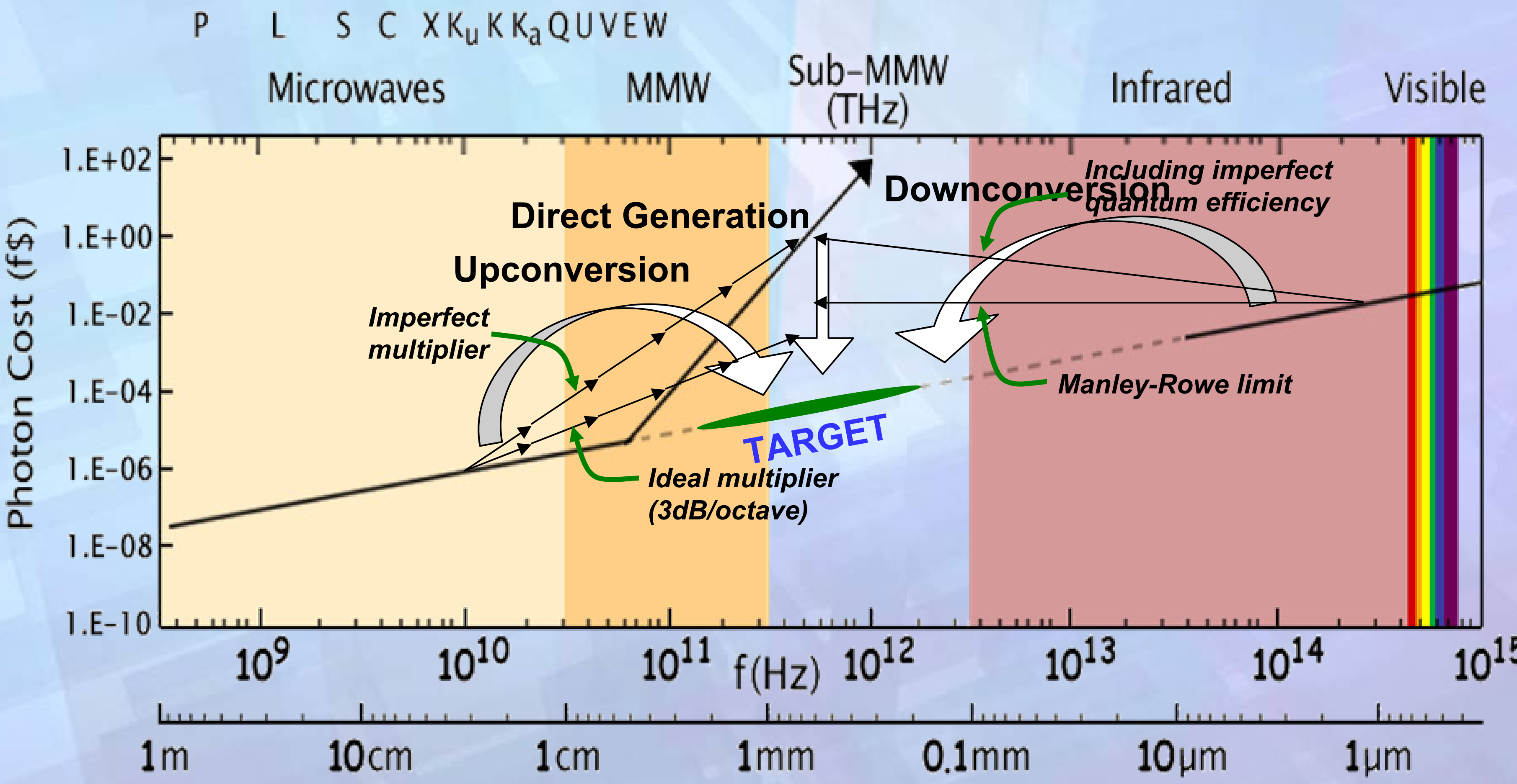
- Transition region: hv ~ kT
- Narrow, poor transparency windows
- Only weak sources available

Optics

- Quantum region (hv >> kT)
- Critical dimensions > λ
- Atmosphere transparent
- Sources available (many at specific λ)

Chart reference: http://envisat.esa.int/instruments/mipas/descr/concept.html#introduction

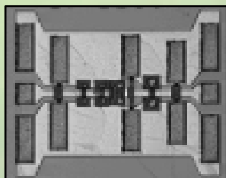
How Much Is that Photon?
(The Rosker Chart)

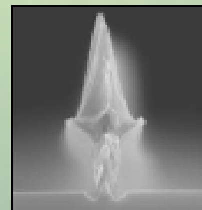


(Some) Source Approaches

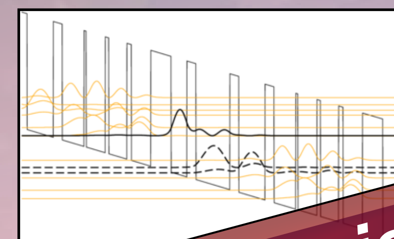
Electronics → ← **Photonics**

Transistors





Lasers

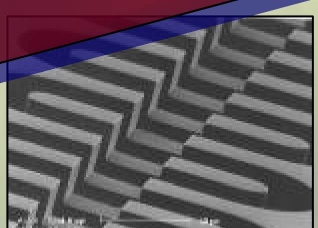


Diodes

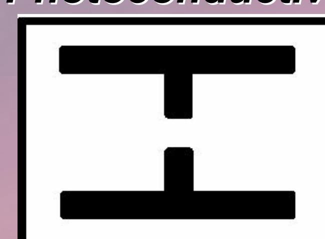
...ear Optics

These are not just different technologies; they are different communities

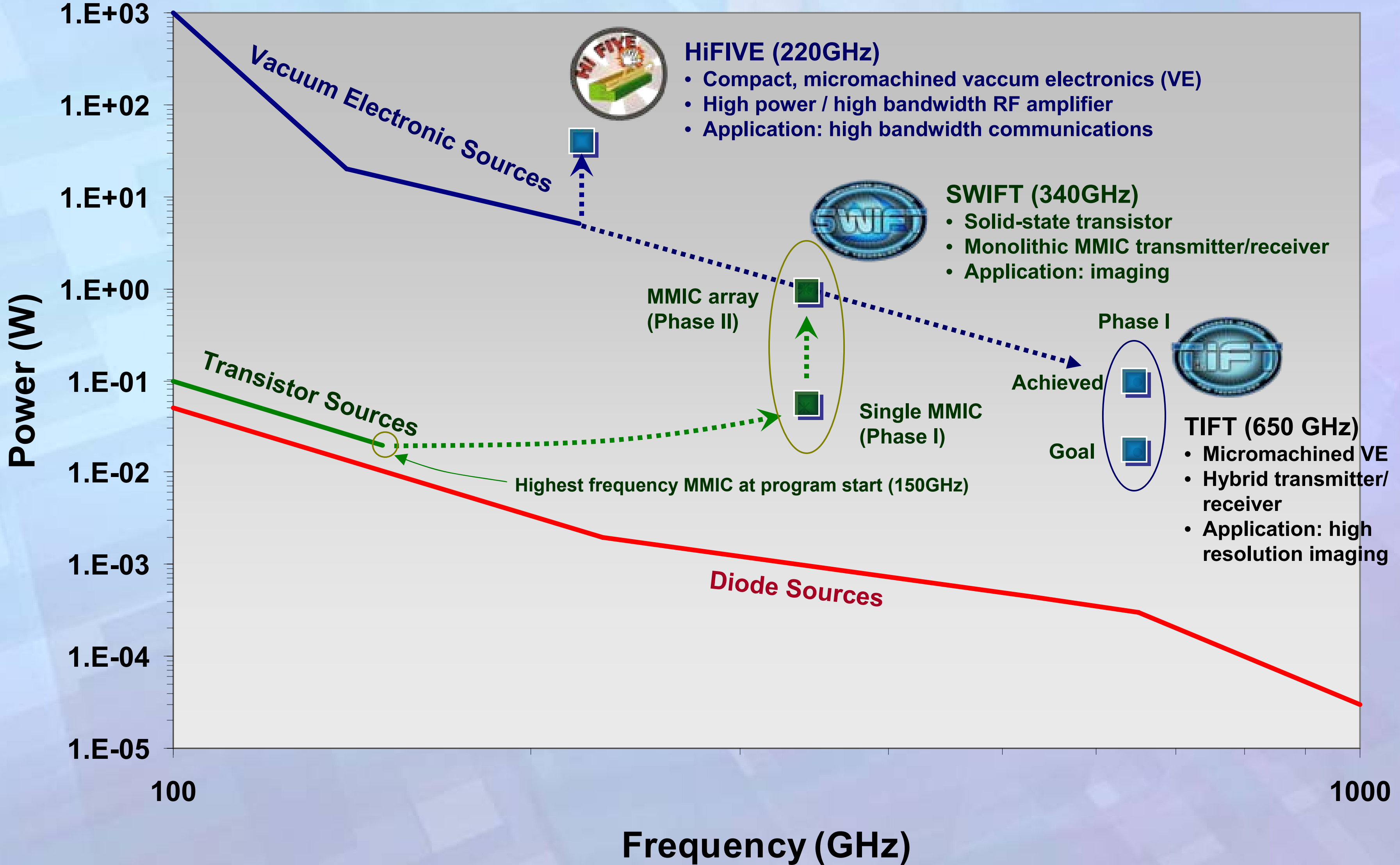
Vacuum Electronics



Photoconductive

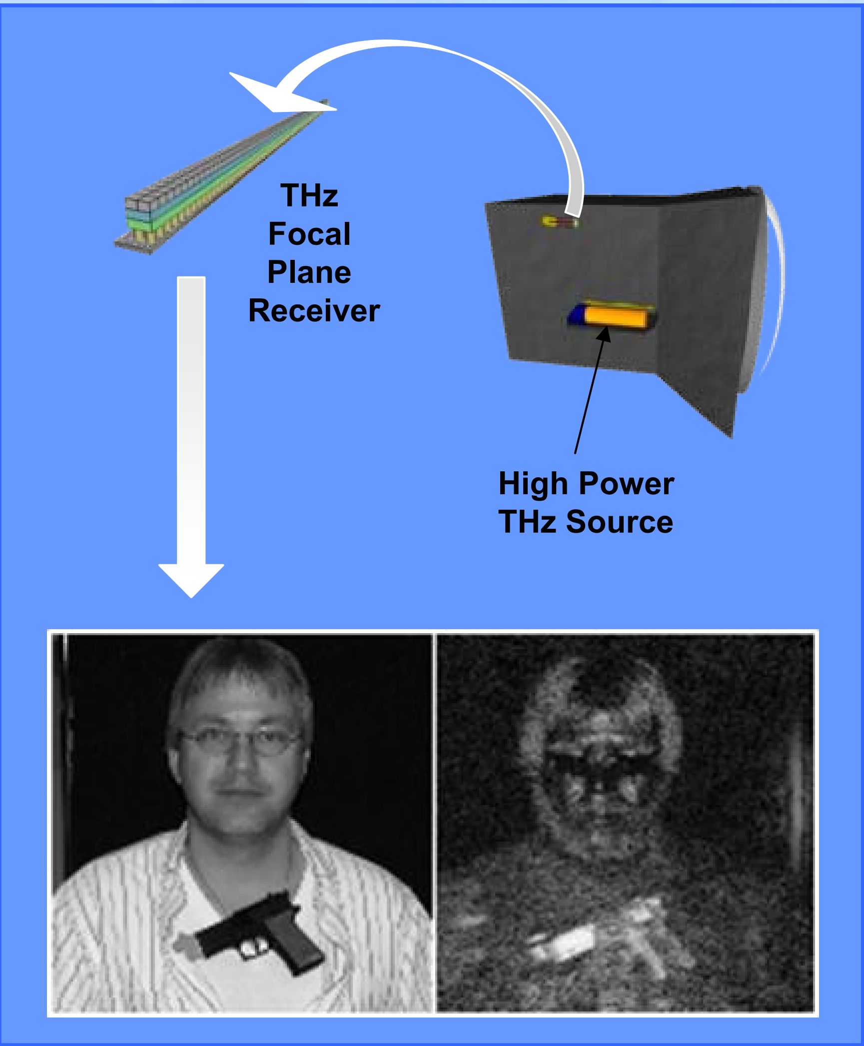


Sources Above 100GHz



TIFT

Terahertz Imaging Focal-Plane Technology (TIFT)



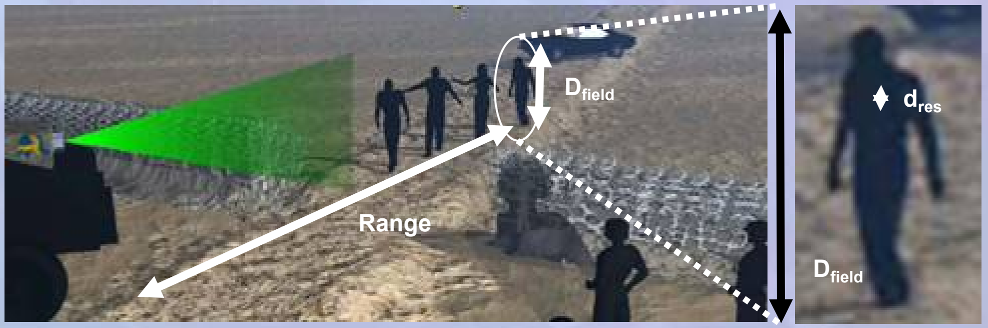
Components for THz Imaging

Program Objective:

- Achieve revolutionary advances in THz transmit and receive technology
- Develop building blocks to enable compact THz (>557 GHz) sensor arrays for diffraction-limited, video-rate imaging

DoD Benefits

- Spectral dominance: will enable exploitation of currently inaccessible region of EM spectrum
- Will develop components needed to enable practical THz systems (sensing, secure communications, spectroscopy, concealed weapons detection)

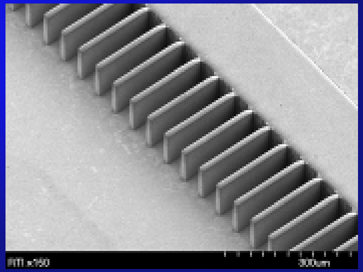


Concealed Weapons Detection at Moderate Range

Technical Challenges

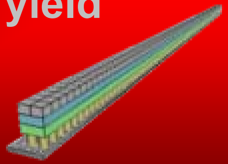
THz Transmitters

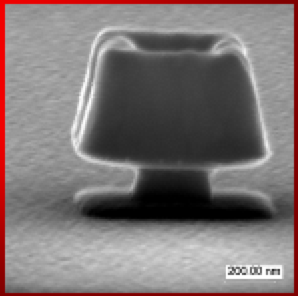
- Higher P_{out}
  - Parasitic loss reduction
  - Circuit feedback optimization
  - Emitter optimization
- High bandwidth
- Thermal management
- Uniformity
- Modulation



THz Array Receivers

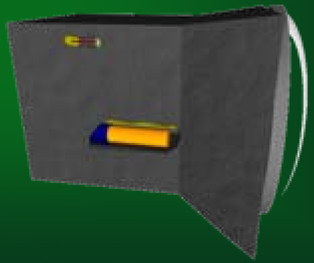
- Integration while maintaining detector sensitivity and minimizing LO power
- Dynamic range
- THz distribution
- Uniformity / yield
- Modulation





THz Active Imagers

- Integration of transmit with receive with minimal losses
- Video rate readout
- Calibration
- Scanning

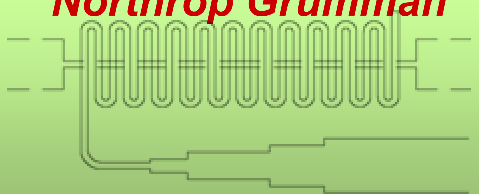


Technical Goals

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

Micromachined Vacuum Electronics‡

Northrop Grumman

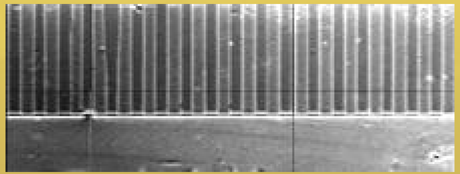


Regenerative Amplifier

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

Photonic Downconversion

Stanford

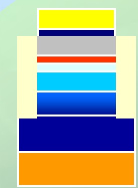


Cascaded OPO

Detectors
- Implement an array-integrable approach achieving NEP′ of 1×10^{-12} W/√Hz (> 100X improvement*)

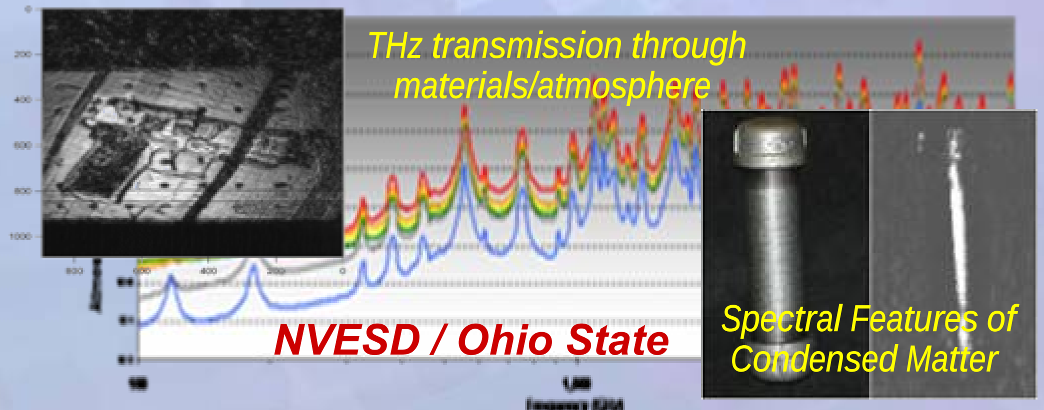
Direct Detectors

UC Santa Barbara



ErAs Diodes

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



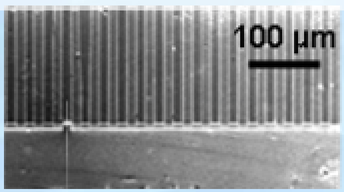
*Comparisons referenced to 0.65THz

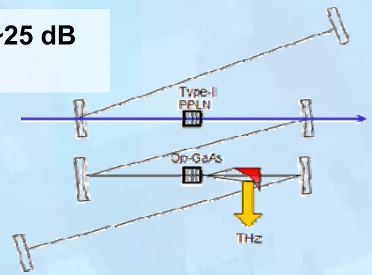
TIFT Accomplishments

THz Source Technology

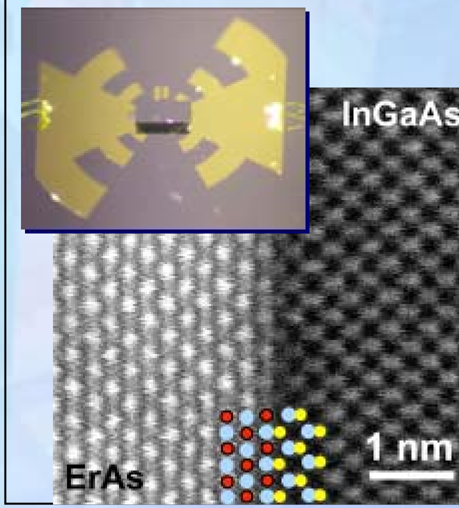
World's first THz micromachined vacuum electronics source

Tunable downconversion source with ~25 dB greater power than SOA at 1.5THz



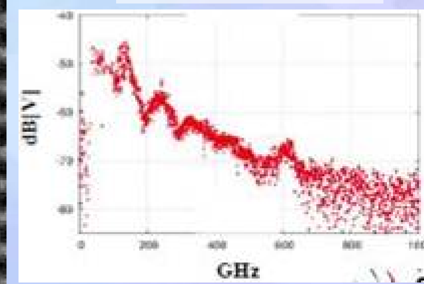


THz Detector Technology



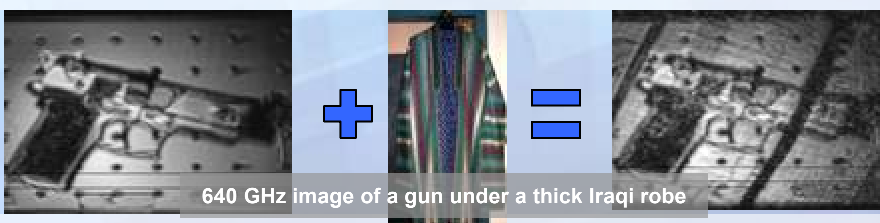
World's most sensitive THz direct detection receiver

4.5 pW/√Hz at 640 GHz



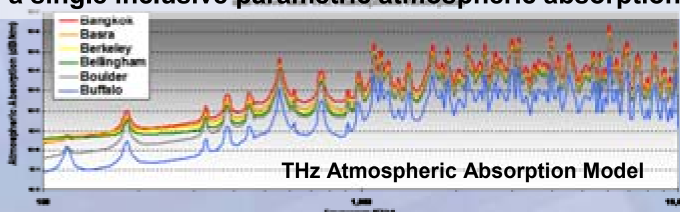
THz Phenomenology

Measured THz transmission through clothing and building materials



640 GHz image of a gun under a thick Iraqi robe

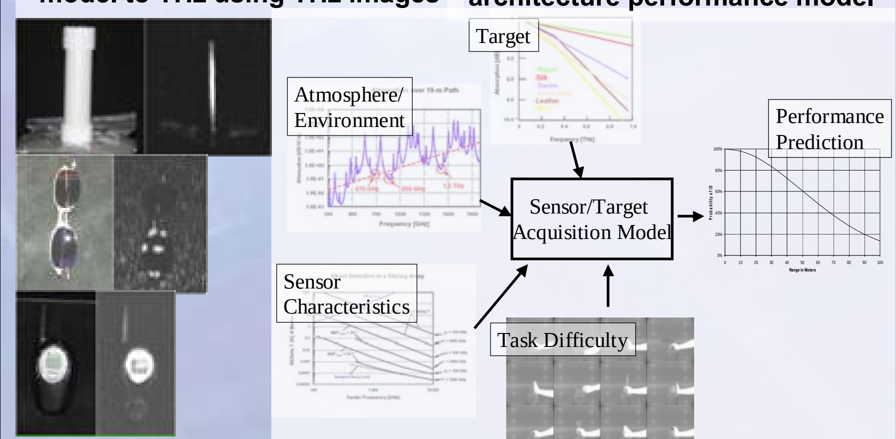
Compiled a single inclusive parametric atmospheric absorption model



THz System Model

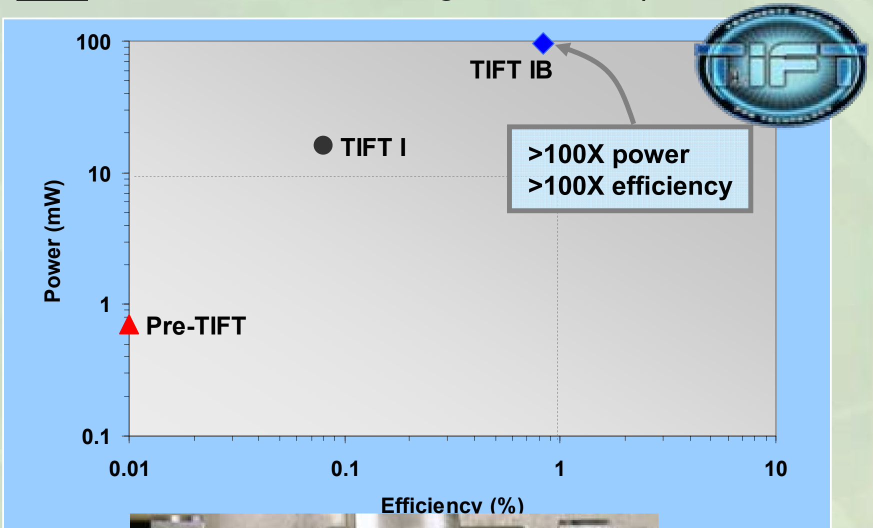
Extended NVESD IR perception model to THz using THz images

Constructed THz imager architecture performance model

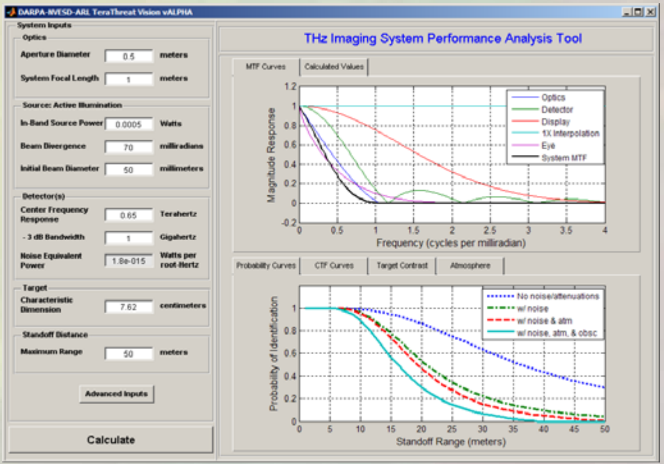


TIFT Performers

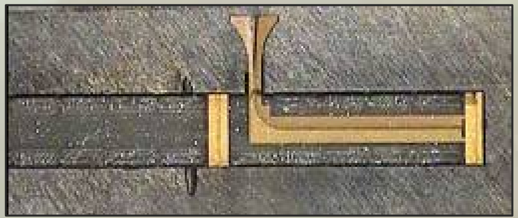
NGC: Micromachined TWT regenerative amplifier



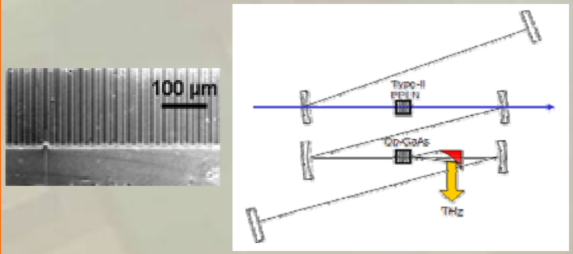
NVESD: THz Imaging Phenomenology and System Performance Model



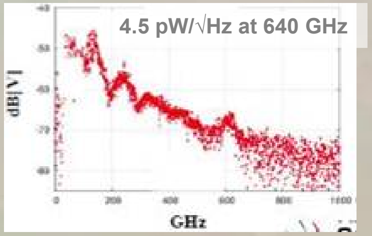
Genvac: Wafer scale manufacturing of diamond and gold BWOs

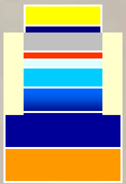


Stanford: Cascaded optical down-conversion based source at 1.5 THz



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





TIFT Metrics

	Metric	Unit	Pre – Program SOA	TIFT Result	TIFT Goal
	Operating frequency	GHz	>557		
Source	Power	mW	0.7	98	16 (1)
Source	Efficiency	%	0.01	0.83	1.0
Source	Duty cycle	%	N/A	3	50
Source	Bandwidth (2)	GHz	30	61*	15
Receiver	Direct detect	pW/√Hz	500	4	1
Receiver	Dynamic range	dB		70	80
Receiver	FPA size	elements		1†	16

(1) Should demonstrate a path to 100mW

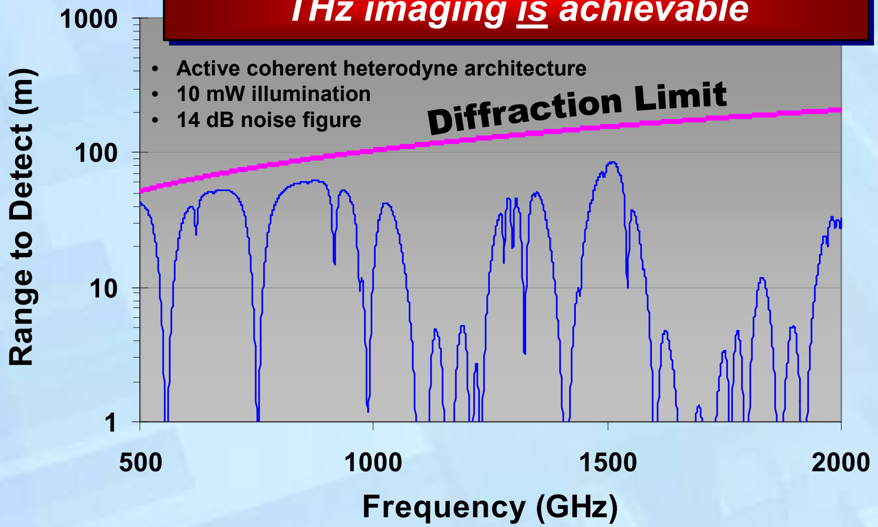
(2) Measured over an integration time of 1μs

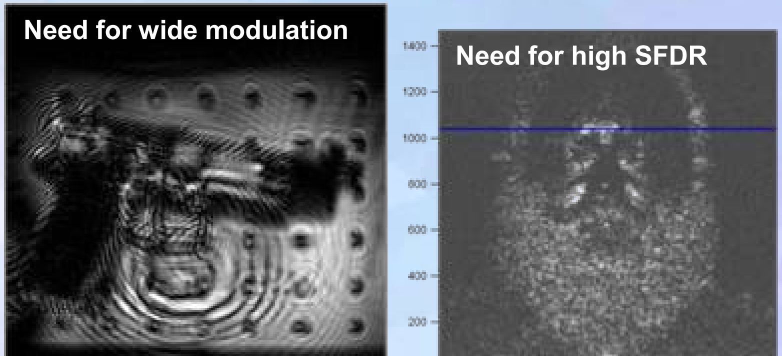
** Value is extrapolated from DC measurements*

† Largest size tested

Lessons Learned from TIFT

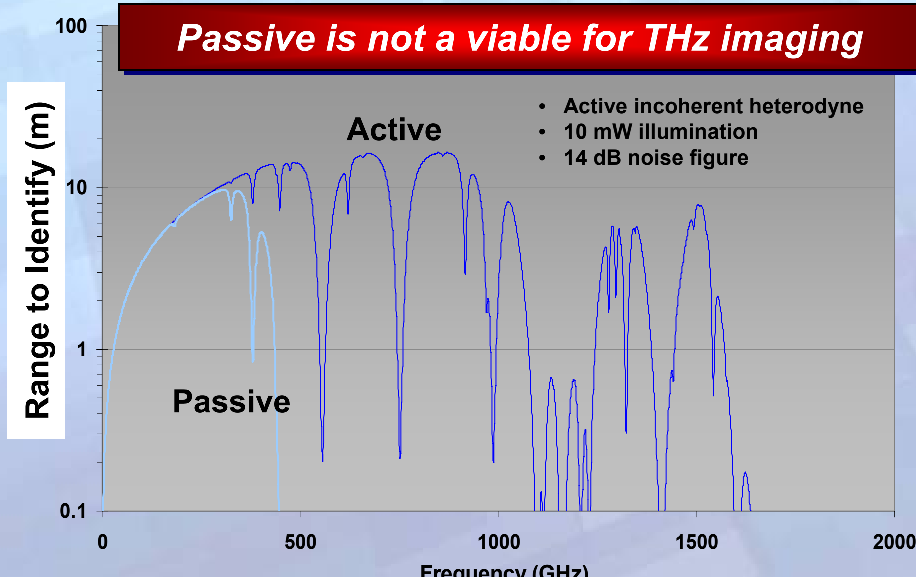
Near-diffraction limit, video-rate THz imaging is achievable



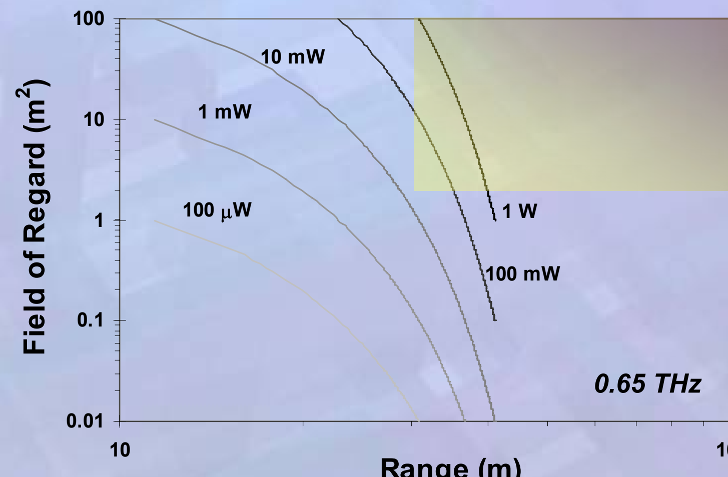


Transmit / receive must satisfy challenging new bandwidth and dynamic range requirements

Passive is not a viable for THz imaging



Total illumination power requirements set by field of regard, not by range

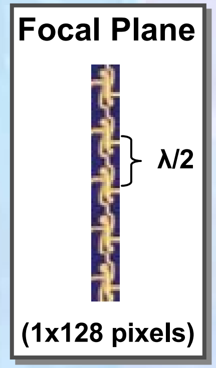


SWIFT

SWIFT Objective and Impact

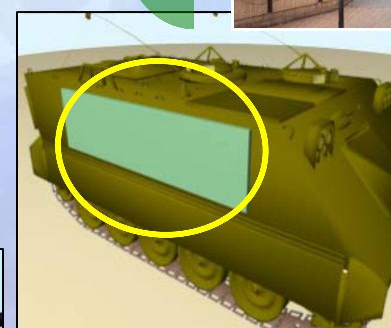
Goal
- Demonstrate high-performance transmit/receive sub-aperture to enable diffraction-limited and video-rate sub-MMW (340 GHz) imaging

Impact
- Push the limits of RF electronics
- Enable imaging in environments where no other sensor can function

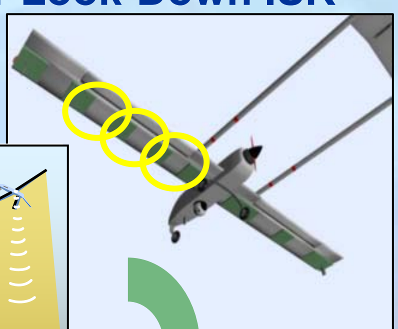


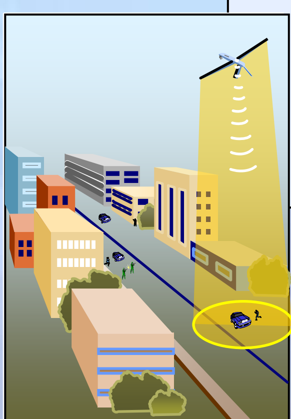
Concealed Weapons Detection at Range

Range ~ 100m



All-Weather Look-Down ISR





Scan angles > 60°

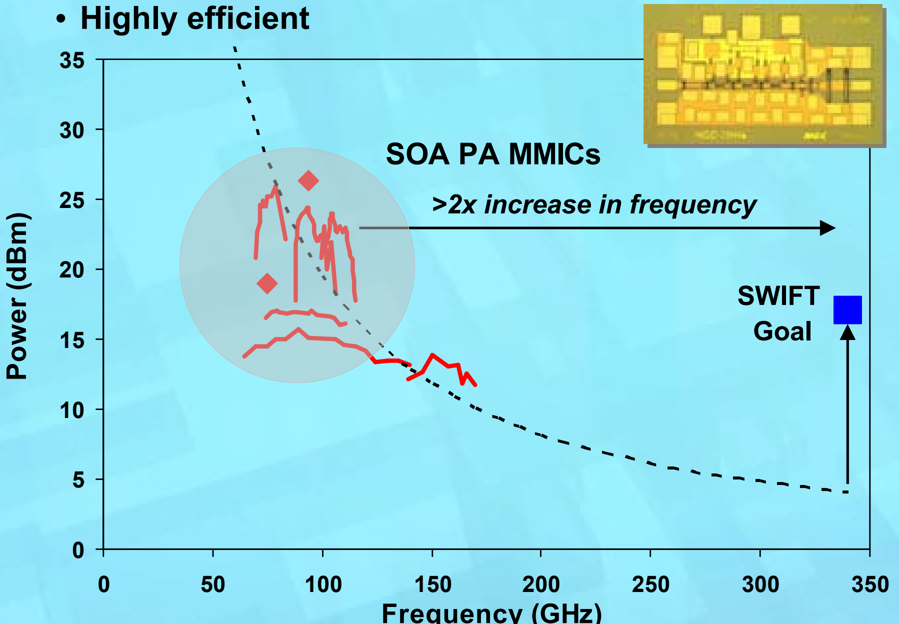
All-Weather Terrain Avoidance

Radome-limited aperture

SWIFT Technical Challenges

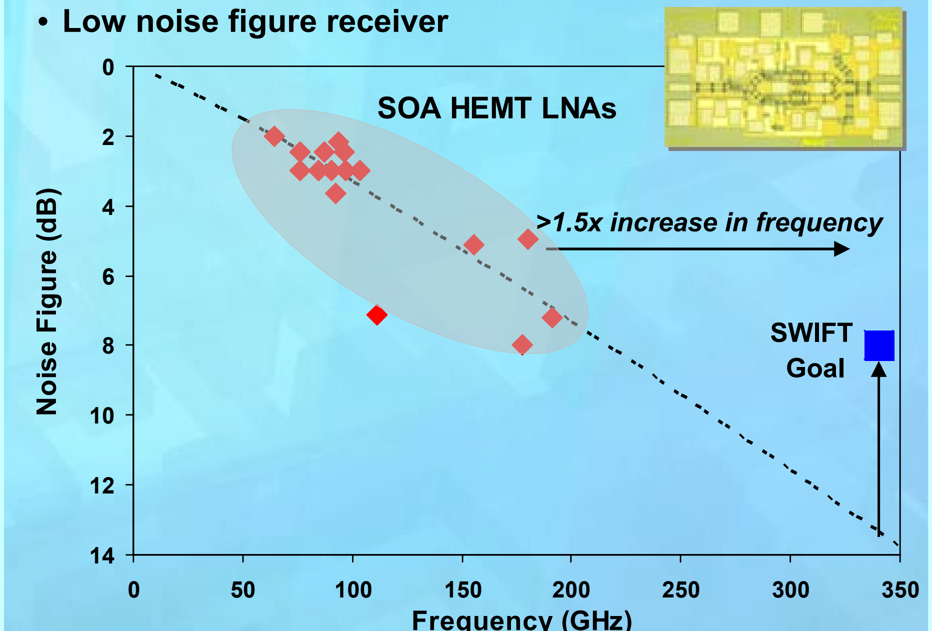
Sub-MMW Sources

- Ultrafast power amplifier MMICs
- Highly efficient



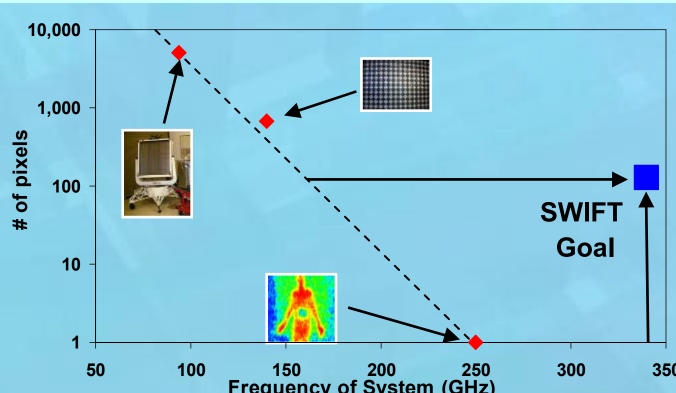
Sub-MMW Receivers

- Ultrafast LNA MMICs and mixers
- Low noise figure receiver



Imaging Array Architecture

- Minimization of LO power
- Low loss interconnects



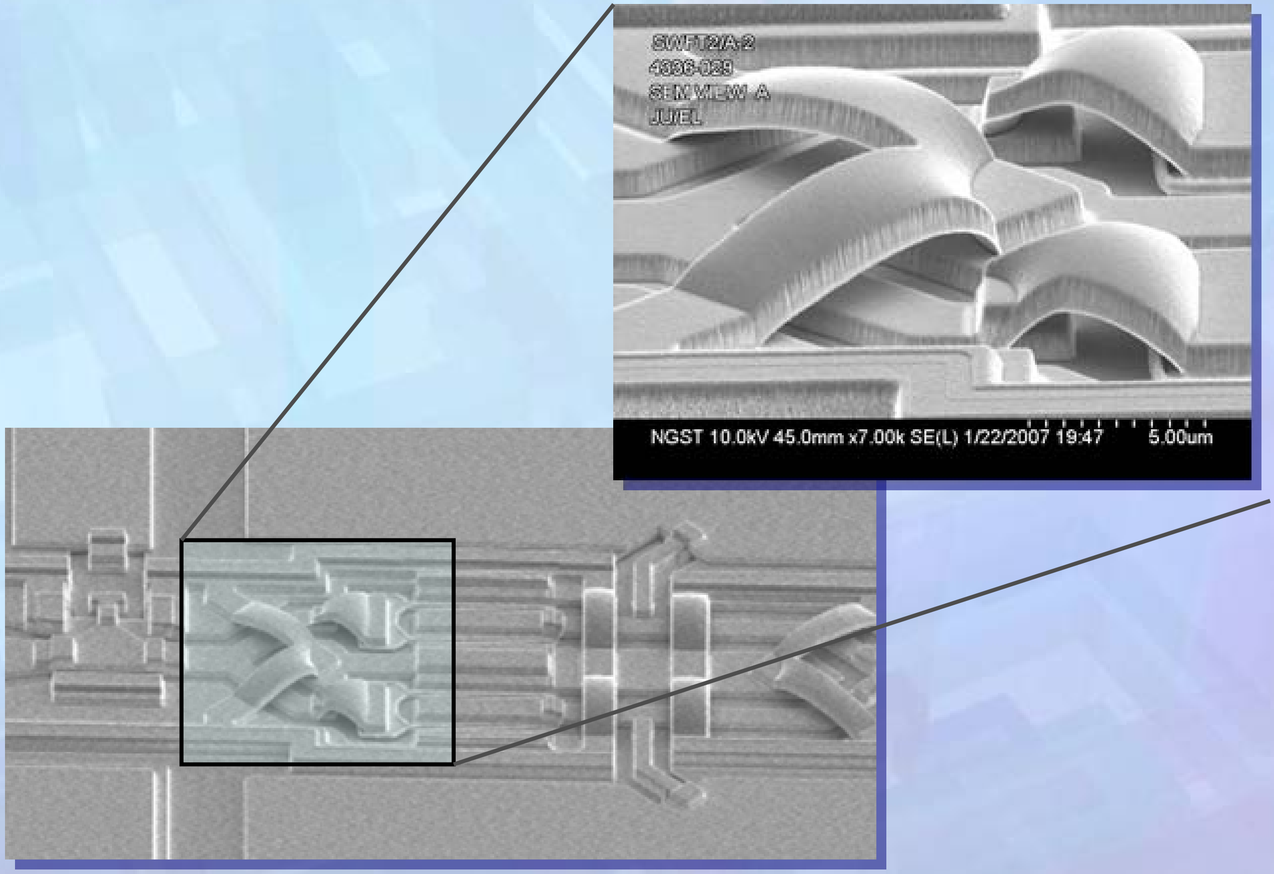
SWIFT Program Metrics

Metric*	Unit	Today	Phase I		Phase II
			Mid-term MMIC Demo	MMIC GNG	Sub-Aperture GNG
PA P_{out}	mW	None**	5	50	
PA PAE	%	None	2.5	5	
RF bandwidth	%	None	≥ 5	≥ 5	
Receiver NF	dB	None**	12	8	
Phase noise ‡	dBc/Hz	None	-38	-38	
Transmit power	mW	N/A			1000
Sub-array receiver NF	dB	N/A			8
Level of integration	pixels	N/A			128
Frame rate	Hz	N/A			30
Receiver LO power	mW	N/A			< 500

* At 340GHz
** Best reported value for <u>hybrid</u> PA power/LNA NF at 340 GHz are 0.1 mW and 12 dB, respectively
† Azimuthal (height) x cross-track (width)
‡ Value to be measured at f_c = 340GHz at offset frequency of 100Hz

Revised 28Apr2005

What Does an s-MMIC Look Like?

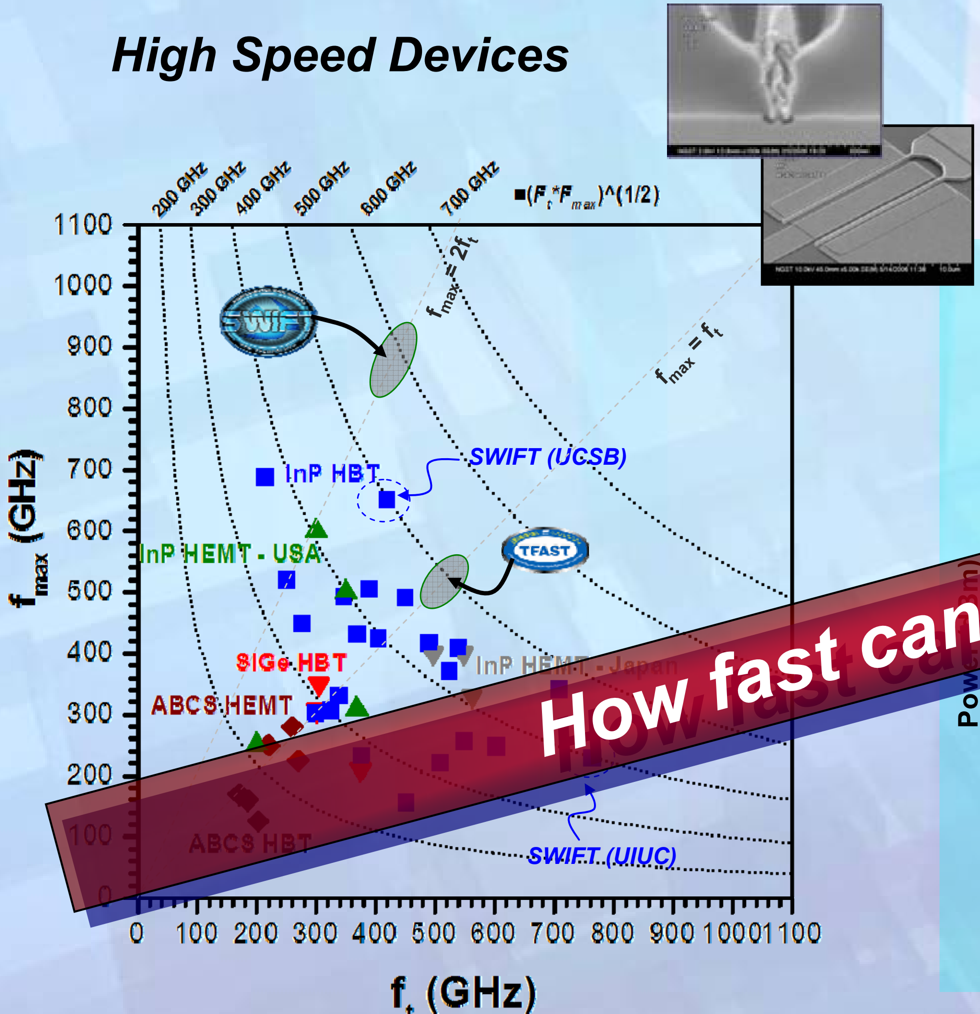


NORTHROP GRUMMAN

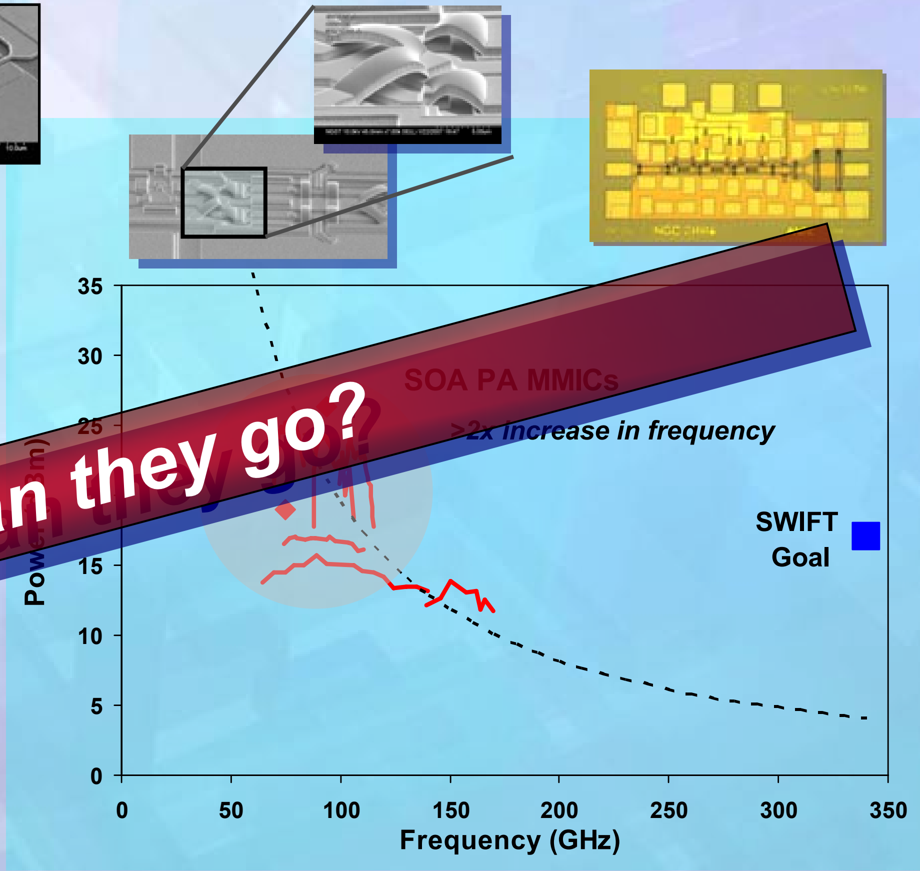
Compact.

Transistor Electronics

High Speed Devices



High Speed MMICs



How fast can they go?

Big Advantage: Integration & Interconnects
Big Challenge: Fmax, Circuit Design

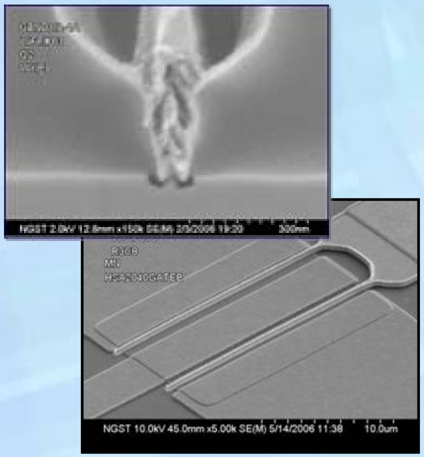
SWIFT Accomplishments

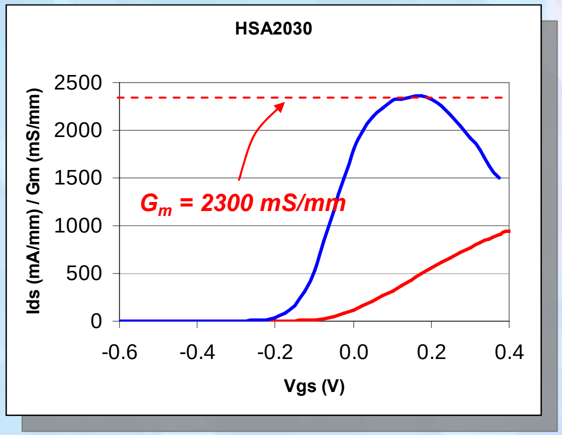
World's Fastest MMICs

35nm InP HEMT Devices

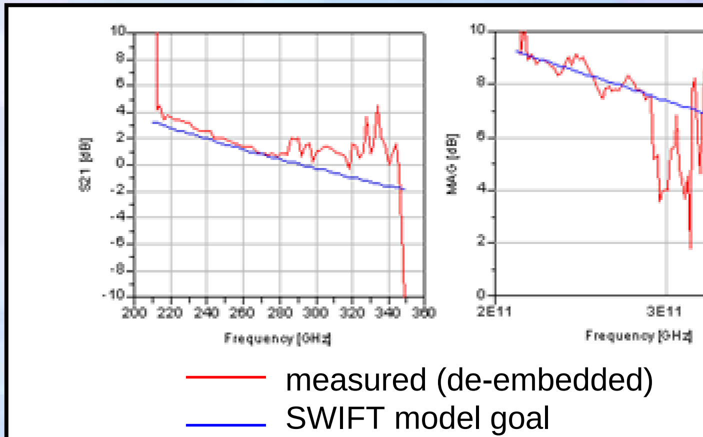
NORTHROP GRUMMAN

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



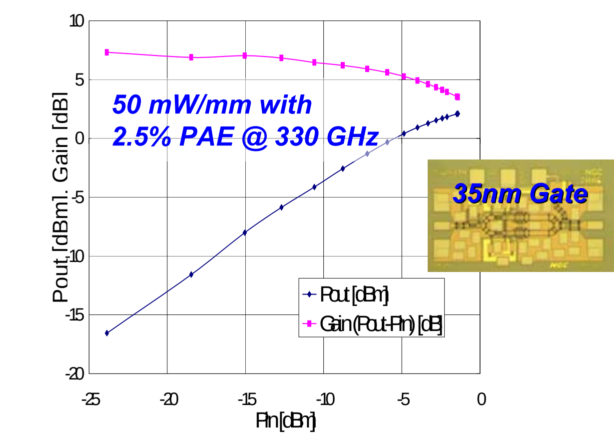


MAG@340 GHz > 6 dB for both model & measured results

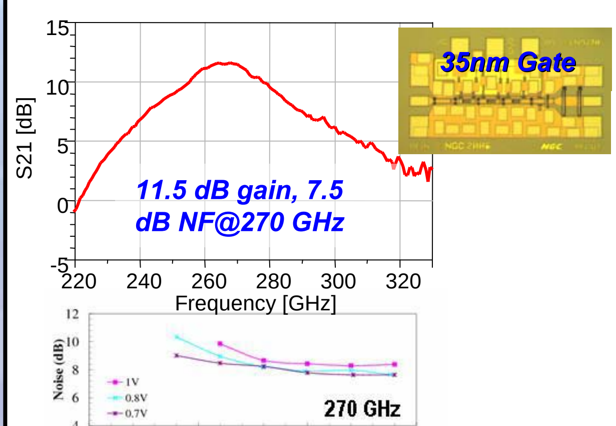


World Record Sub-MMW MMICs ("s-MMIC")

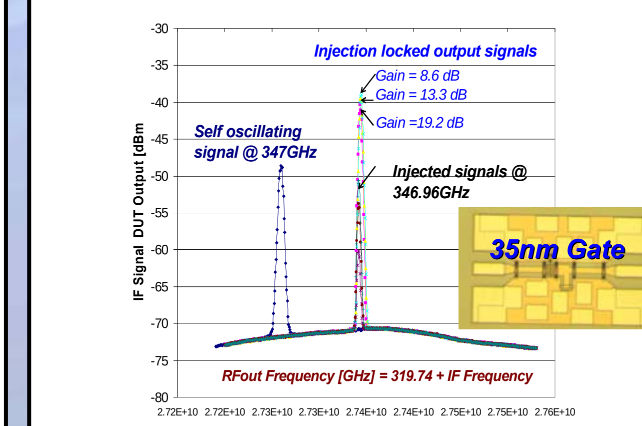
3-stage Power Amplifier @ 330 GHz



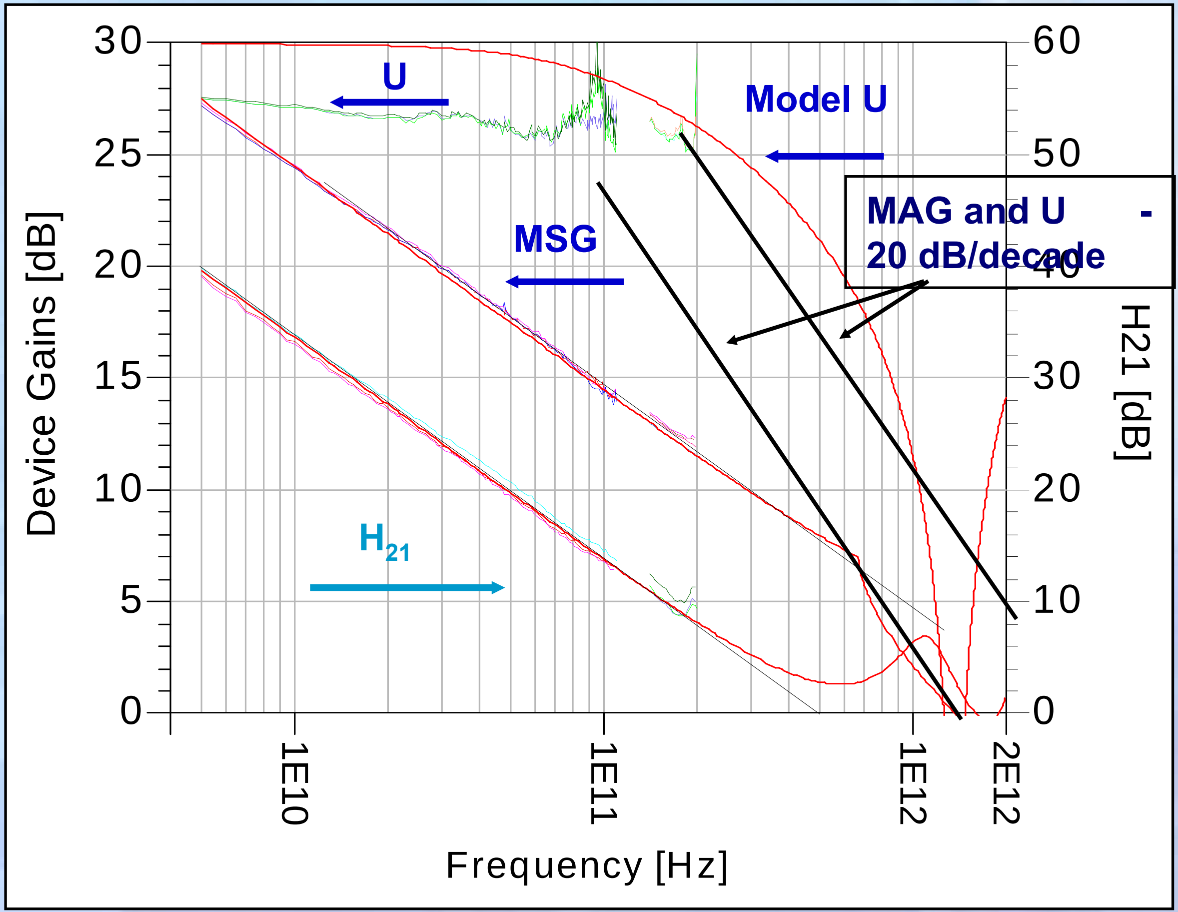
3-stage Low Noise Amplifier @270 GHz



First s-MMIC: a 347GHz HEMT VCO



Fmax

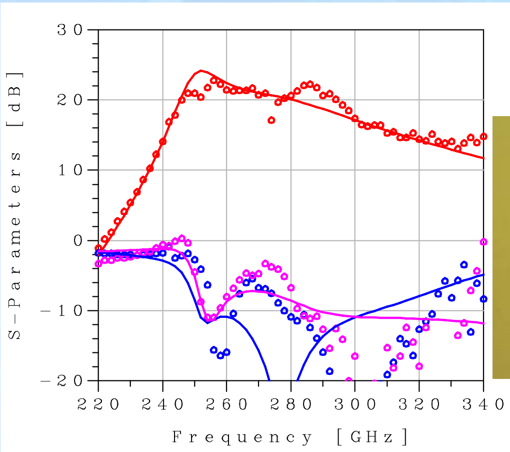


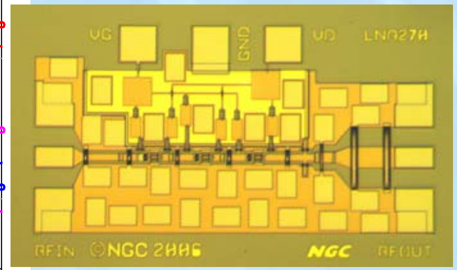
- 4 finger 60 um device
  - 1-110 GHz; 140-220 GHz
- TRL cal structure used
  - better 140-220 GHz measurement accuracy
- U follows predicted model
- MSG follows both trend & predicted model
- H21 follows both trend & predicted model

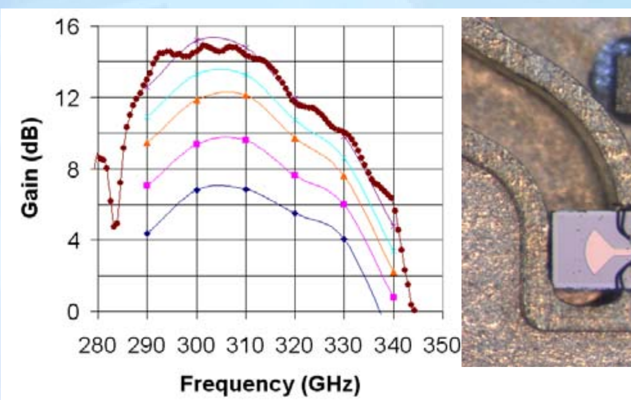
NORTHROP GRUMMAN

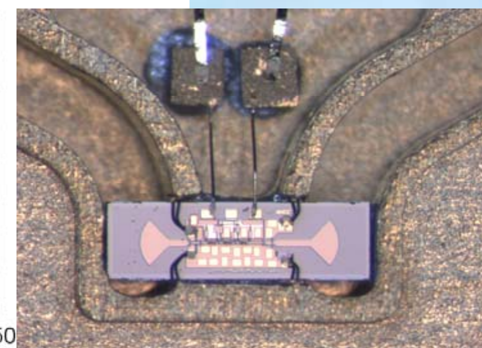
- Fmax ~ 1.2 THz; fT ~ 500 GHz
- Measurements extended to 200 GHz follow gain and H21 trends

Highest Frequency Circuits









Features

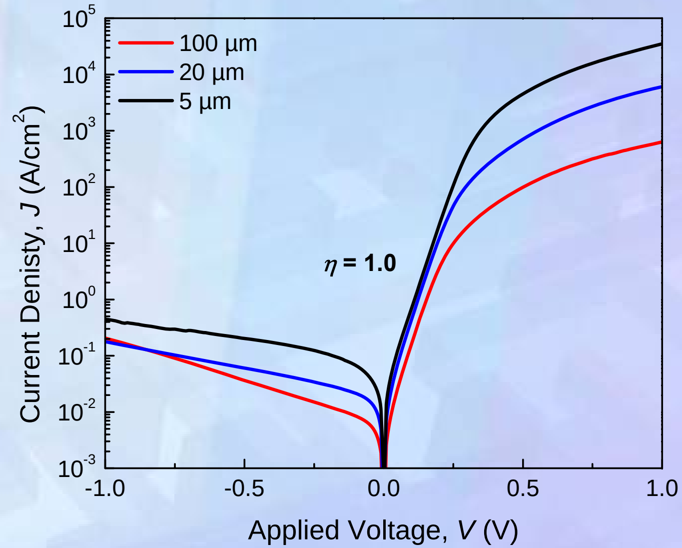
- Sub 50 nm gate InP HEMT
- 2-mil InP thickness with compact vias
- 3-stage MMIC LNA (2f 20 um per stage)
  - 21 dB gain @280 GHz (7 dB/stage)
  - 17 dB gain @300 GHz (5.7 dB/stage)
  - 15 dB gain @340 GHz (5 dB/stage)
  - Some LNAs show 18 dB gain@340 GHz
- JPL designed integrated radial probes & WR3 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

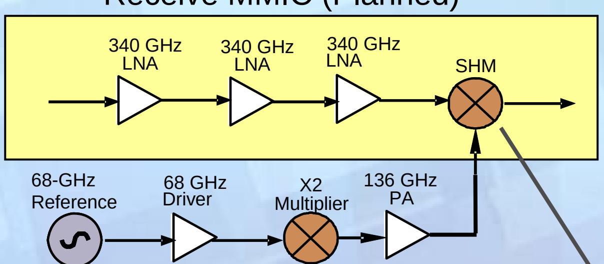
THz Sb-Based Diodes for Sub-Harmonic Mixers

InGaSb/InAlAsSb PN Diodes

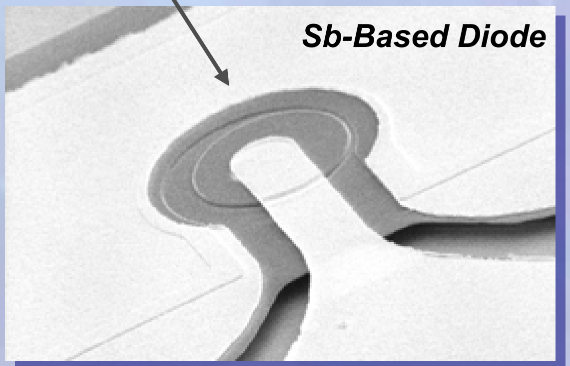
- Excellent ideality factor, $\eta = 1.0$
- Relatively low reverse-bias leakage at low voltage
- Extracted series resistance of 1 Ω for a 5 μm diameter diode
- Cut-off frequency from *S*-parameter extracted *RC* is 1.5 - 9 THz (best fit results in 6.5 THz)

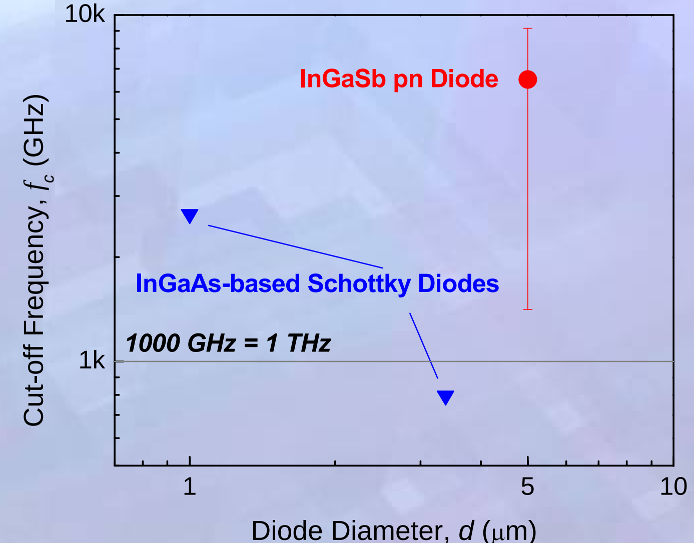


Receive MMIC (Planned)



Performance
- 7-dB NF
- 5% BW

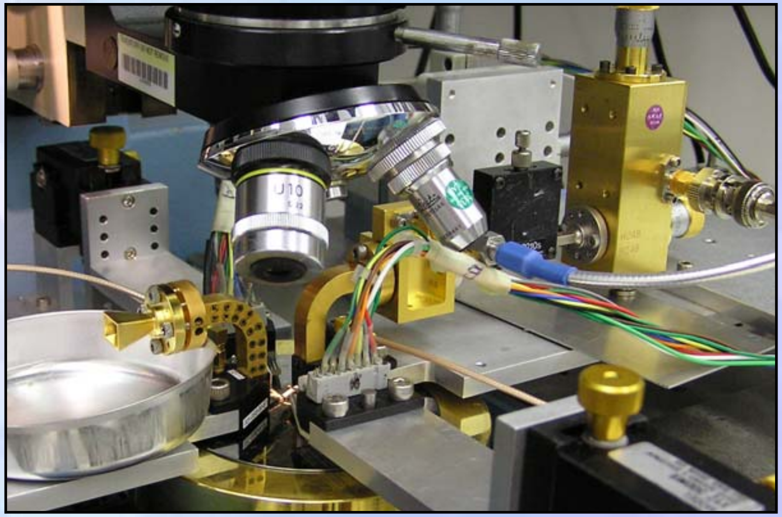




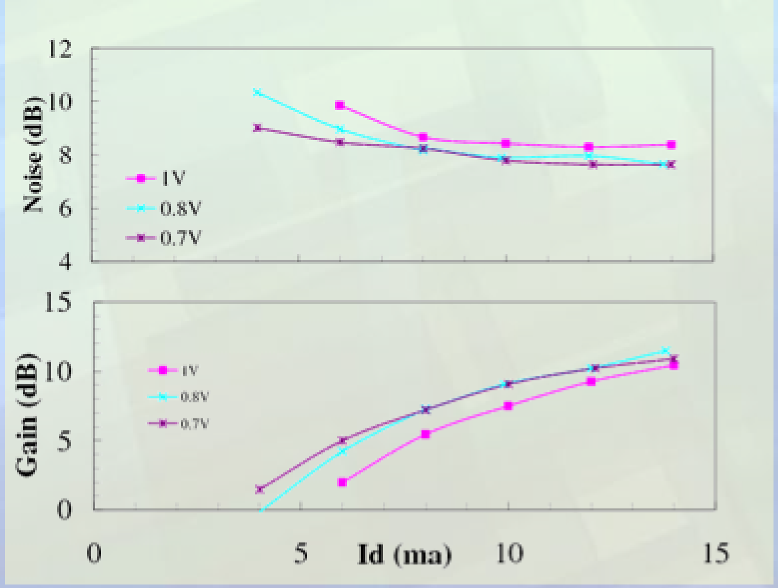
Sub-MMW Metrology: Another DARPA-Hard Challenge

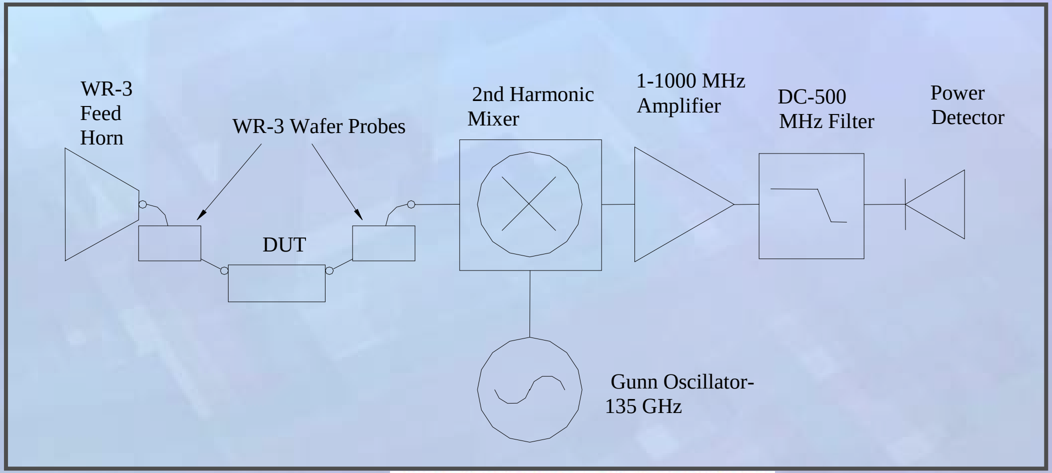
Things that don't exist at 340 GHz…

- 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

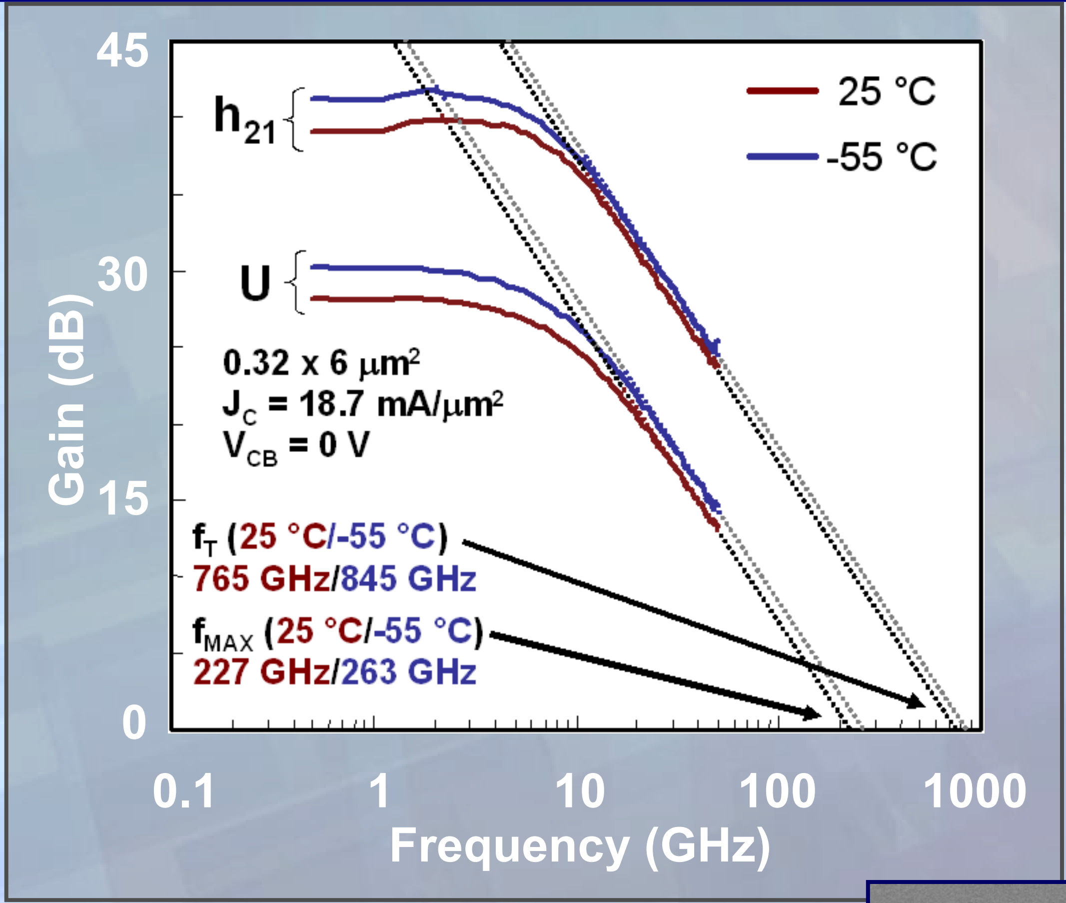


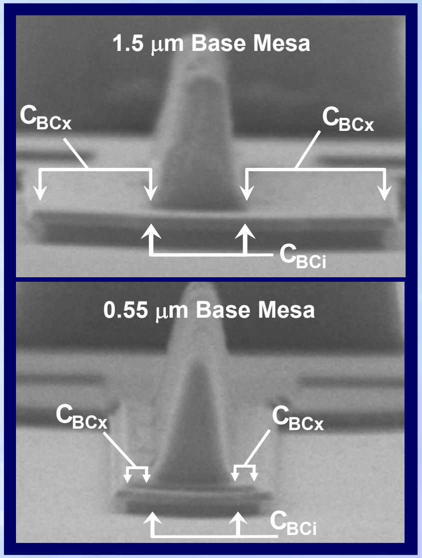


NORTHROP GRUMMAN

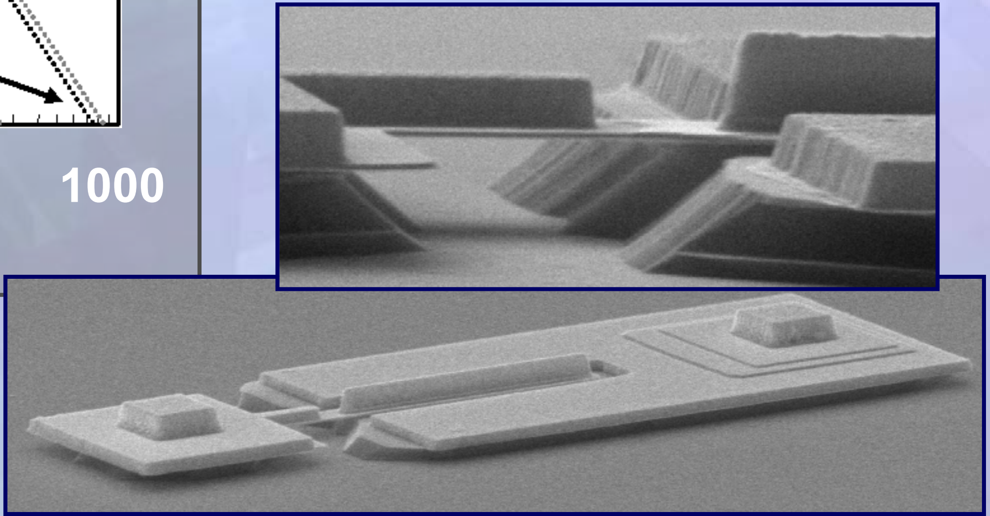
JPL

World's Fastest Transistor





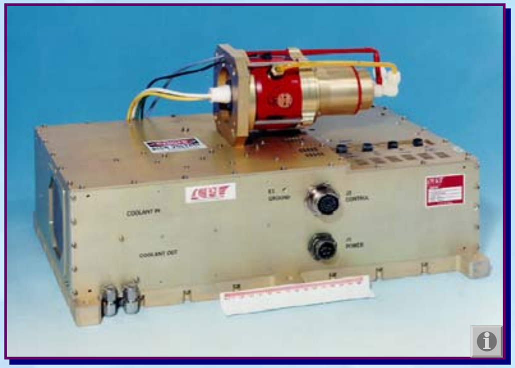
Reduce base contact junction area



μ-bridge Base Contact

HIFIVE

HIgh Frequency Integrated Vacuum Electronics (HIFIVE)



EIK, CPI Canada

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

* In development

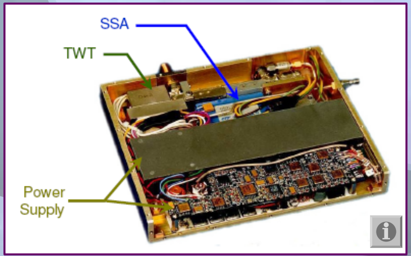
Today:
High frequency sources are large, expensive, and performance-limited

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

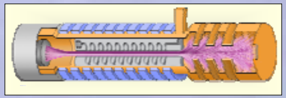
Technologies
- Si micromachining
- High aspect-ratio interaction structures
- Integrated, high current density cathodes

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

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



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



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

*MPM = Microwave Power Module

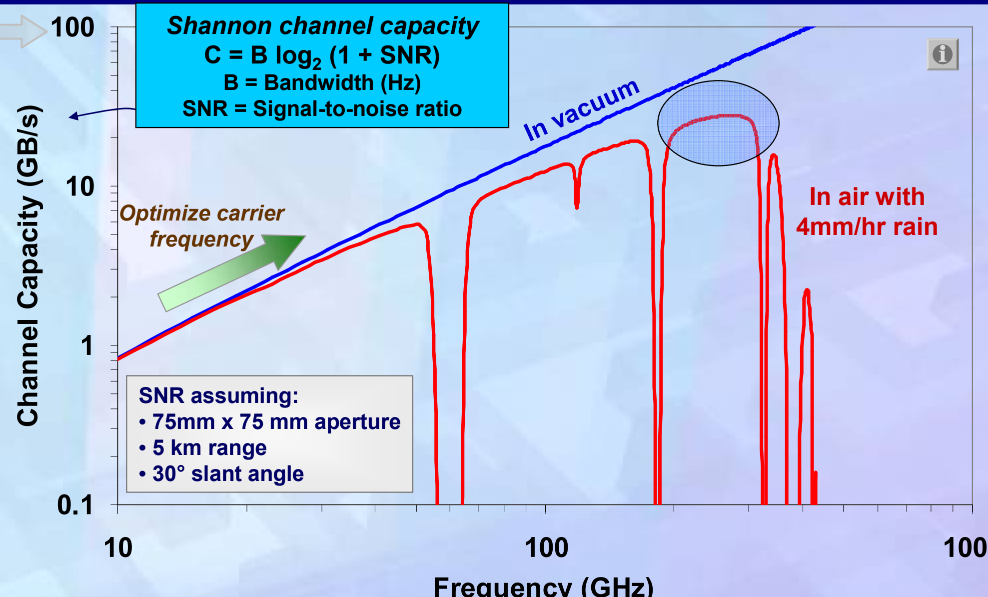
COVERT: Small, high power-bandwidth source

Program Impact

Source for high bandwidth datalinks

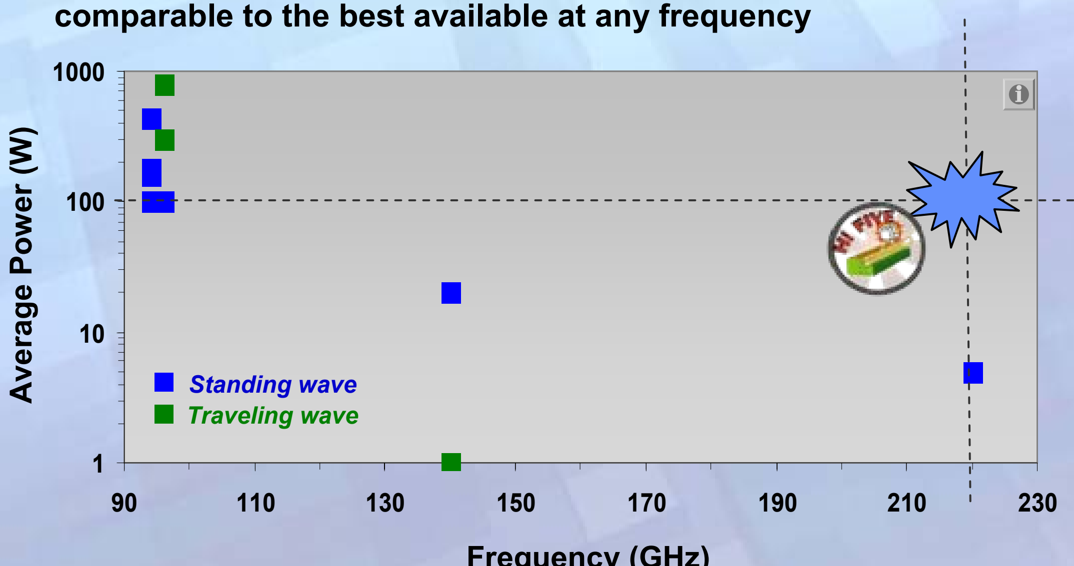
- Offers ~10x higher Shannon capacity than Ku-band (for same antenna area), or
- Offers ~100X smaller antenna area than Ku-band (for same Shannon capacity)

Today: UAVs use Ku- band MPMs for tactical comms



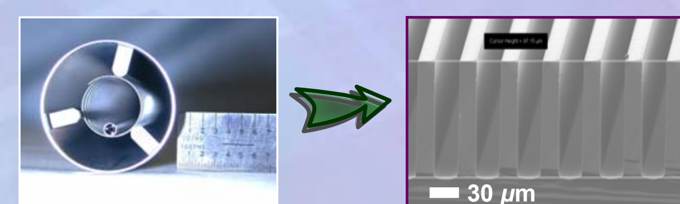
First high power source above 200GHz

- 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



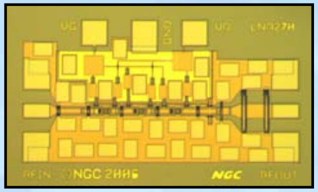
Tactical communications

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

Technical Challenges

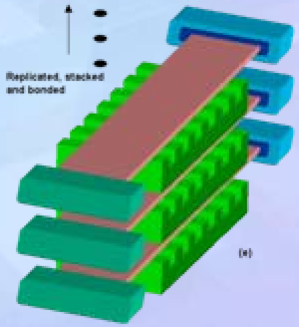
High Power MMIC Driver

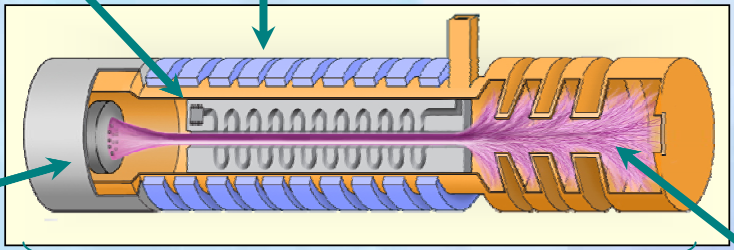
- Accommodate relatively low VE gain at 220 GHz



High Aspect-Ratio Devices

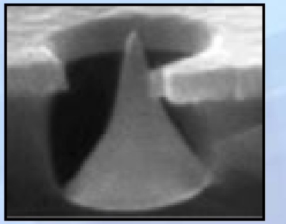
- High efficiency interaction structures
- Single vs. multi-beam topologies
- Magnetic compression to achieve high aspect ratio beam (N~100)
- Mitigation of parasitic oscillations





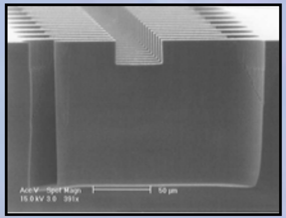
High Current Density, Long Life Cathodes

- High unfocused current density (~100A/cm^2)
- Life > 10^4 hrs



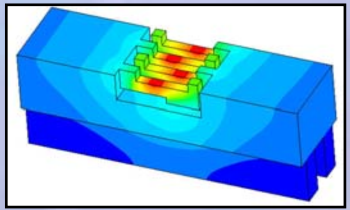
High Precision Micromachined Fabrication and Integration

- Achieve required smoothness & aspect ratio
- Material/technology/process compatibility
- Heterogeneous integration
- Maintain high vacuum



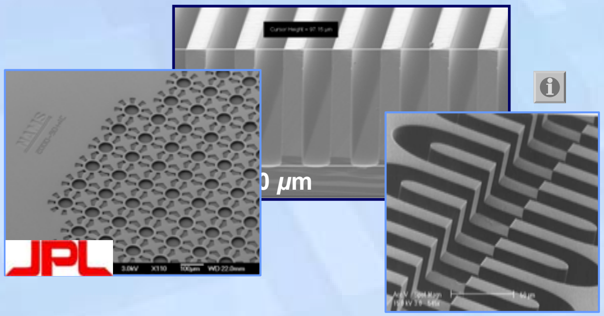
High Efficiency Thermal Management

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



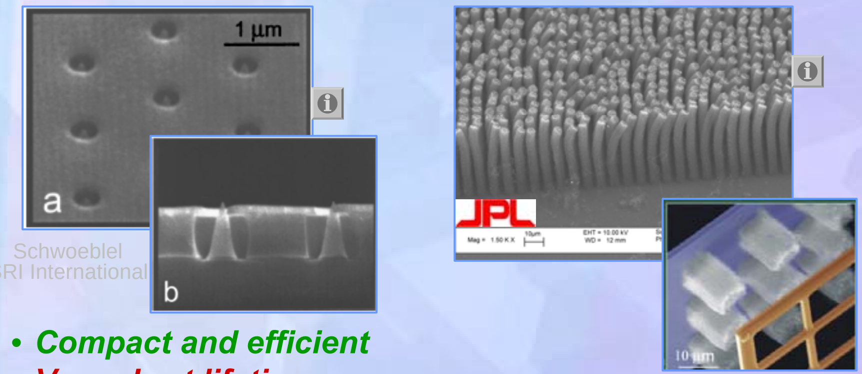
Why Now?
HIFIVE Enablers

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

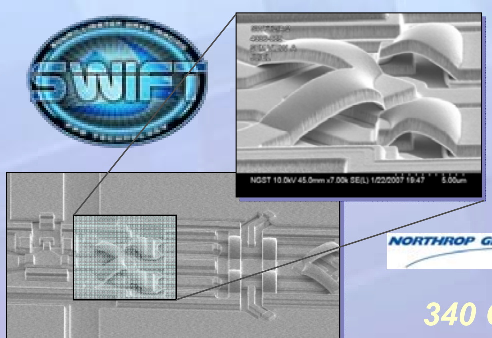


Schwoeblel
SRI International

Wei Zhu
Agere Systems

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

High Frequency MMIC Process

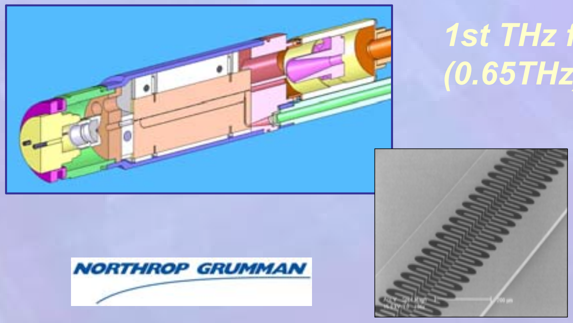


NORTHROP GRUMMAN

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*

Program Schedule

Demonstrations

1. Beam stick: Demonstrate a high aspect ratio beam with required power and transport efficiency
2. Cold test: Validation of interaction structure design

Critical Components

Phase I

Key challenges addressed:

- High-aspect ratio electron beam
- Interaction structure topology
- High current density cathode

Demonstrations

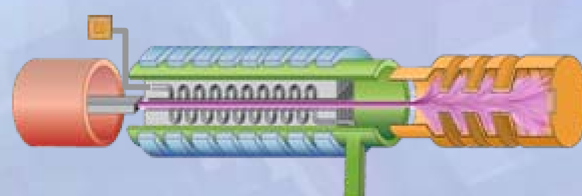
1. HPA demo: Demonstrate a high power-bandwidth product and high power density amplifier
2. Integrable cathode demo: long-life high current density cathode

High Power Amplifier

Phase II

Key challenges addressed:

- High power driver
- High efficiency thermal management
- High current density cathode



Objective Demonstration

- Demonstrate an integrated power amplifier with ultrahigh power density and power-bandwidth product

Fully-integrated High Power Amplifier

Phase III

Key challenges addressed:

- Heterogeneous Integration
- Maintain high vacuum

Phase durations to be proposed by the bidders

Program Metrics

Metric	Unit	SOA	Phase I	Phase II	Phase III
Go/No Go Metrics					
Beam voltage	kV		20		
Cathode current density (1)	A/cm^2	10	750		
Beam aspect ratio (2)		1	25		
Beam transport efficiency	%		95		
Center frequency accuracy	%		± 2		
P_{out} (3)	W	5 (4)		50	50
Bandwidth	GHz	0.4 (4)		5	5
Power-bandwidth product	W*GHz	2 (4)		250	500
Efficiency (5)	%	<1%		5%	5%
Total current (6)	mA	100		250 (7)	250 (8)
Other Metrics					
Spectral purity (9)	dBc			-50	-50
Driver output power (3)	mW	50 (4)		50	50

(1) Measured in beam stick; pulsed
(2) Defined as sum of the width of all beams/thickness of beams
(3) Average power at 220GHz, measured external to device
(4) Projected performance at 220GHz; research device
(5) Total wallplug efficiency
(6) Measured at cathode surface, for 1000 hours life
(7) As a component
(8) Integrated into HPA
(9) Measured 250kHz from carrier

HIFIVE Kickoff!