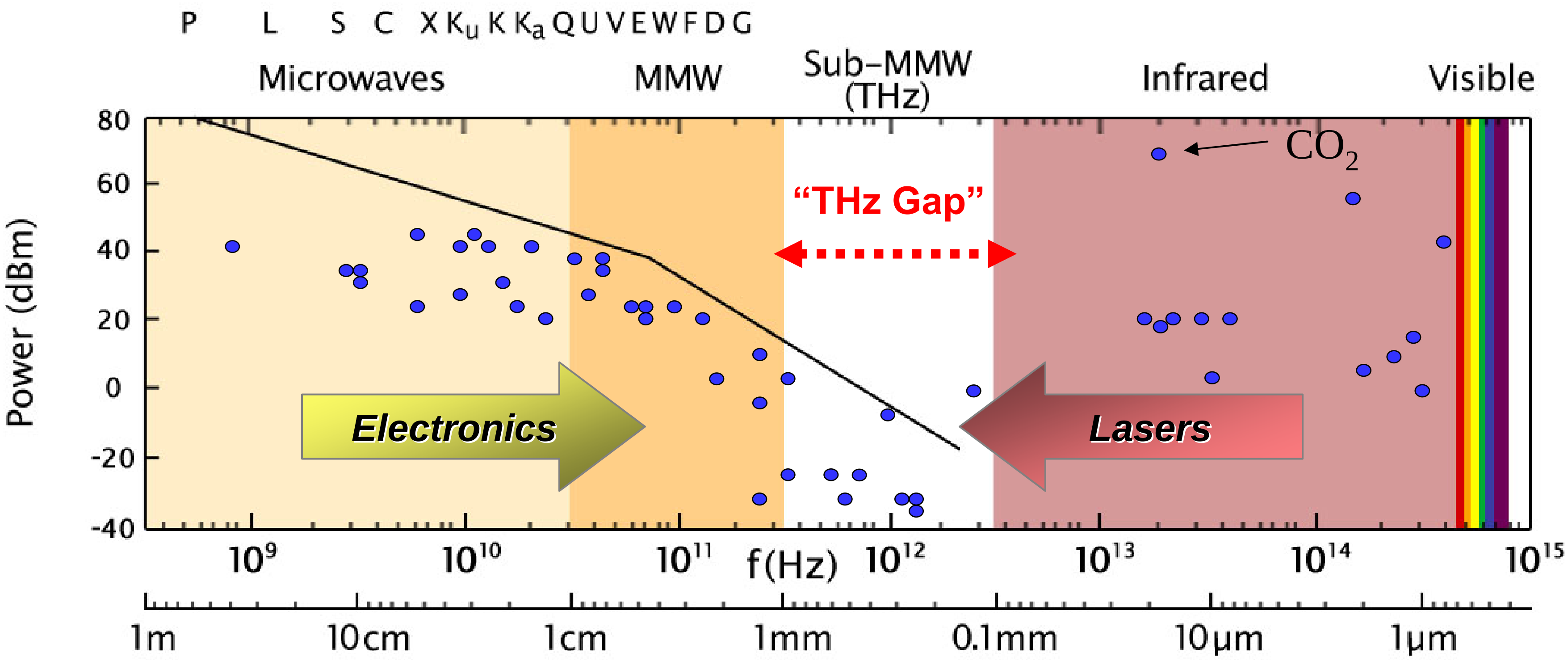
Solid-State, Coherent THz Sources and Amplifiers
(all at room temperature)



Electronics
- **Classical region (hν << kT)**
- **Critical dimensions << λ**
- **Atmosphere transparent**
- **Sources readily available**

THz / Sub MMW
- **Transition region: hν ~ kT**
- **Narrow, poor transparency windows**
- **Only weak sources available**

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

Courtesy, Dr. Mark Rosker, DARPA/MTO

Why THz Solid-State Electronics is so Challenging

Classical Regime of Transport Theory

- Drift and diffusive transport of free carriers

Requires: $\omega\tau << 1$, $h\nu < k_BT$, τ = momentum relaxation time

$h\nu < k_BT \rightarrow \nu < 6.2$ THz @ 300 K (no problem)

$\omega\tau << 1 \rightarrow \nu < 350$ GHz (assuming $\tau = 0.5$ ps)

Quantum Regime

- Real-space (e.g., tunneling) transitions or k-space (e.g. dipole) transitions between well defined quantum states

Requires: $\omega\tau >> 1$, $h\nu > k_BT$

$h\nu > k_BT$ is easy to satisfy in visible and infrared regions; impossible in THz regime at room temperature

Alternative Approach (and Most Successful to Date)

- Avoid THz fundamental oscillation (or gain) transport requirements by basing oscillator(s) in RF or optical regimes

(1) Varactive Frequency Multiplication of Tunable RF Sources
(2) Photoconductive Mixing or Rectification of near-IR Diode Lasers

Legacy Semiconductor Two-Terminal Fundamental Oscillators

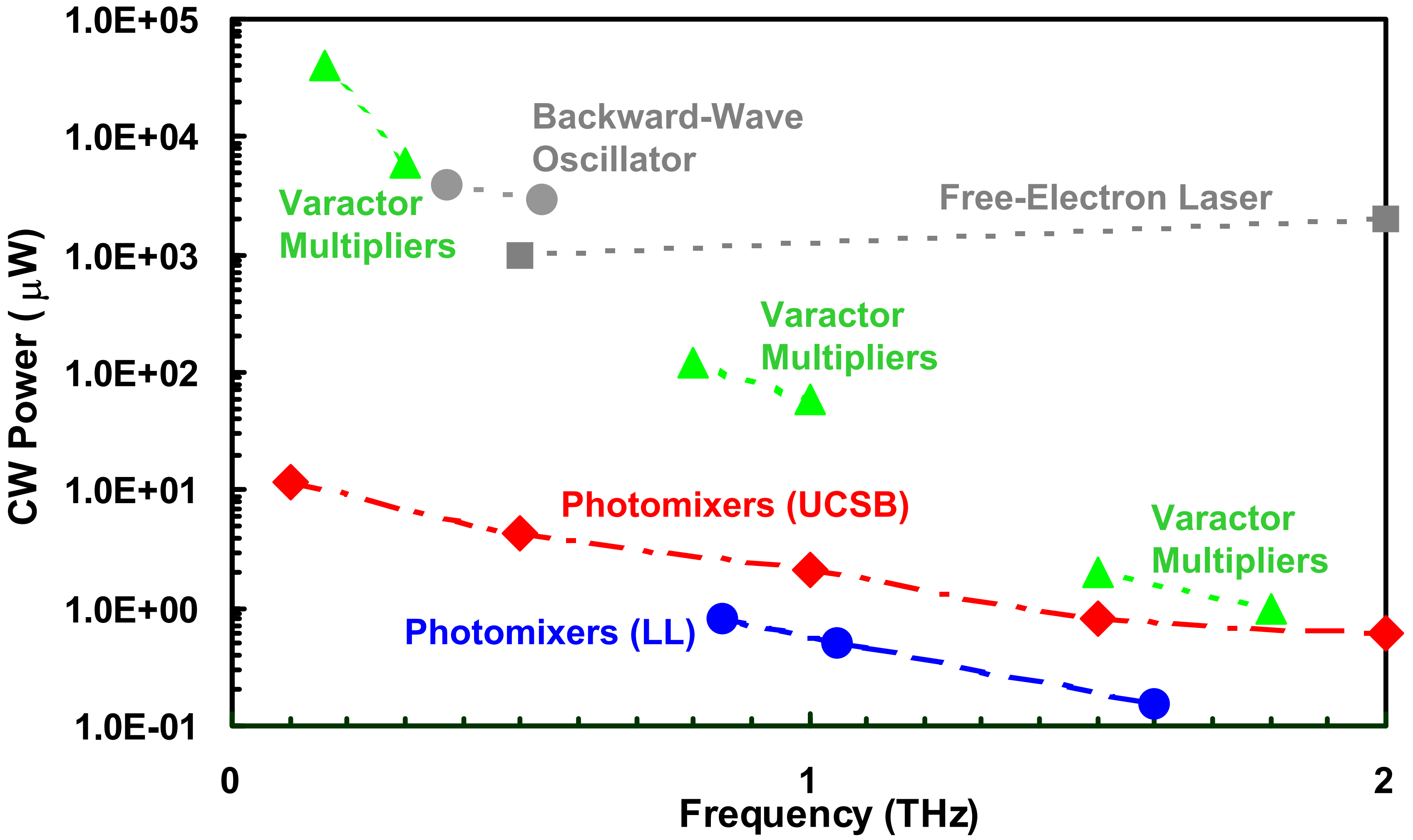
- **InP Gunn Oscillators**
  - **f_{max} < 200 GHz (fundamental mode)**
  - **Advantage: High power (up to ~100 mW cw)**
  - **Disadvantage: Limited tunability (a few %)**

- **Si IMPATT Diodes**
  - **f_{max} > 300 GHz**
  - **Advantage: High power (up to ~1 W peak) and efficiency**
  - **Disadvantage: Noisy**

- **Resonant Tunnel Diodes**
  - **f_{max} ~ 1 THz (highest experimental: 712 GHz)**
  - **Advantage: Easily integrated in MMICs**
  - **Disadvantage: Power limited by dc negative resistance stability requirements**

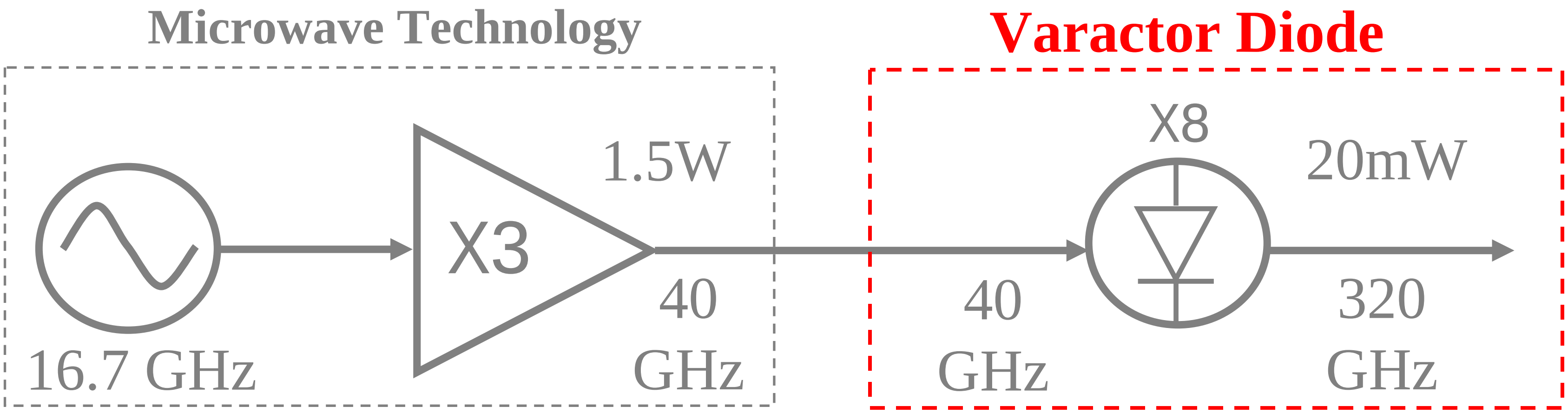
Tunable Room-Temperature THz Sources

(Tunability of at Least 10%)



Varactor Multipliers

Example: A frequency multiplier – use a varactor Schottky diode (nonlinear reactance) to generate harmonics from a microwave source

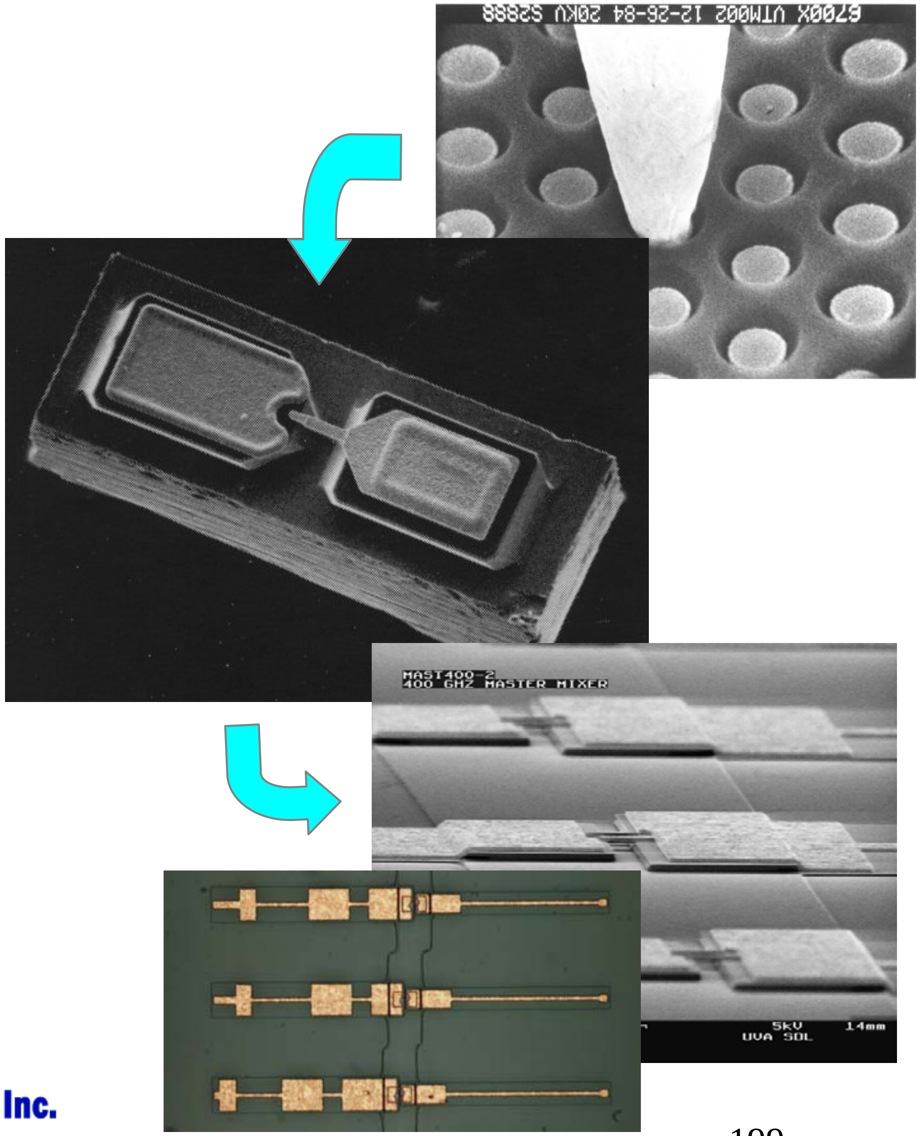


Key Technologies

- Careful Circuit Design and Modern CAD Tools
- Advanced Diode Fabrication and Integration

Schottky Diode Fabrication Technology

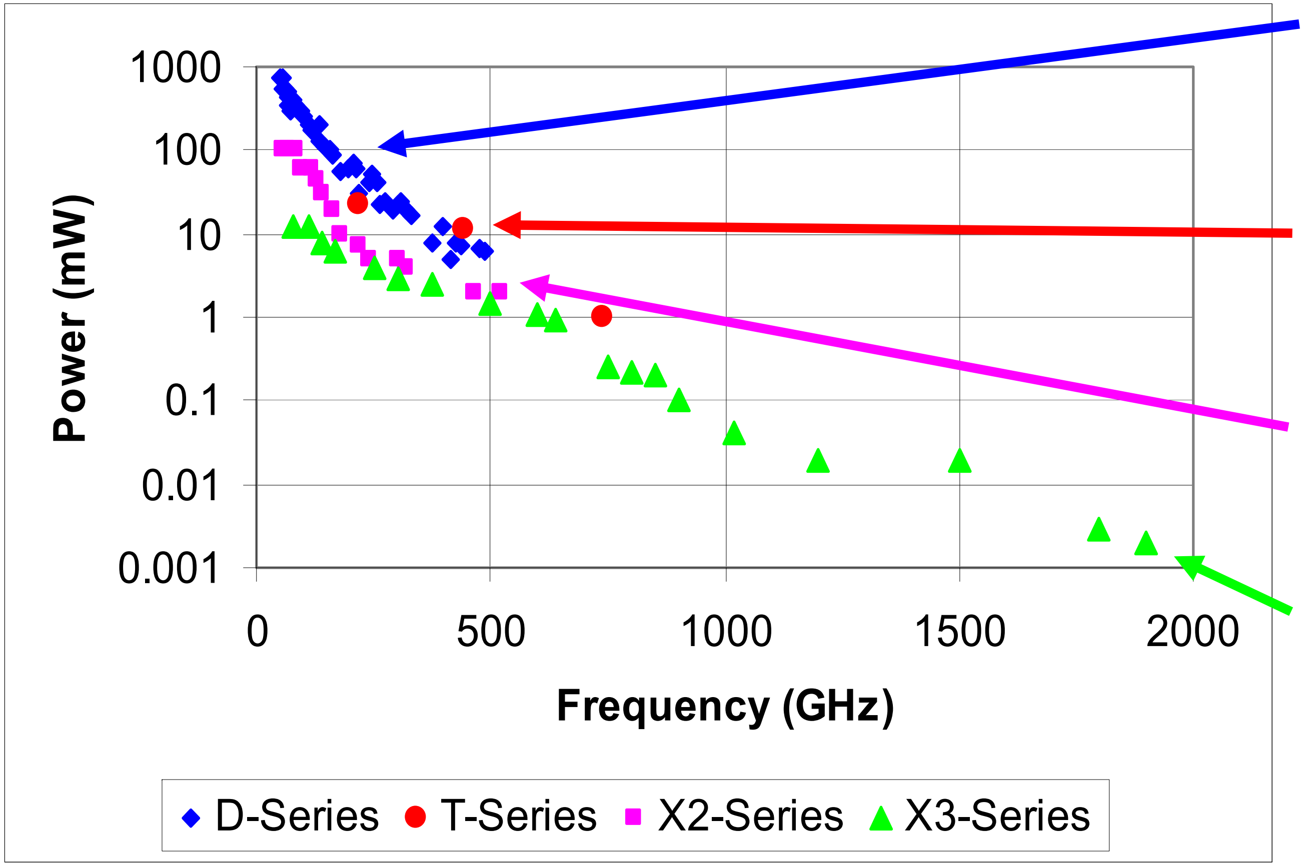
- Moved from whiskered to planar diodes
  - Whiskered diode fragile, difficult to reproduce
- Planar Schottky Diodes
  - Flip-chip and integrated diode-circuits
  - Multiple diode configurations possible
    - Power handling
    - Balanced designs
  - Commercialization of diode fabrication process



Virginia Diodes, Inc.

Courtesy of T. Crowe

VDI Multipliers



High-Efficiency Doublers

B ~ 15-20%

High-Efficiency Triplers

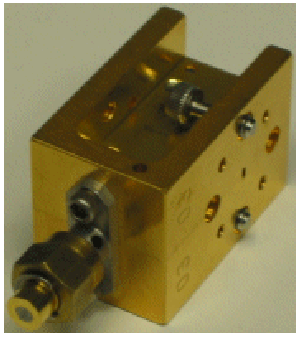
B ~ 5%

Broadband Doublers

B ~ 40-50%

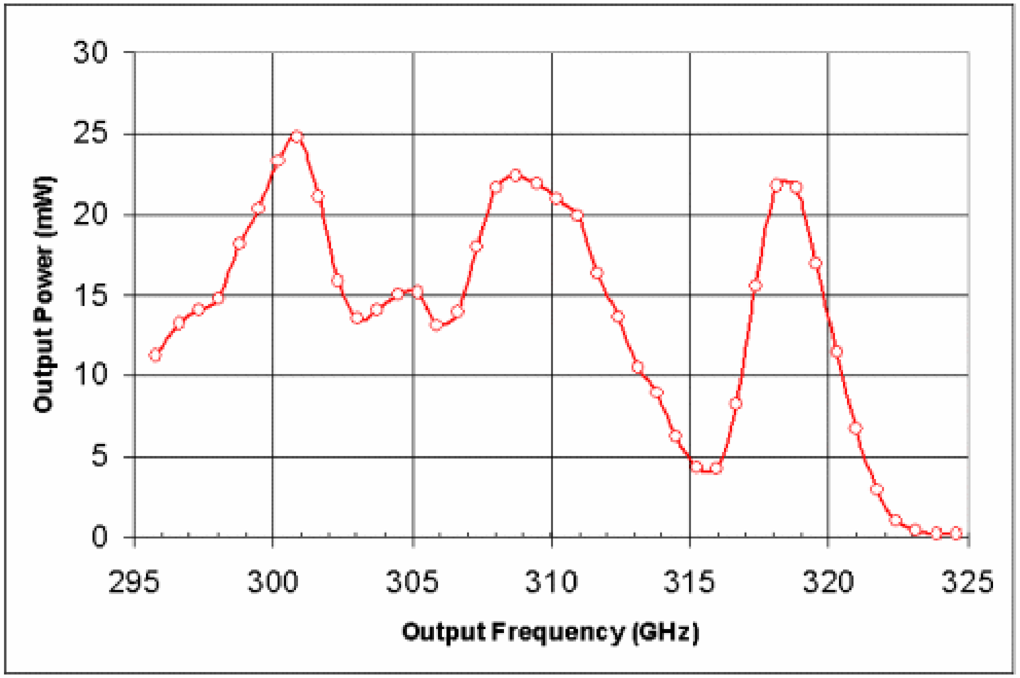
Broadband Triplers

B ~ 40-50%



Fundamental tradeoff between power and bandwidth.

320 GHz Multiplier Chain

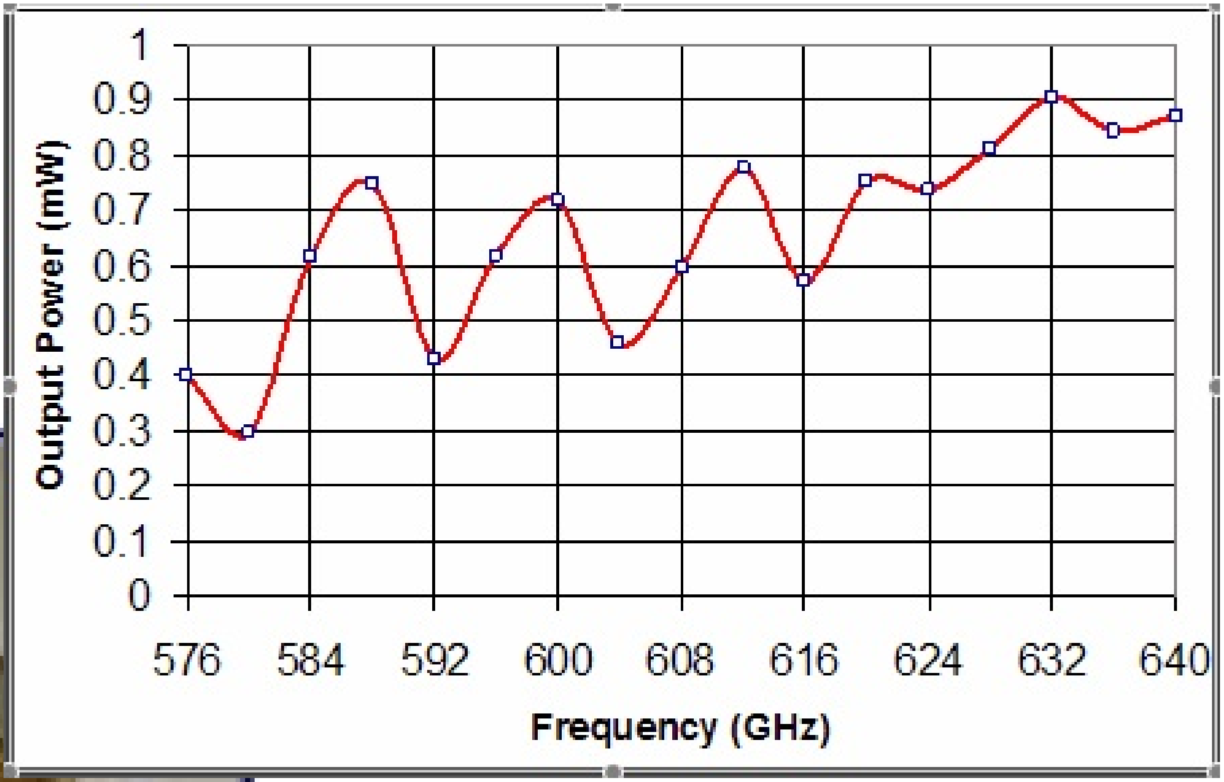


- **Components can be cascaded**
- **All Electronic Tuning**
  - **Bias usually required for varactive components**

Virginia Diodes, Inc.

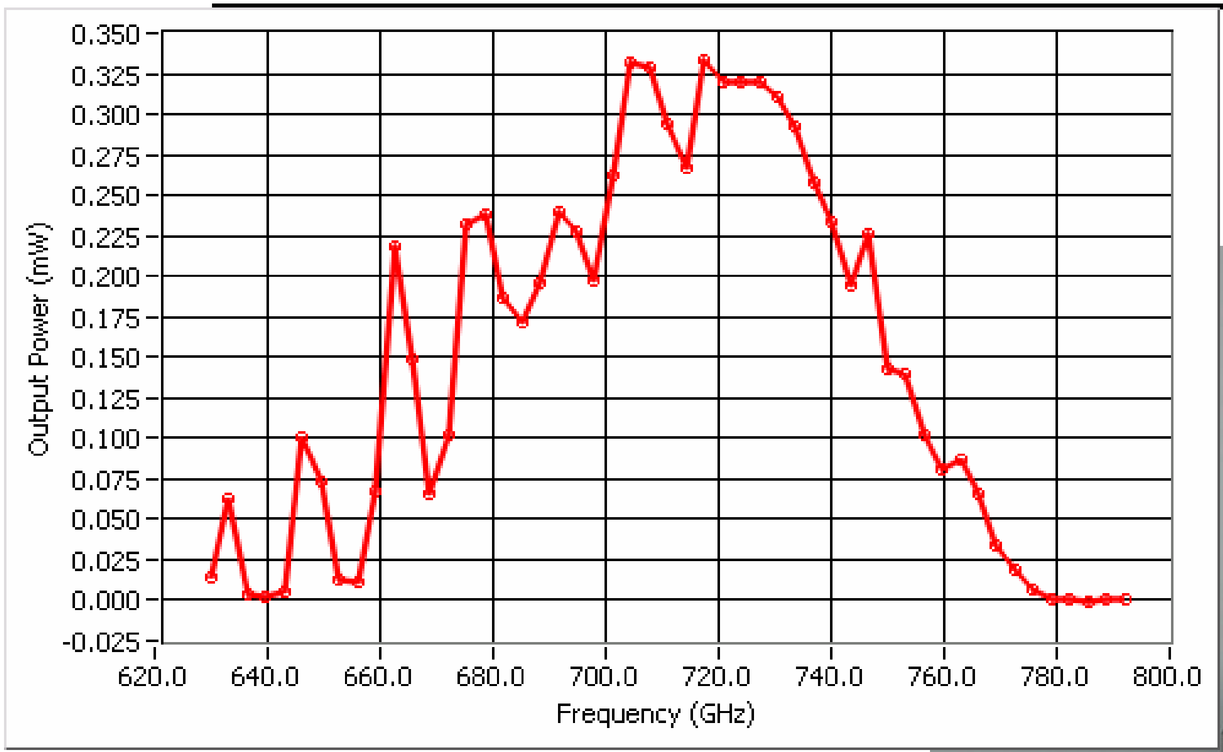
Schottky-Varactor Frequency Multiplier Chain

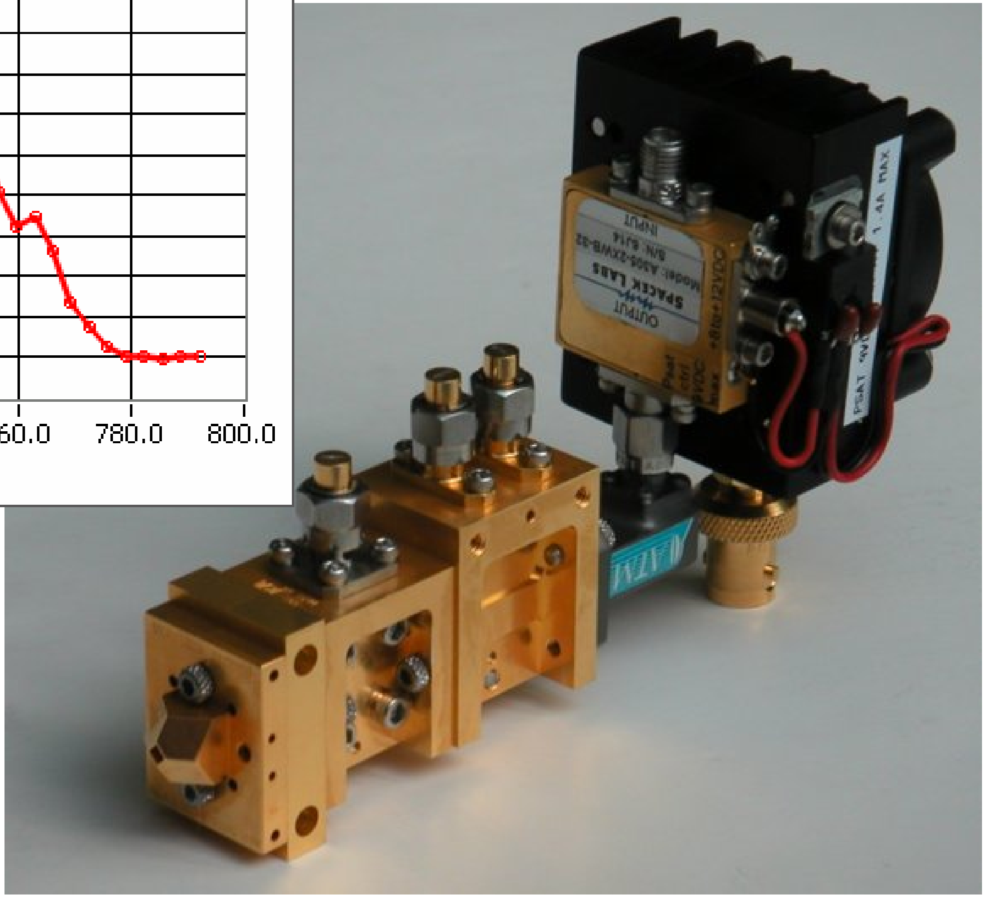
(w/ amplification at Ka Band)



Virginia Diodes Inc.
FEM 2x amplifier Waveguide:
2x2x2x3x

660-760 GHz Source



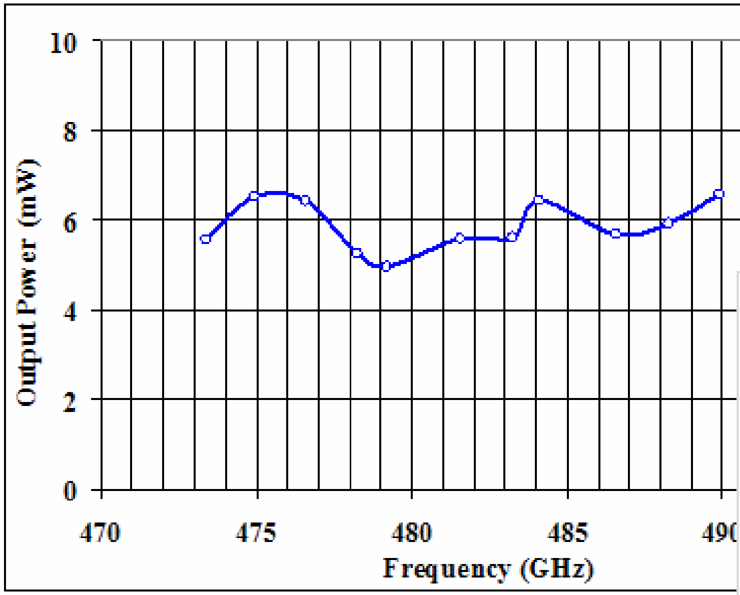


- **Compact, tunerless**
- **Input drive 14-16 GHz**

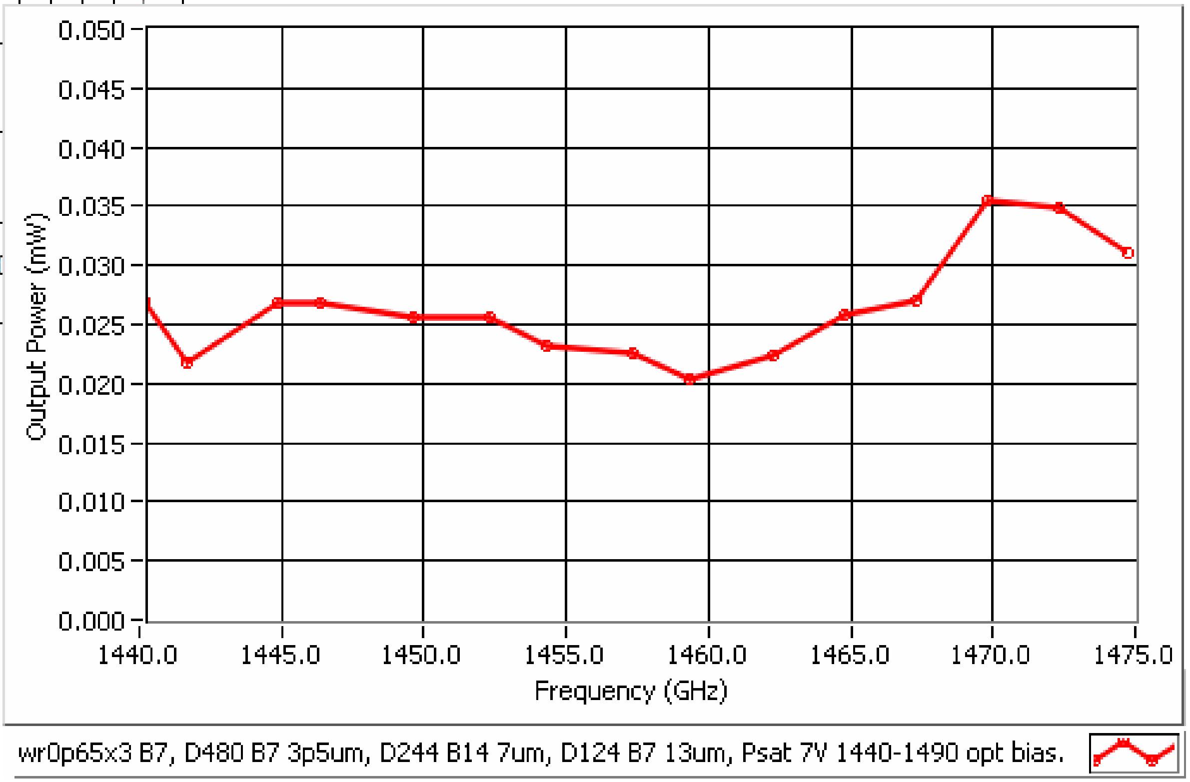
Virginia Diodes, Inc.

1.46 THz Varactor Multiplier Source

D480 Doubler – 6-7 mW

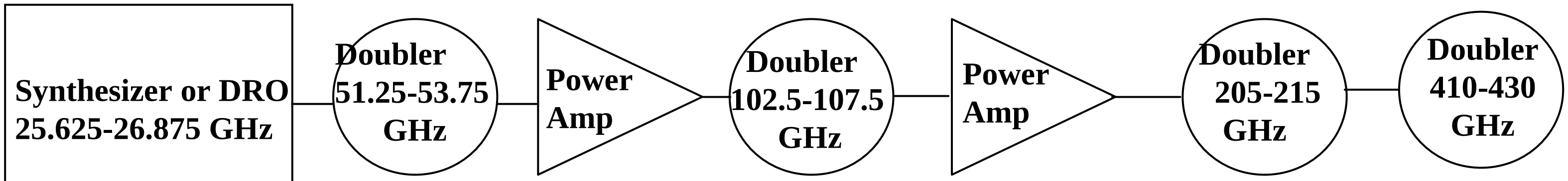


- **20-30 uW at 1.46 Thz**
- **Room temperature operation**



Virginia Diodes, Inc.

Schottky-Varactor Frequency Multiplier Chain
(w/ amplification at W Band, Jet Propulsion Lab/NG Corp)



Synthesizer or DRO 25.625-26.875 GHz

Doubler 51.25-53.75 GHz

Power Amp

Doubler 102.5-107.5 GHz

Power Amp

Doubler 205-215 GHz

Doubler 410-430 GHz

Commercial Unit
Pout=10mW

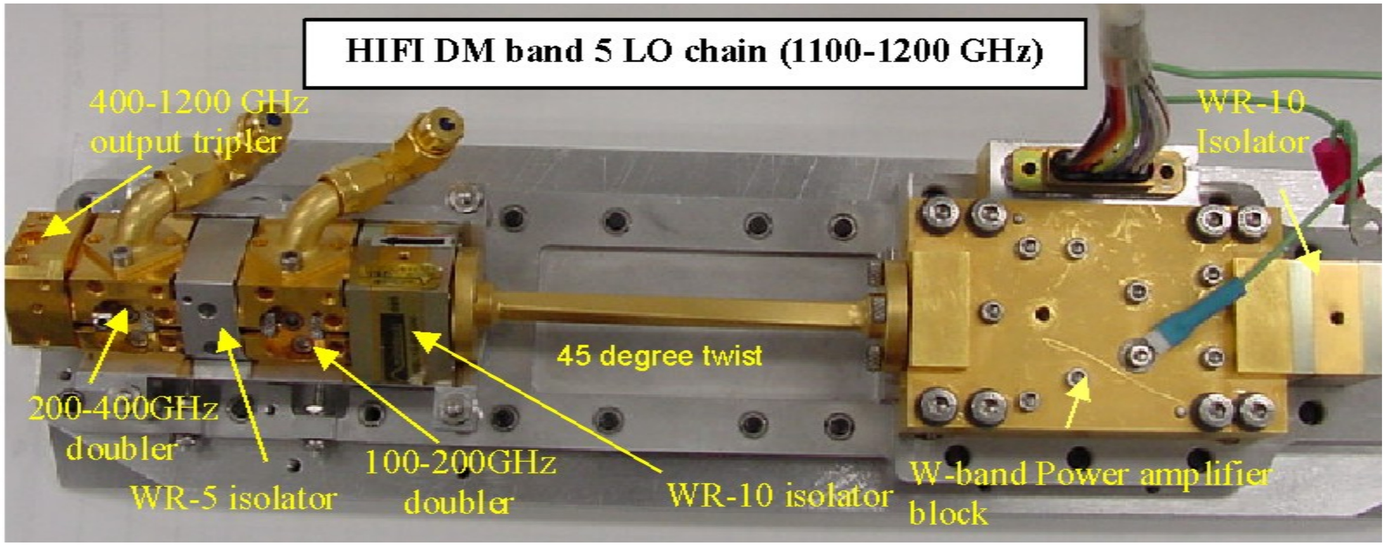
Commercial Active Quadrupler
Pout=10mW

Custom Power Amp
Pout=200mW

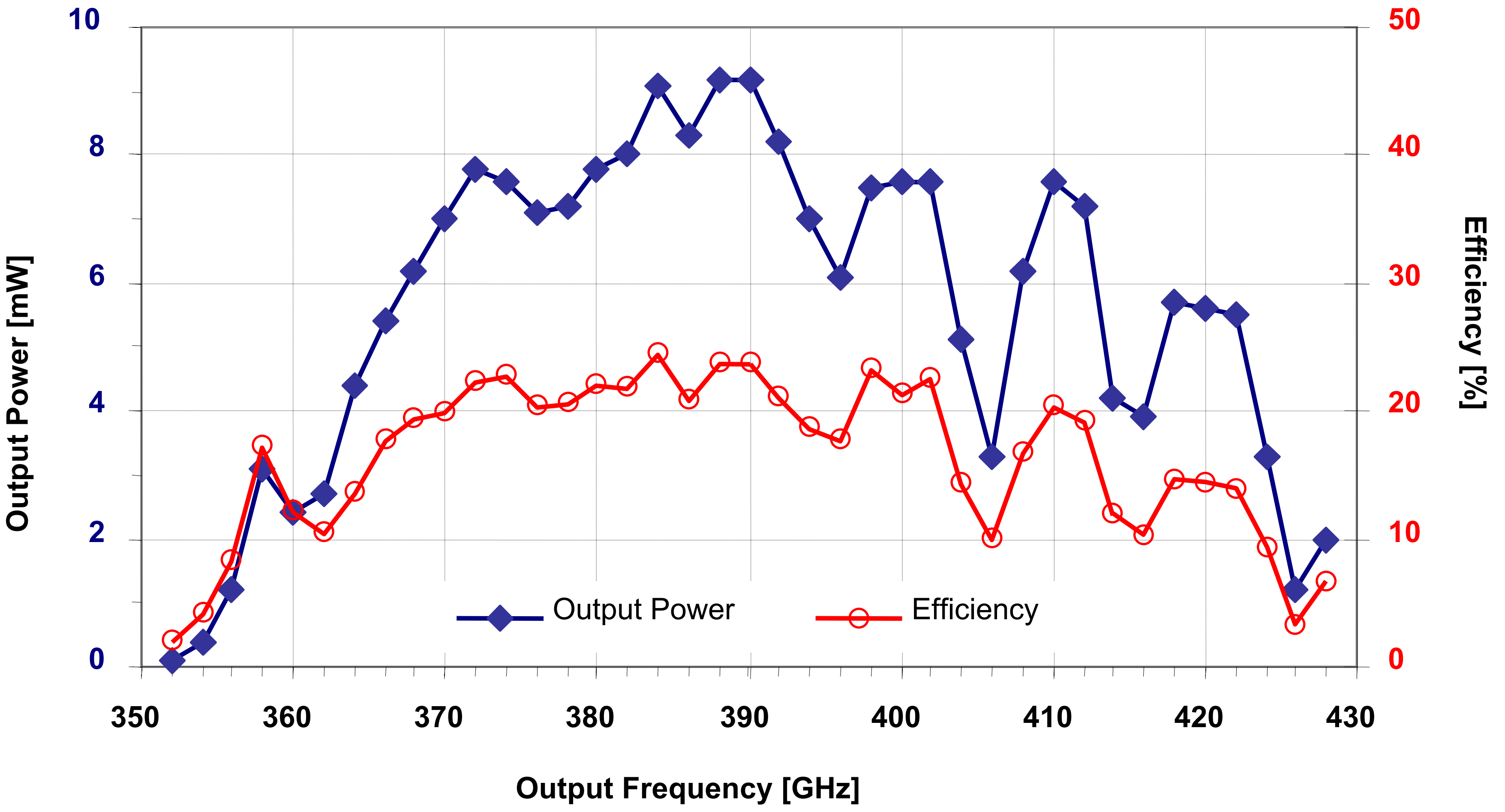
Custom Multiplier
Pout=50mW

Custom Multiplier
Pout=5mW

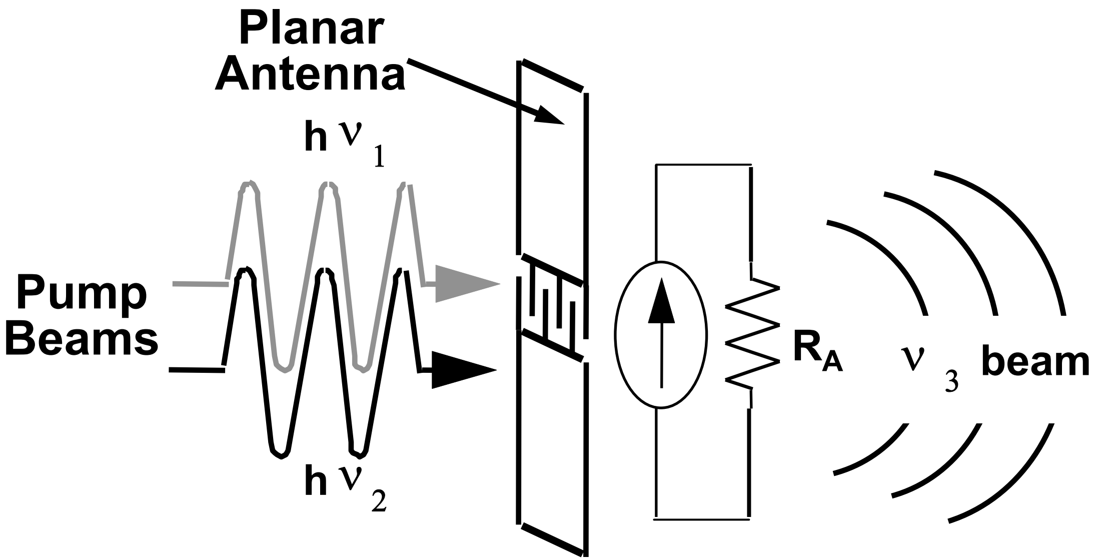
Block diagram of proposed electronically tuned transmitter based on a synthesized source followed by solid-state amplifiers and frequency doublers. Demonstrated output power is >5mW at 420 GHz.



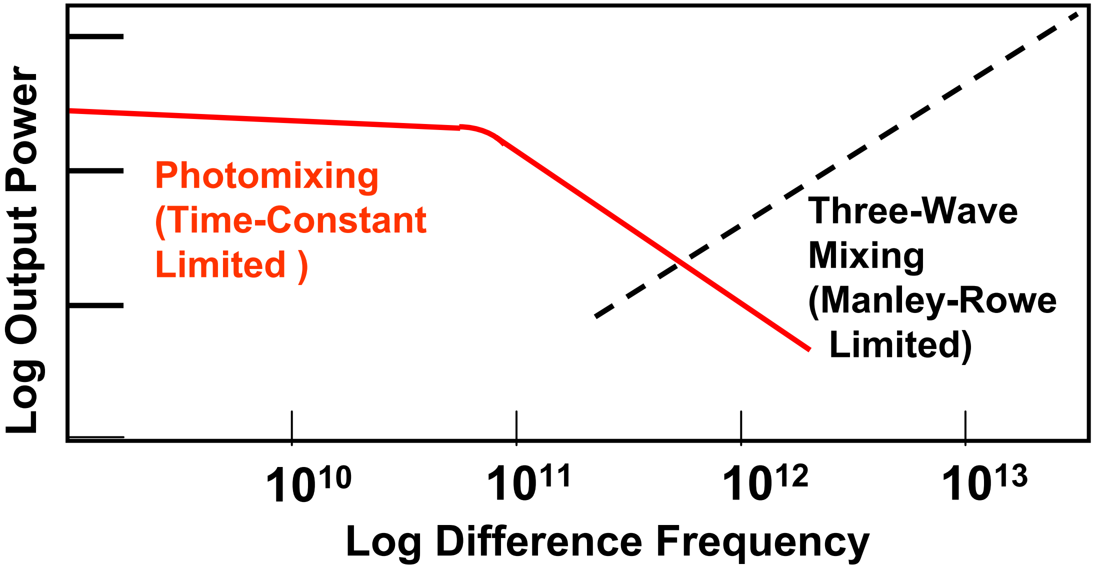
JPL/NGC Varactor Multiplier Chain Performance



Photo(conductive) Mixing



$$\nu_3 = |\nu_2 - \nu_1|$$



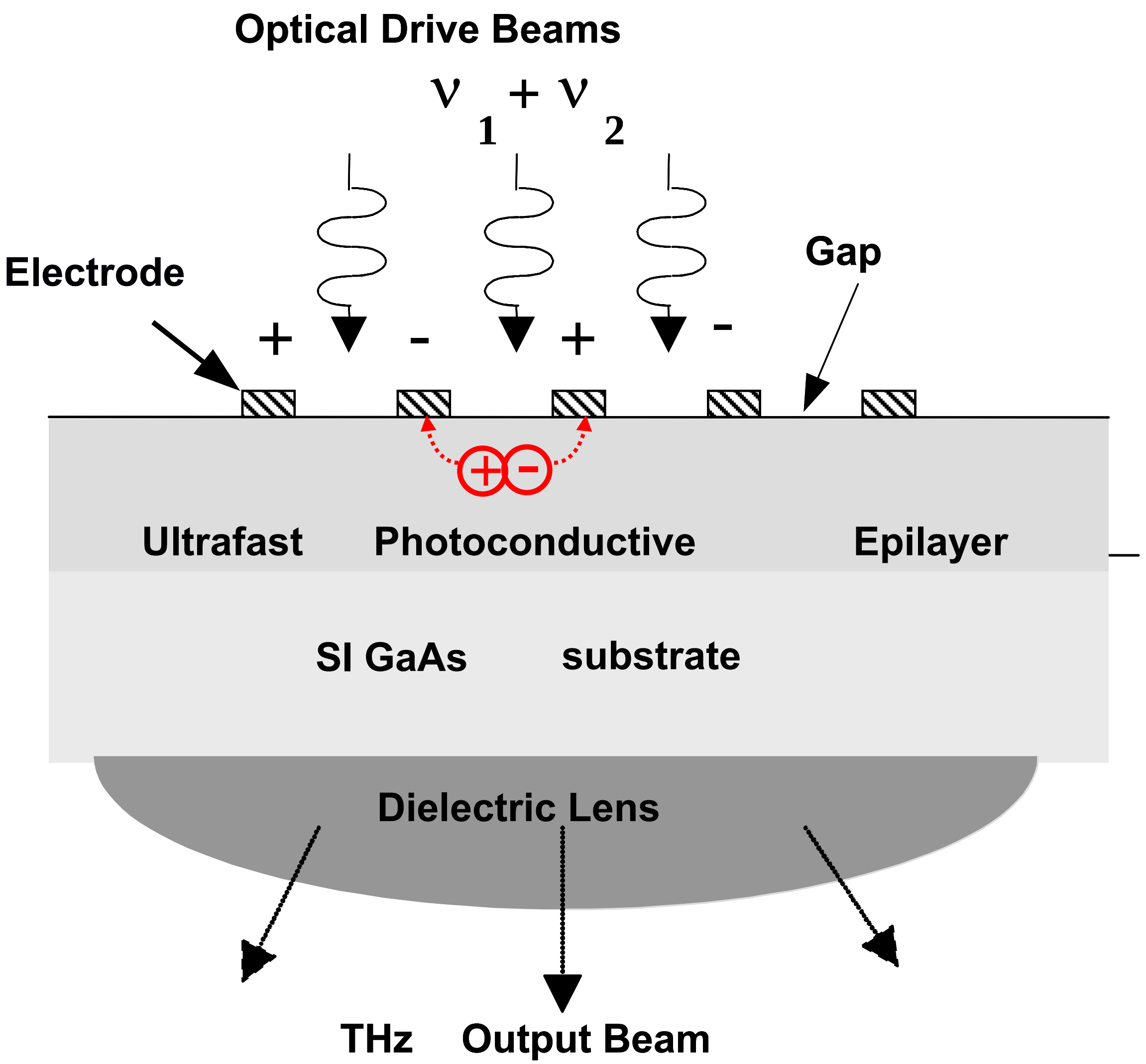
Recall Manley-Rowe Limit for Three-Wave Mixing:
No more than one photon out for two (pump) photons in ⇒

Max Conversion Efficiency:

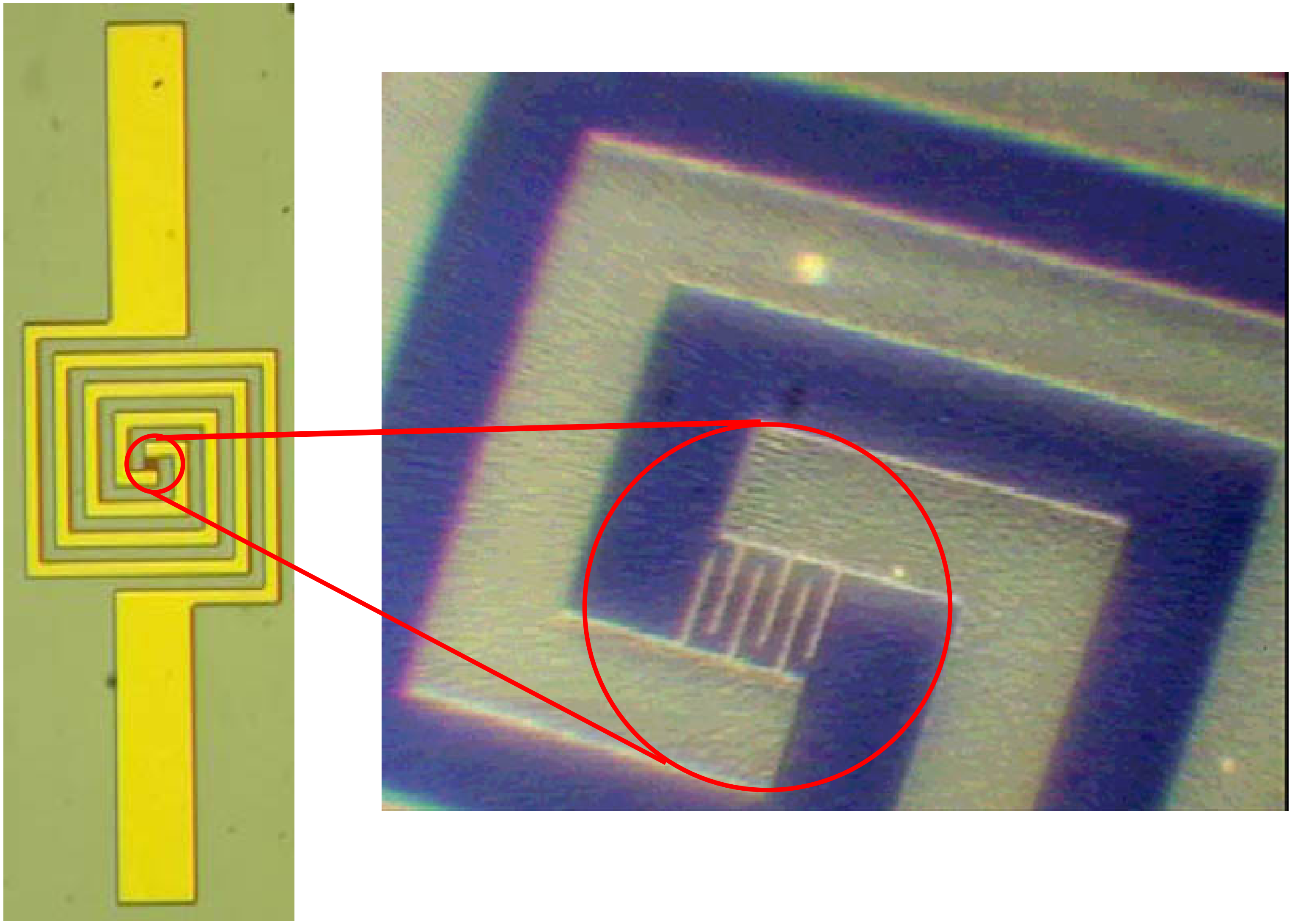
$$\eta = \frac{h\nu_3}{h\nu_1 + h\nu_2} \underset{\uparrow}{\approx} \frac{\lambda_P}{2\lambda_3}$$

Assuming both pump photons in near-IR or visible

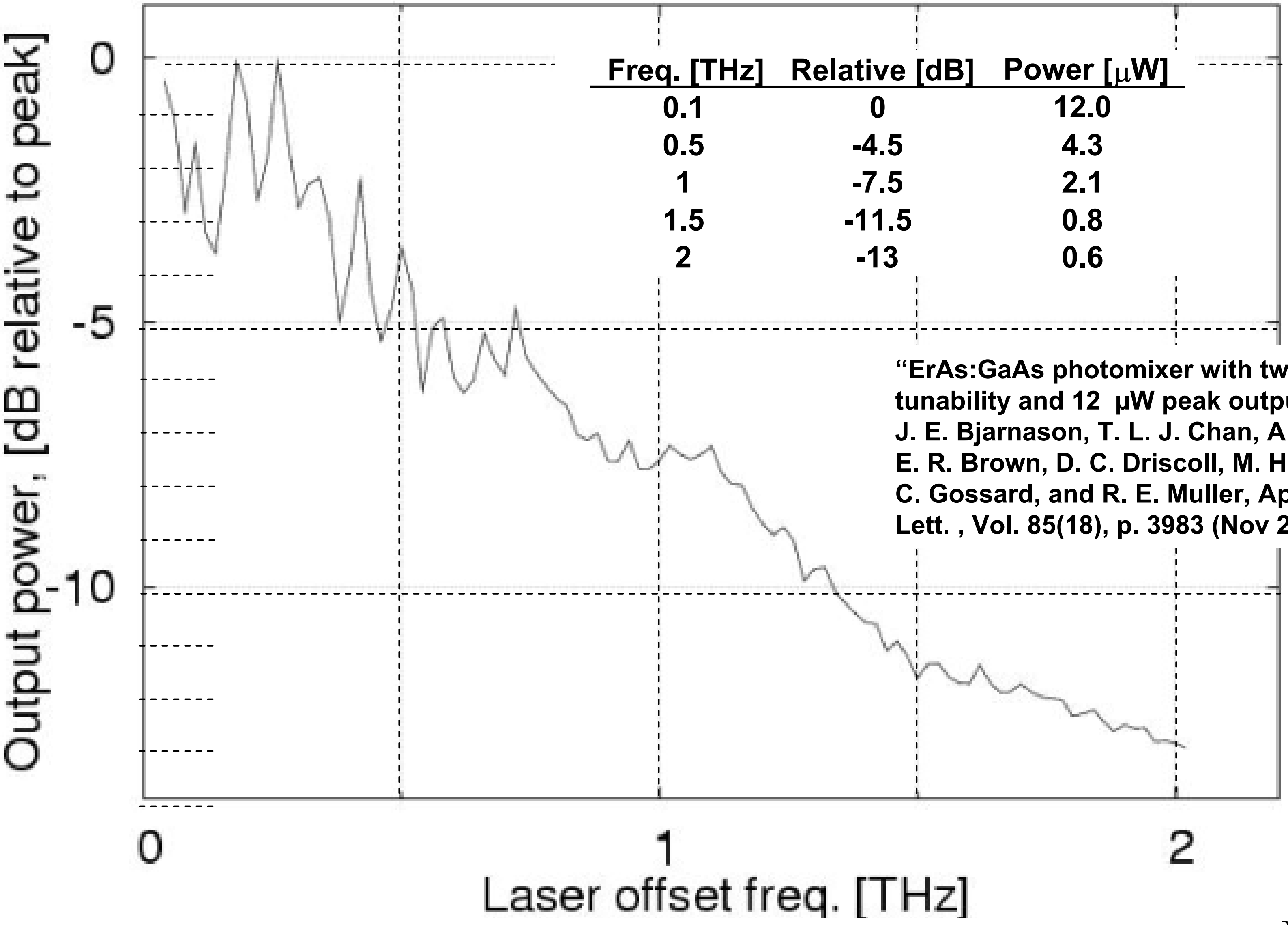
Low-Capacitance Interdigital-Electrode Structure



Self-Complementary Rectangular-Spiral THz Antenna



Calibrated CW Output Power from Square-Spiral Photomixer



Freq. [THz]	Relative [dB]	Power [μW]
0.1	0	12.0
0.5	-4.5	4.3
1	-7.5	2.1
1.5	-11.5	0.8
2	-13	0.6

“ErAs:GaAs photomixer with two-decade tunability and 12 µW peak output power,” J. E. Bjarnason, T. L. J. Chan, A. W. M. Lee, E. R. Brown, D. C. Driscoll, M. Hanson, A. C. Gossard, and R. E. Muller, Appl. Phys. Lett. , Vol. 85(18), p. 3983 (Nov 2004).

THz Transistors and Amplifiers

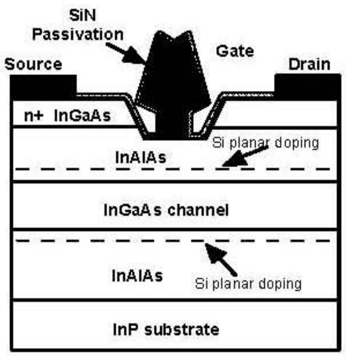
- Arguably the most enabling component in all regions of the electromagnetic spectrum has been the solid-state amplifier:
  (1) low-noise and power semiconductor amplifiers have driven RF wireless communications and radar
  (2) erbium-doped fiber amplifiers have driven fiber-optic telecommunications

- Progress on semiconductor amplifiers has been steady during the past decade, largely due to DARPA Investment:

(1) Pseudomorphic high-electron-mobility transistors (pHEMTs)
(2) Heterojunction bipolar transistors (HBTs)
(3) Scaled CMOS (e.g., 45-nm gate length)

State-of-art V-band SSPA MMIC and Module Performance

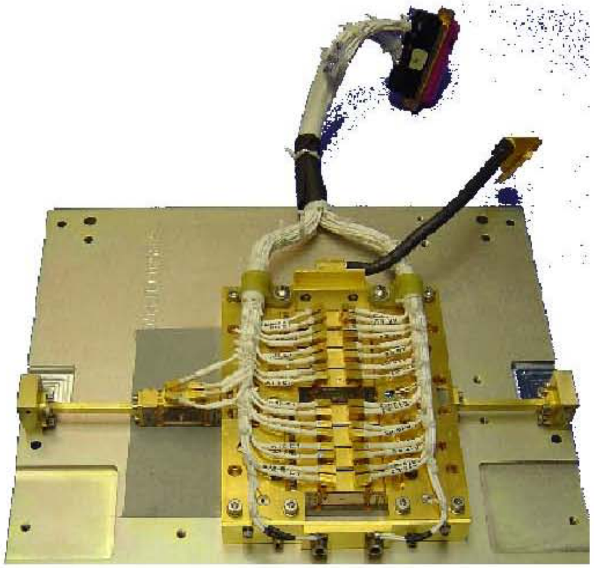
NORTHROP GRUMMAN
Space Technology



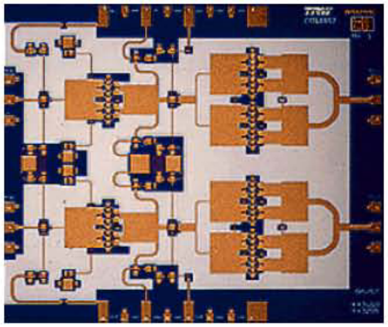
GaAs and InP HEMT

0.1, 0.15 um gates

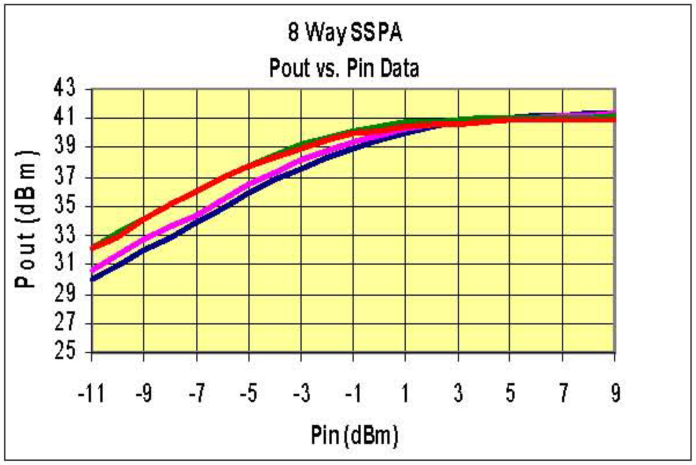
2-mil vias



200 mW, 40% PAE
60 GHz InP HEMT



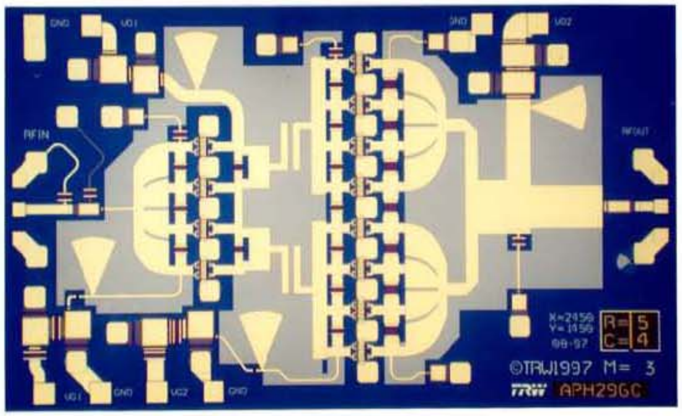
>0.5W, 20% PAE
60 GHz GaAs HEMT

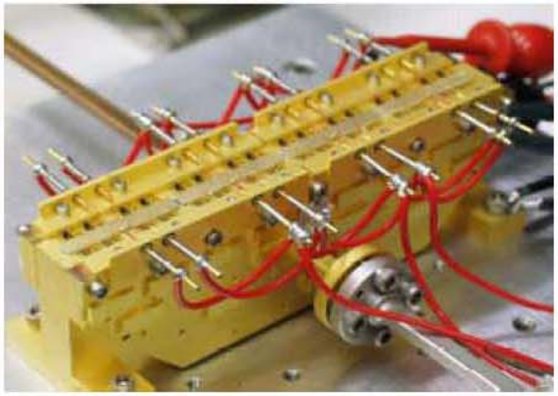


Courtesy: Dr. Rich Lai

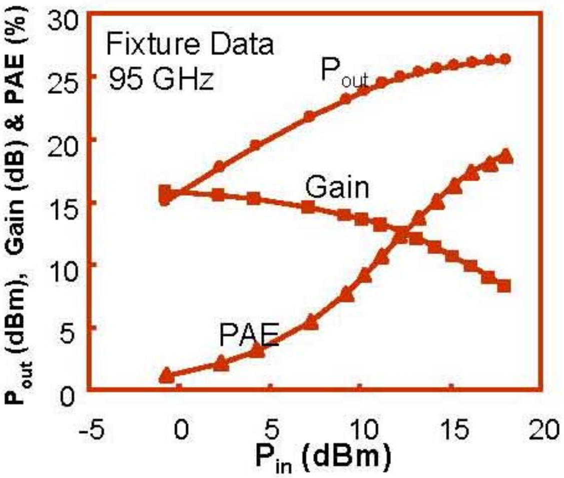
State-of-art W-band SSPA MMICs and Modules

NORTHROP GRUMMAN
Space Technology

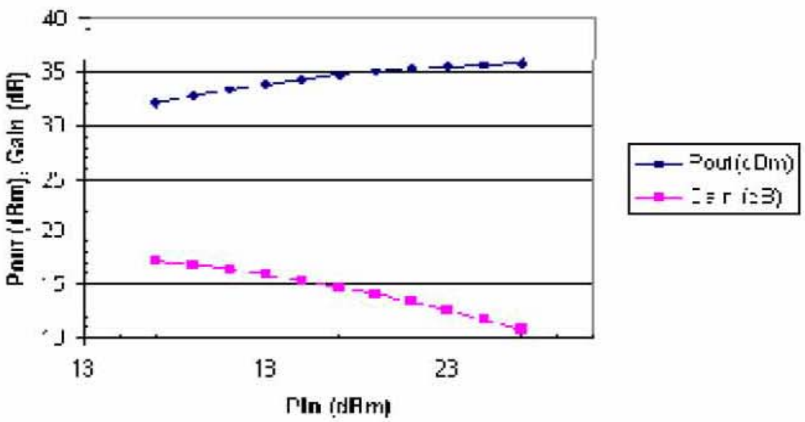




Power Performance at 95 GHz



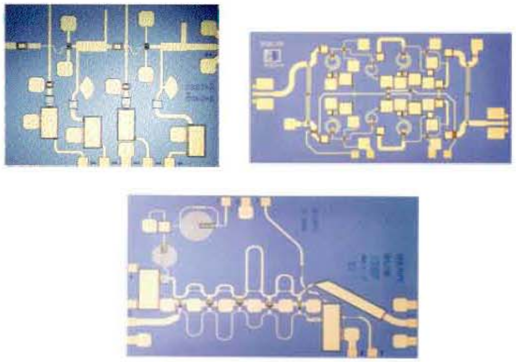
16-Way W-Band High Power Module Using GaAs HEMT

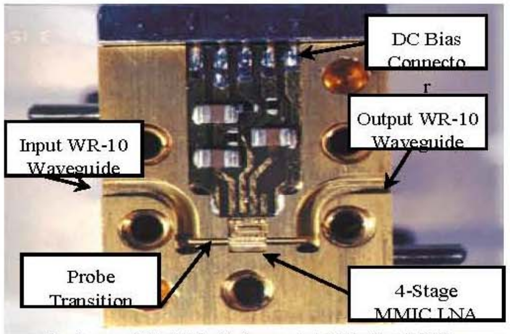


Courtesy: Dr. Rich Lai

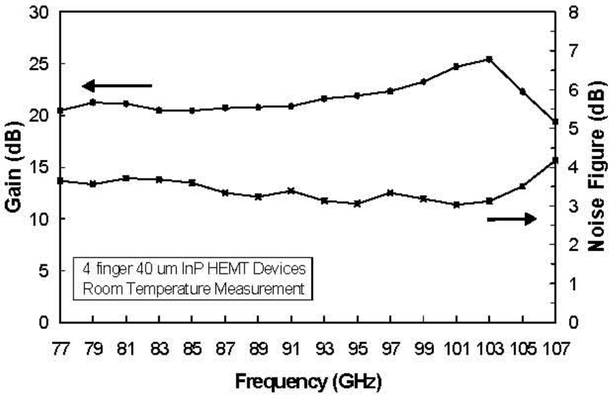
State-of-art MMW LNA MMICs

NORTHROP GRUMMAN
Space Technology

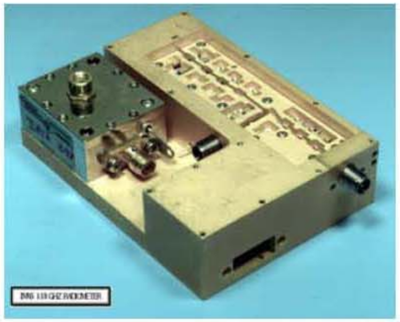




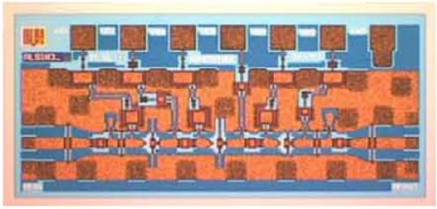
4-stage 100 GHz 0.1 um InP HEMT LNA



94 GHz LNA Receiver

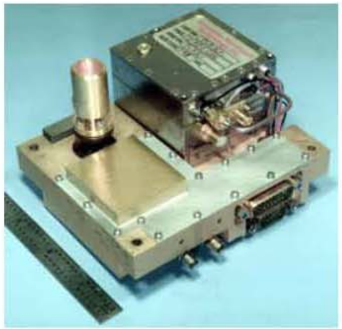


ABCS HEMT LNA
Gain: ~ 11 dB
DC Power: 1.8 mW
Noise Figure: < 5.4 dB

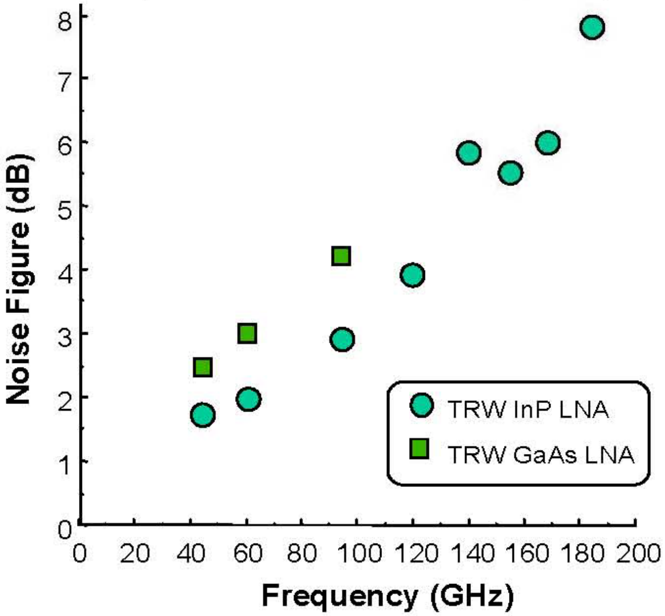


InP HEMT LNA
Gain: ~20 dB
Noise Figure: 3 dB

112-118 GHz LNA Receiver



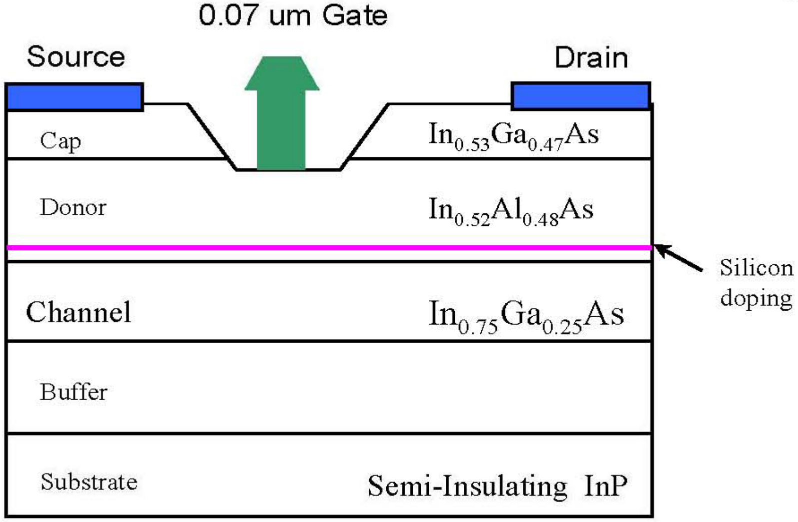
World Class LNA Performance to 200 GHz and Beyond



Courtesy: Dr. Rich Lai

State-of-art High Frequency MMW MMICs

NORTHROP GRUMMAN
Space Technology



0.07 um Gate

Source

Drain

Cap $In_{0.53}Ga_{0.47}As$

Donor $In_{0.52}Al_{0.48}As$

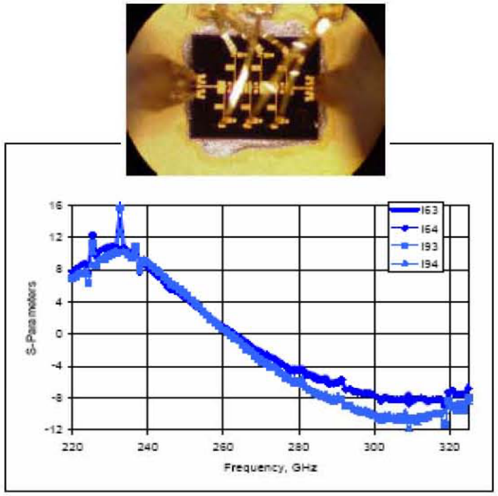
Silicon doping

Channel $In_{0.75}Ga_{0.25}As$

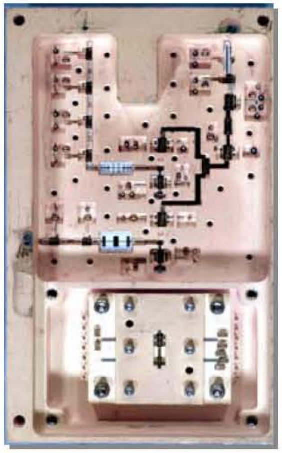
Buffer

Substrate Semi-Insulating InP

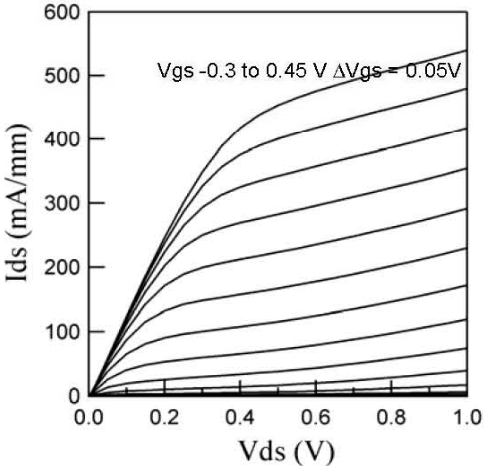
10 dB gain 3-stage LNA @235 GHz

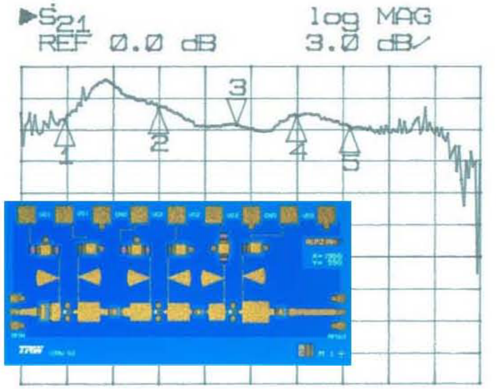


7.4 dB NF 183 GHz Radiometer



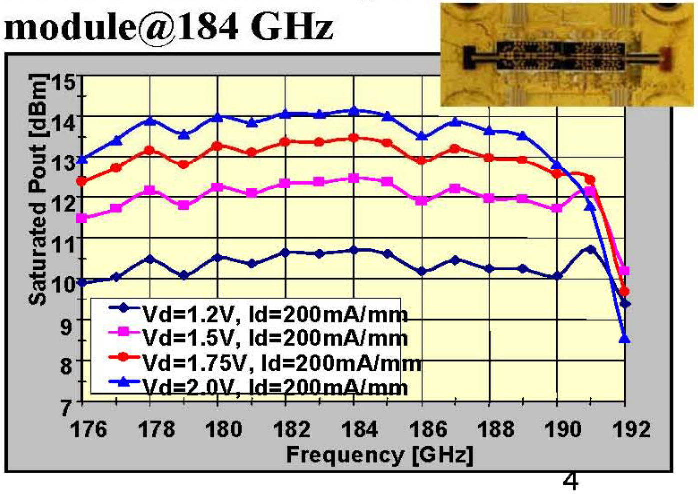
Gmp ~ 1500 mS/mm; fT = 350 GHz





12 dB gain LNA@215 GHz

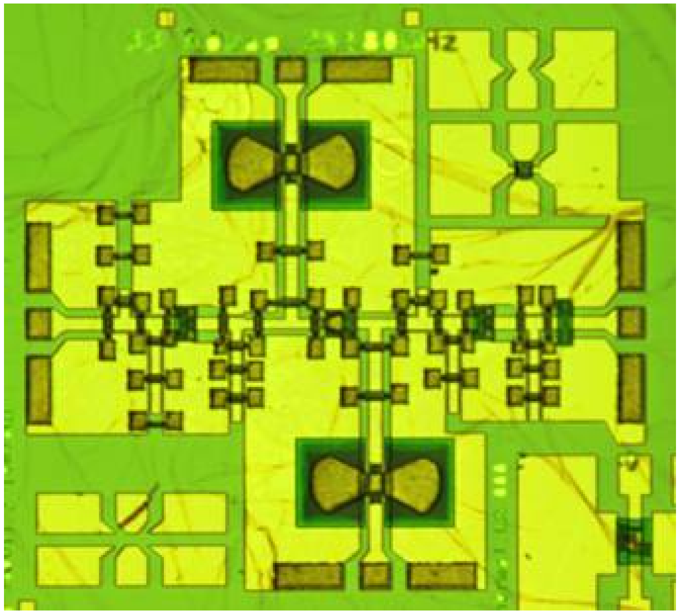
25 mW InP HEMT power module@184 GHz



Courtesy: Dr. Rich Lai

176 GHz Two-Stage HBT Amplifier

(Prof. Rodwell's Group, UCSB)

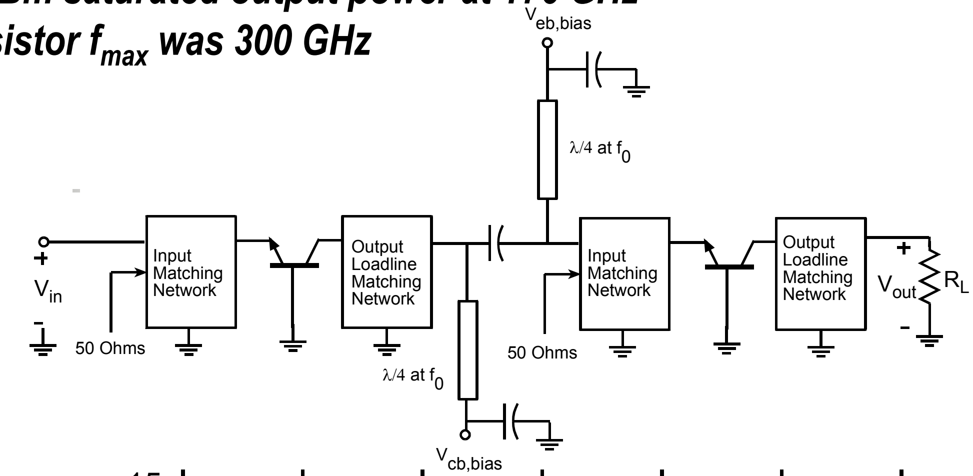


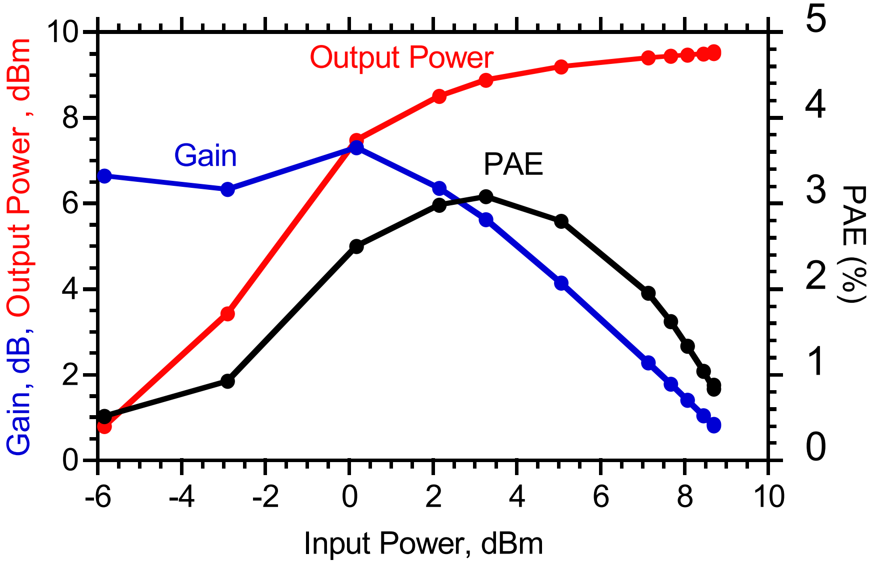
7-dB gain at 176 GHz

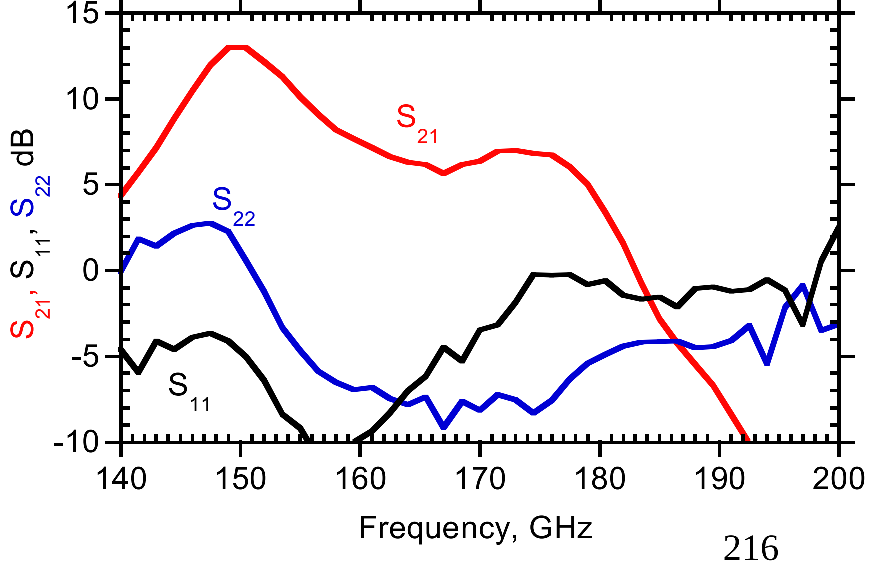
8.1 dBm output power, 6.3 dB power gain at 176 GHz

9.1 dBm saturated output power at 176 GHz

transistor f_{max} was 300 GHz







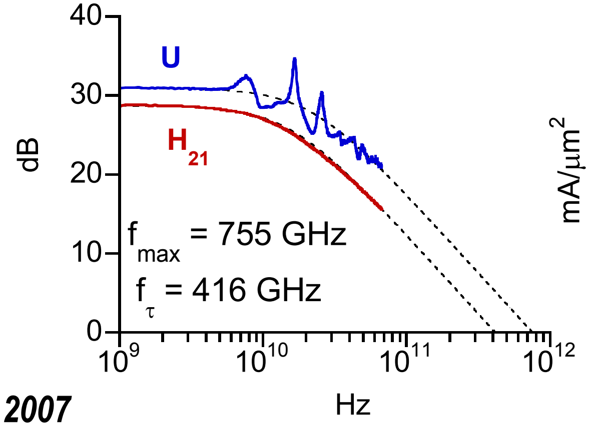
V. Paidi et al., IEEE RFIC conference, Long Beach, CA 2004

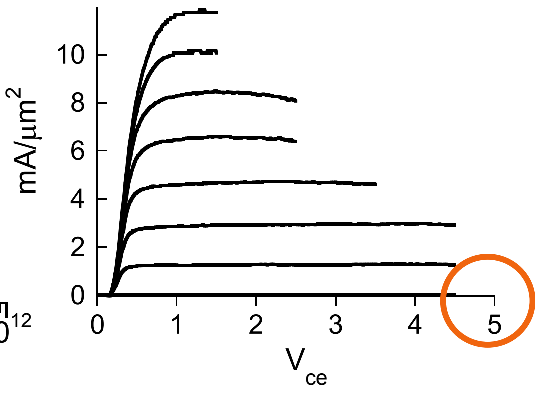
THz Transistors are Coming Soon

(Prof. Rodwell's Group, UCSB)

InP Bipolars: 250 nm generation: → 750 GHz f_{max}, 400 GHz f_{τ}, 5 V BV_{CEO}

125 nm & 62 nm nodes
→ ~ THz devices



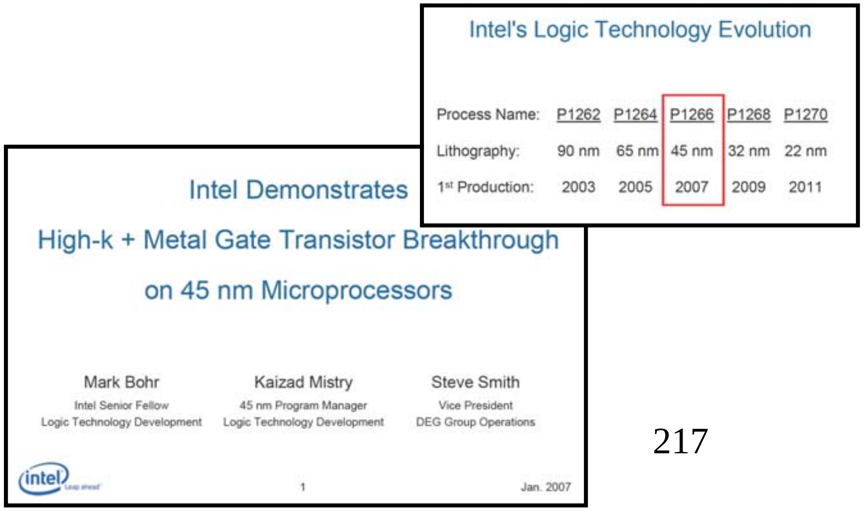


Z. Griffith et al., IEEE IPRM conference, Matsue, Japan 2007

IBM IEDM '06: 65 nm SOI CMOS → 450 GHz f_{max}, ~1 V operation

Intel Jan '07: 45 nm / high-K / metal gate

→ continued rapid progress



Intel's Logic Technology Evolution

Process Name:	P1262	P1264	P1266	P1268	P1270
Lithography:	90 nm	65 nm	45 nm	32 nm	22 nm
1st Production:	2003	2005	2007	2009	2011

Intel Demonstrates

High-k + Metal Gate Transistor Breakthrough

on 45 nm Microprocessors

Mark Bohr	Kaizad Mistry	Steve Smith
Intel Senior Fellow	45 nm Program Manager	Vice President
Logic Technology Development	Logic Technology Development	DEG Group Operations

1

Jan. 2007