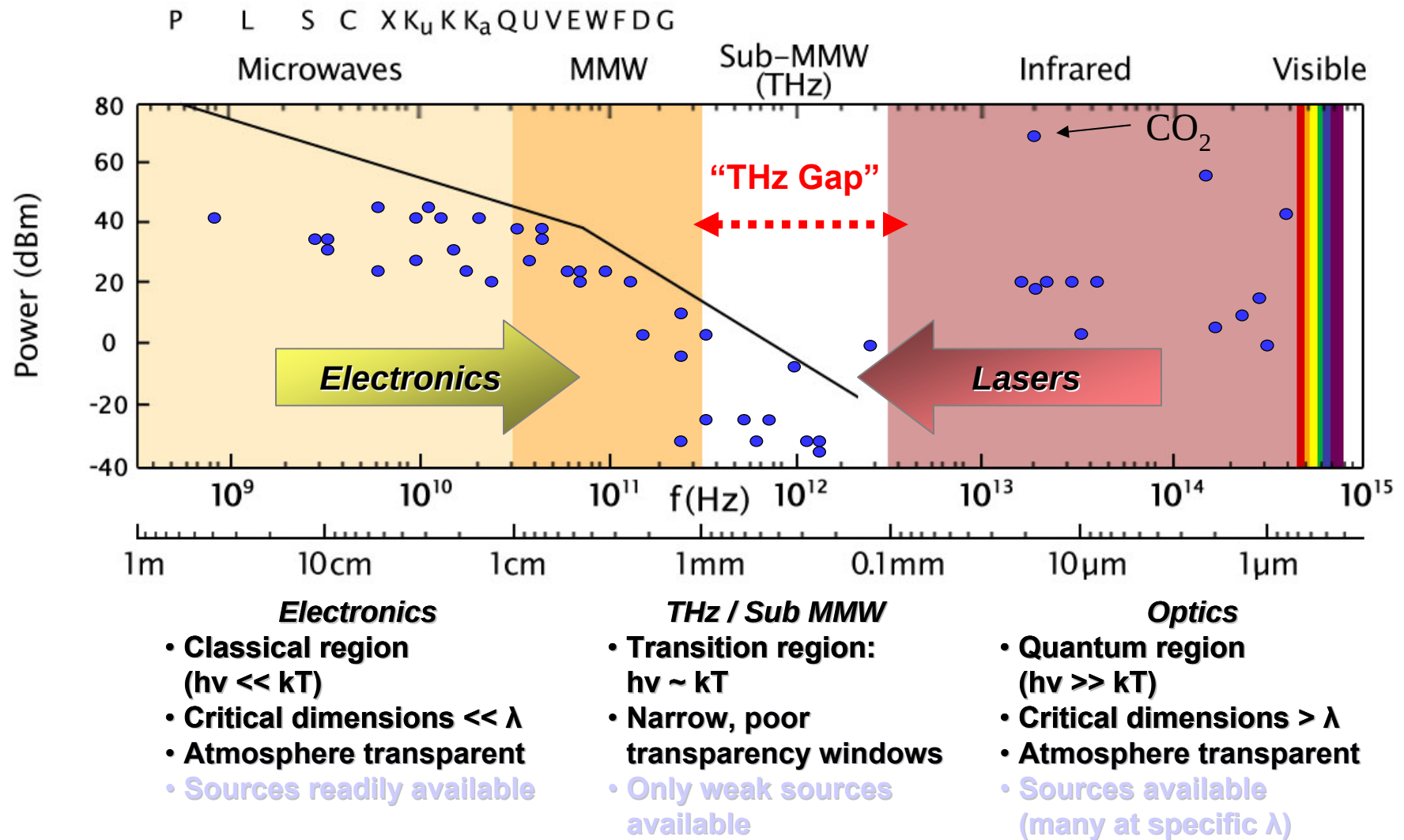


Solid-State, Coherent THz Sources and Amplifiers (all at room temperature)



Why THz Solid-State Electronics is so Challenging

Classical Regime of Transport Theory

- Drift and diffusive transport of free carriers

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

$h\nu < k_B T \rightarrow \nu < 6.2 \text{ THz @ } 300 \text{ K (no problem)}$

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

Quantum Regime

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

Requires: $\omega\tau \gg 1$, $h\nu > k_B T$

$h\nu > k_B T$ 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

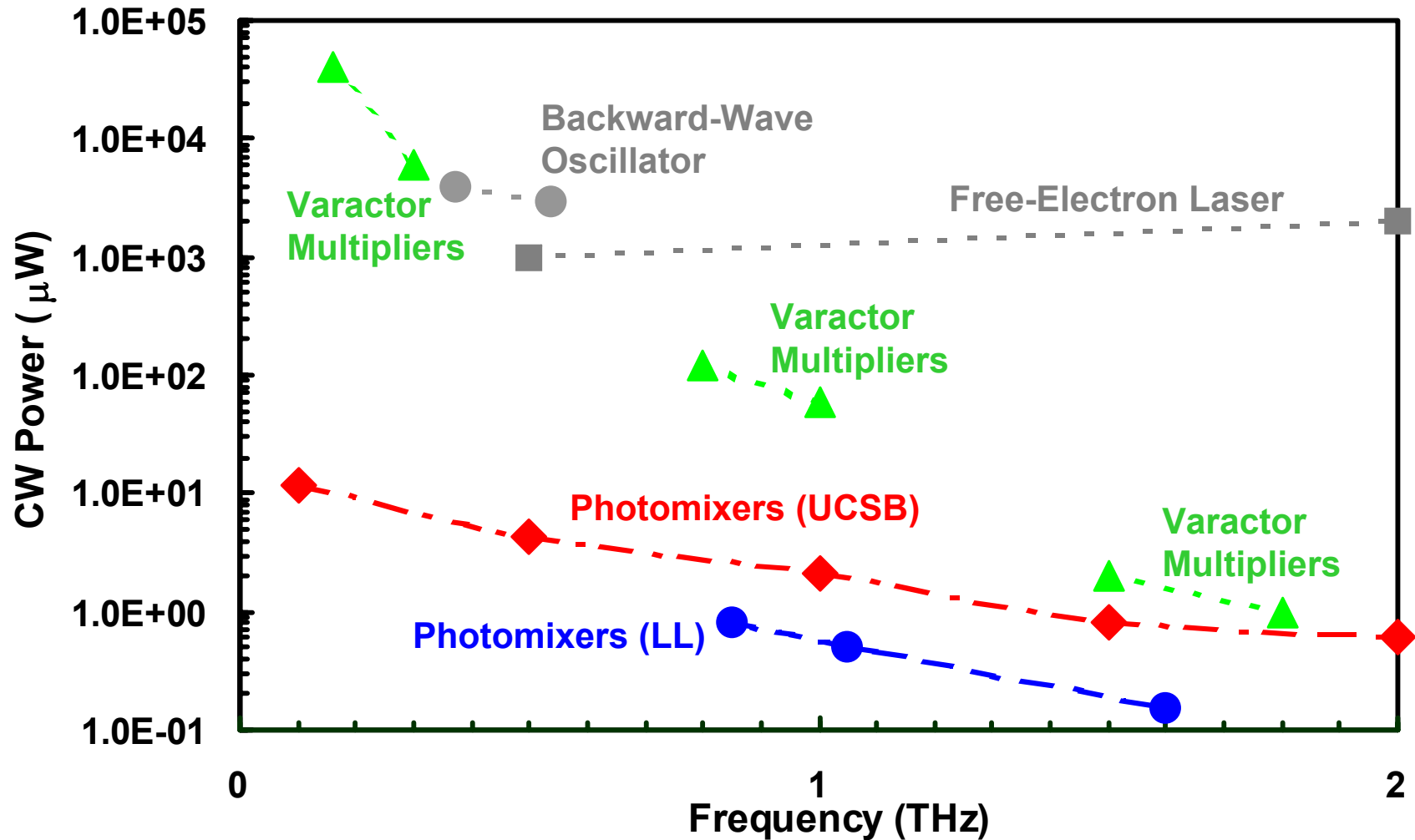
(1) Varactive Frequency Multiplication of Tunable RF Sources

(2) Photoconductive Mixing or Rectification of near-IR Diode Lasers

Legacy Semiconductor Two-Terminal Fundamental Oscillators

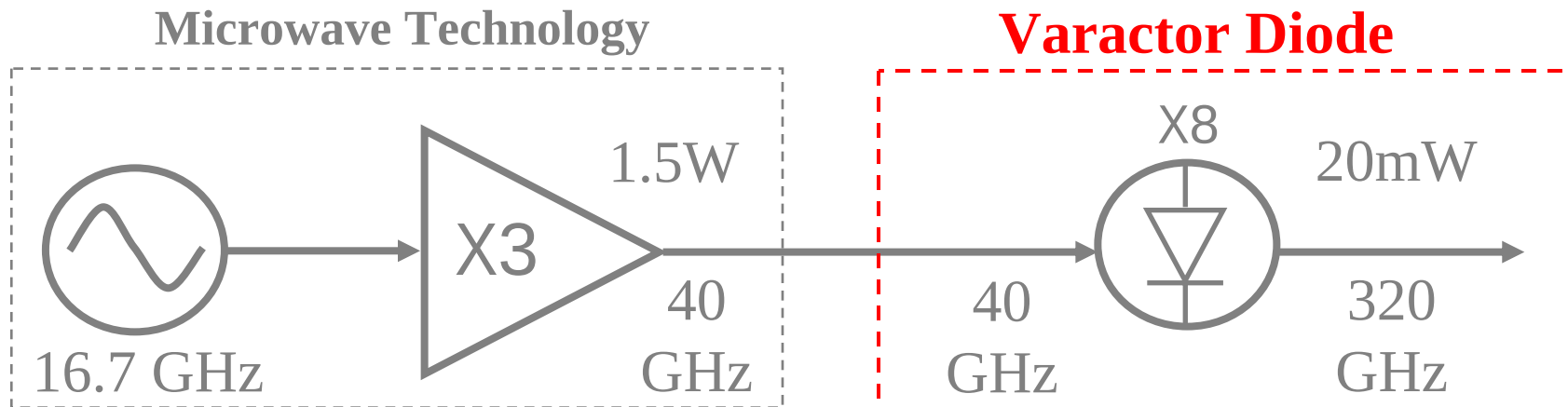
- **InP Gunn Oscillators**
 - $f_{\max} < 200$ GHz (fundamental mode)
 - **Advantage:** High power (up to ~100 mW cw)
 - **Disadvantage:** Limited tunability (a few %)
- **Si IMPATT Diodes**
 - $f_{\max} > 300$ GHz
 - **Advantage:** High power (up to ~1 W peak) and efficiency
 - **Disadvantage:** Noisy
- **Resonant Tunnel Diodes**
 - $f_{\max} \sim 1$ 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

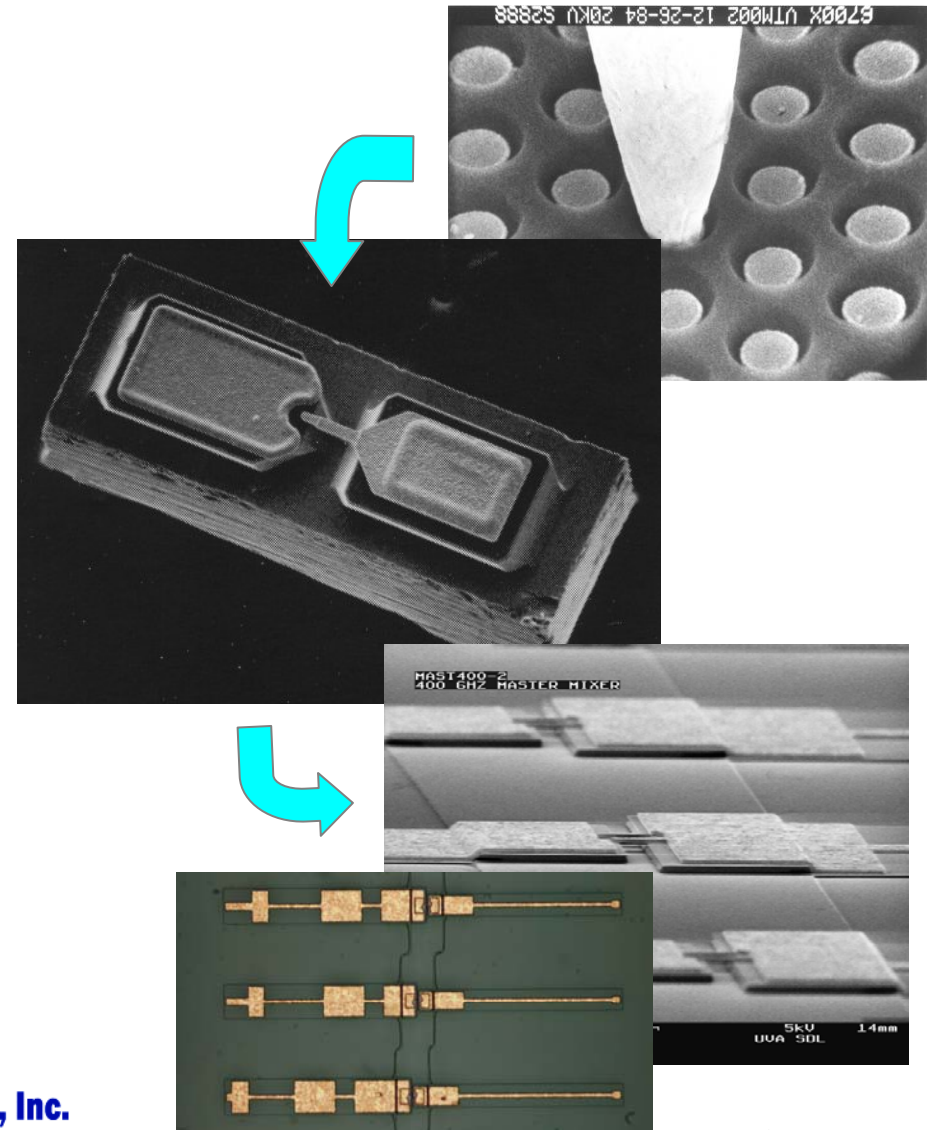


Key Technologies

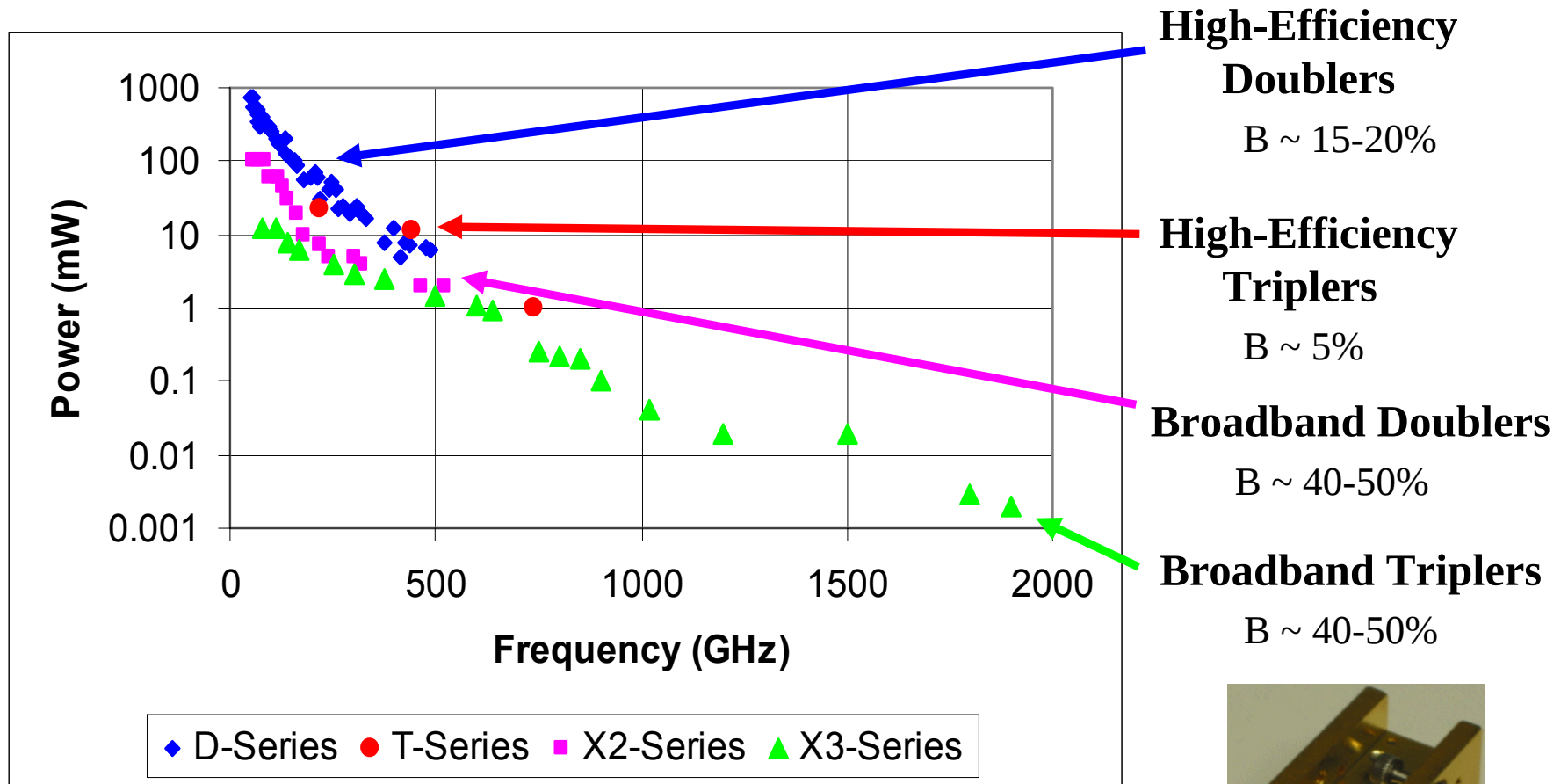
- Careful Circuit Design and Modern CAD Tools
- Advanced Diode Fabrication and Integration

Schottky Diode Fabrication Technology

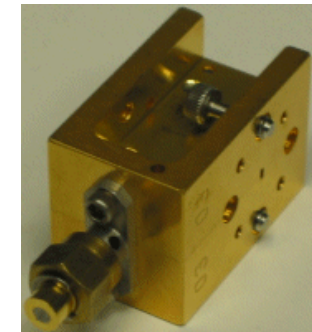
- Moved from whiskered to planar diodes
 - Whiskered diode fragile, difficult to reproduce
- Planar Schottky Diodes
 - Flip-chip and integrated diode-circuits
 - Multiple diode configurations possible
 - Power handling
 - Balanced designs
 - Commercialization of diode fabrication process



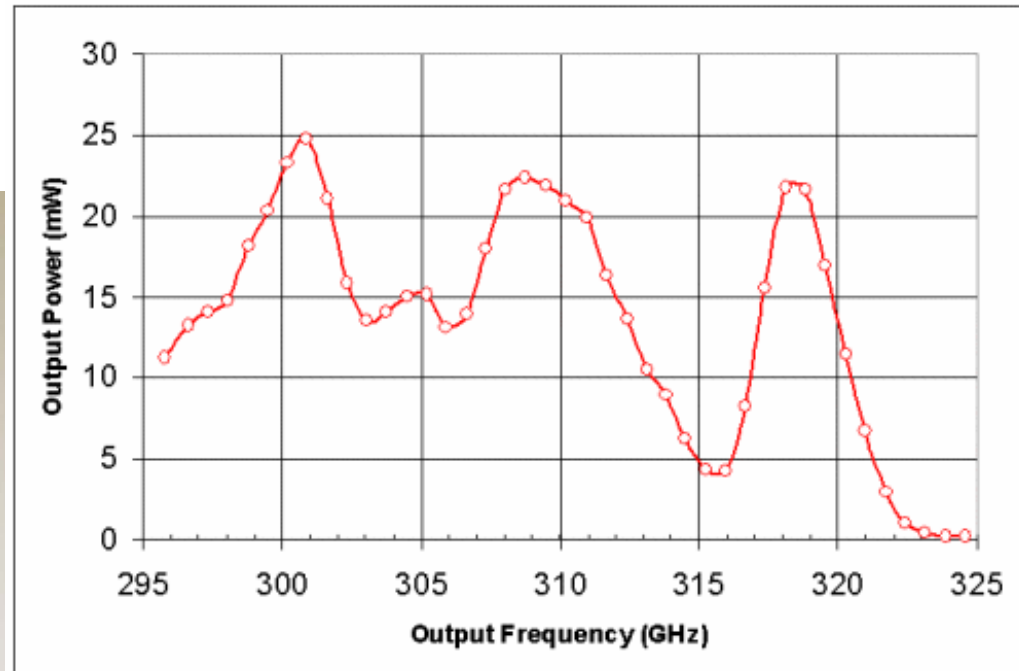
VDI Multipliers



Fundamental tradeoff between power and bandwidth.



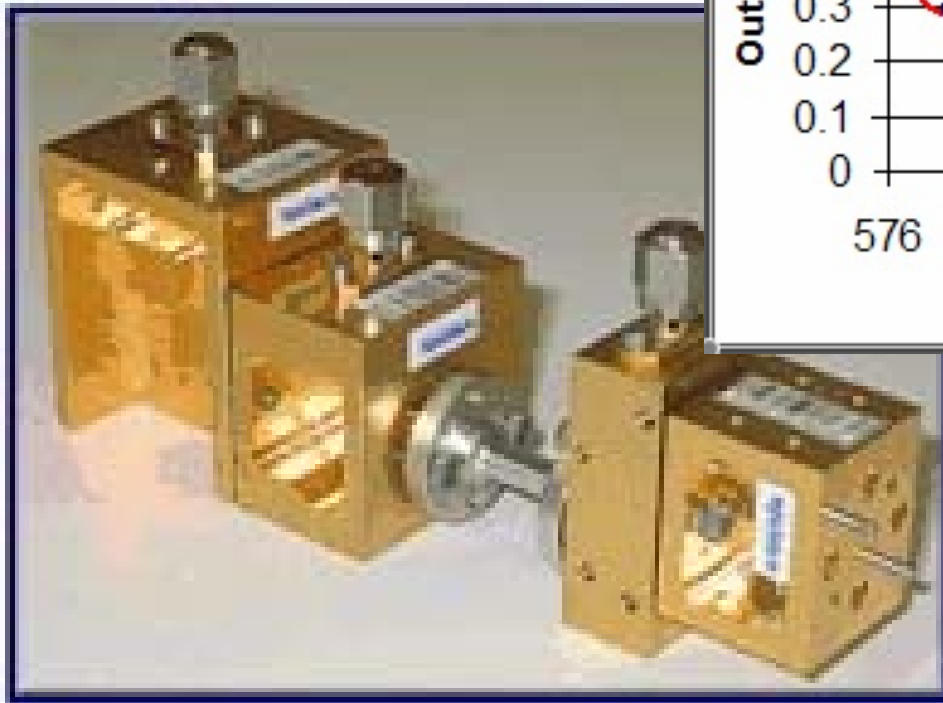
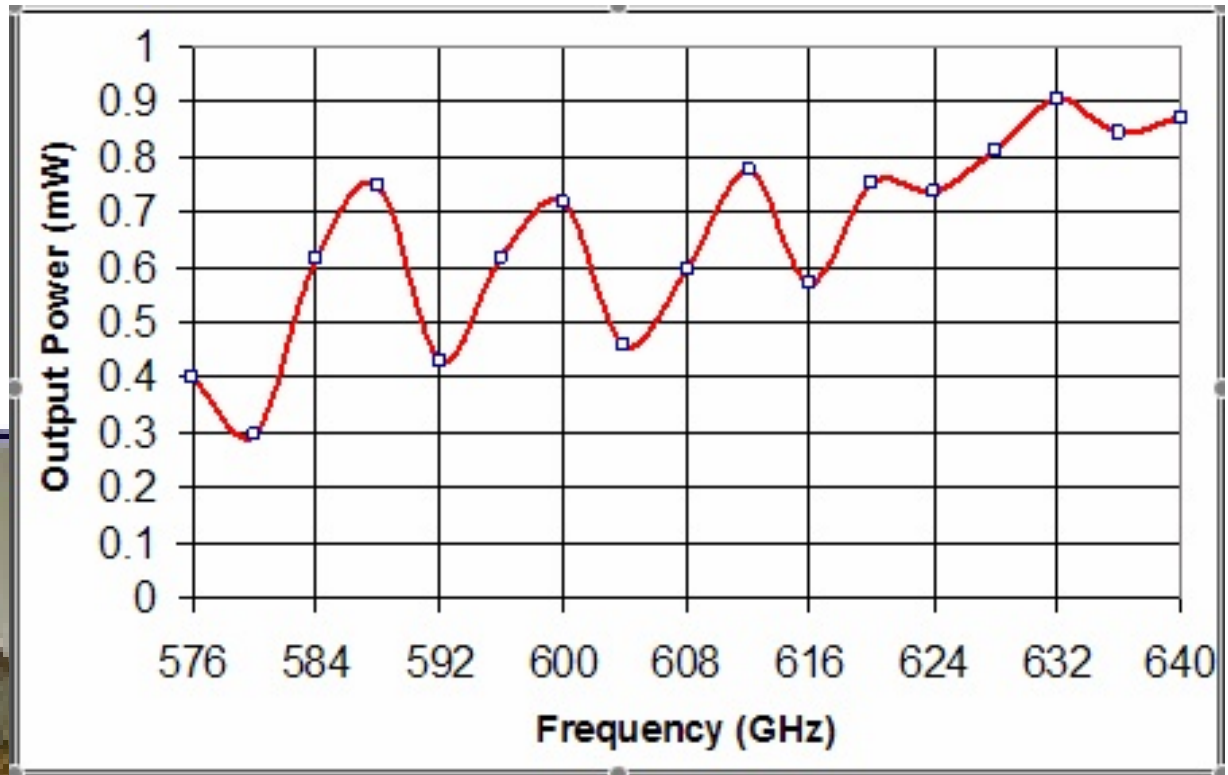
320 GHz Multiplier Chain



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

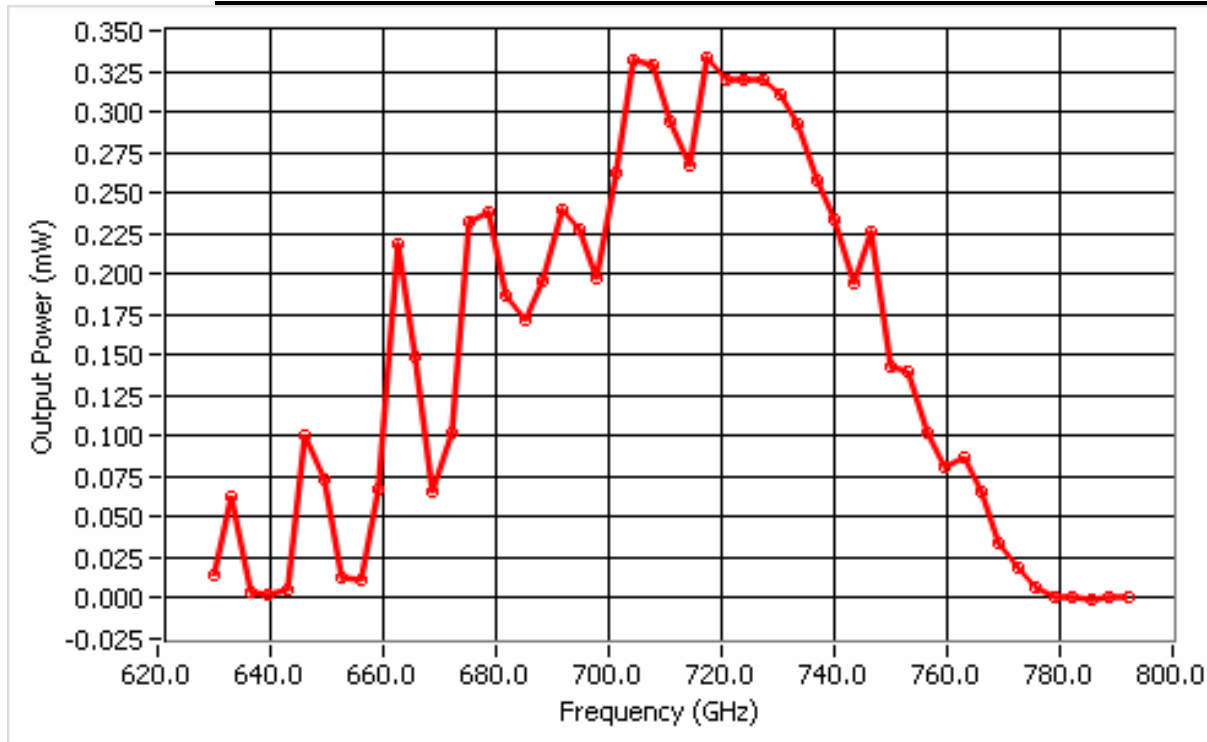


Schottky-Varactor Frequency Multiplier Chain (w/ amplification at Ka Band)

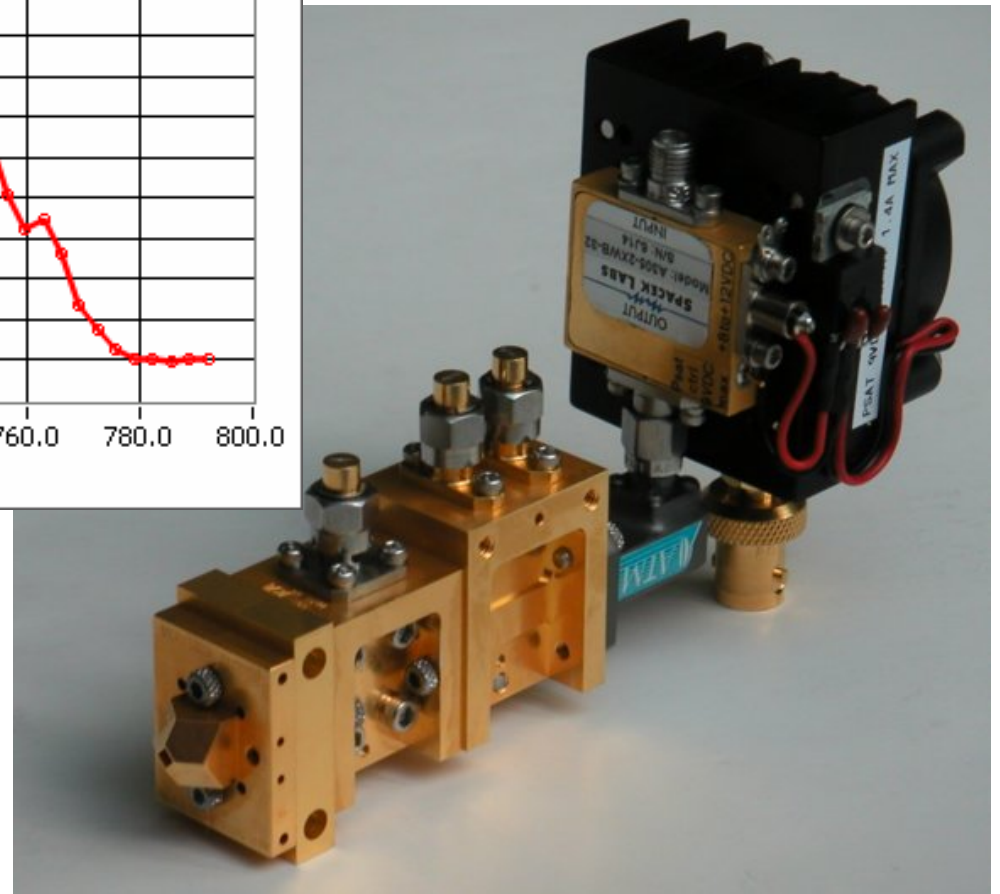


Virginia Diodes Inc.
FEM 2x amplifier Waveguide:
2x2x2x3x

660-760 GHz Source

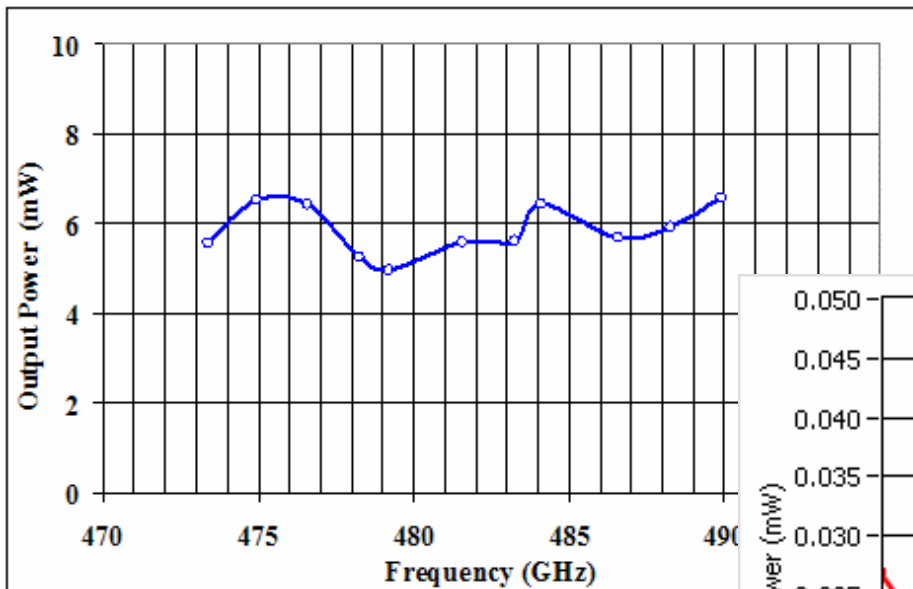


- **Compact, tunerless**
- **Input drive 14-16 GHz**

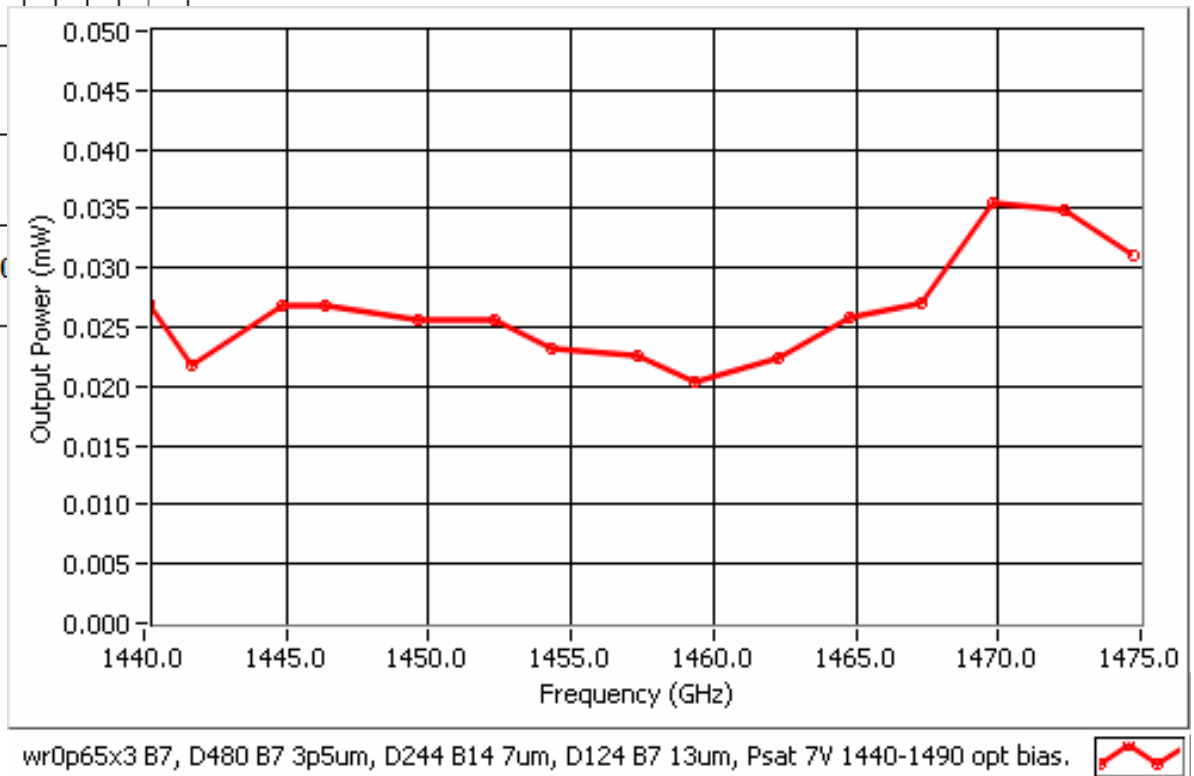


1.46 THz Varactor Multiplier Source

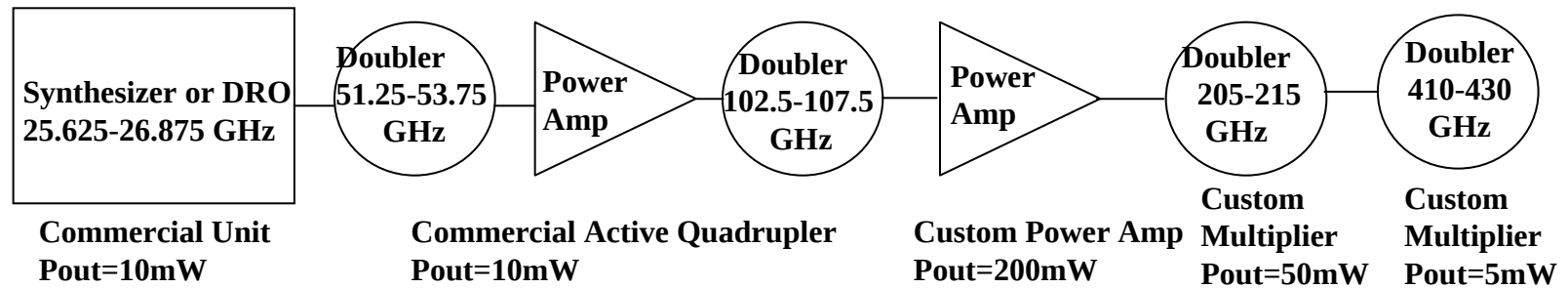
D480 Doubler – 6-7 mW



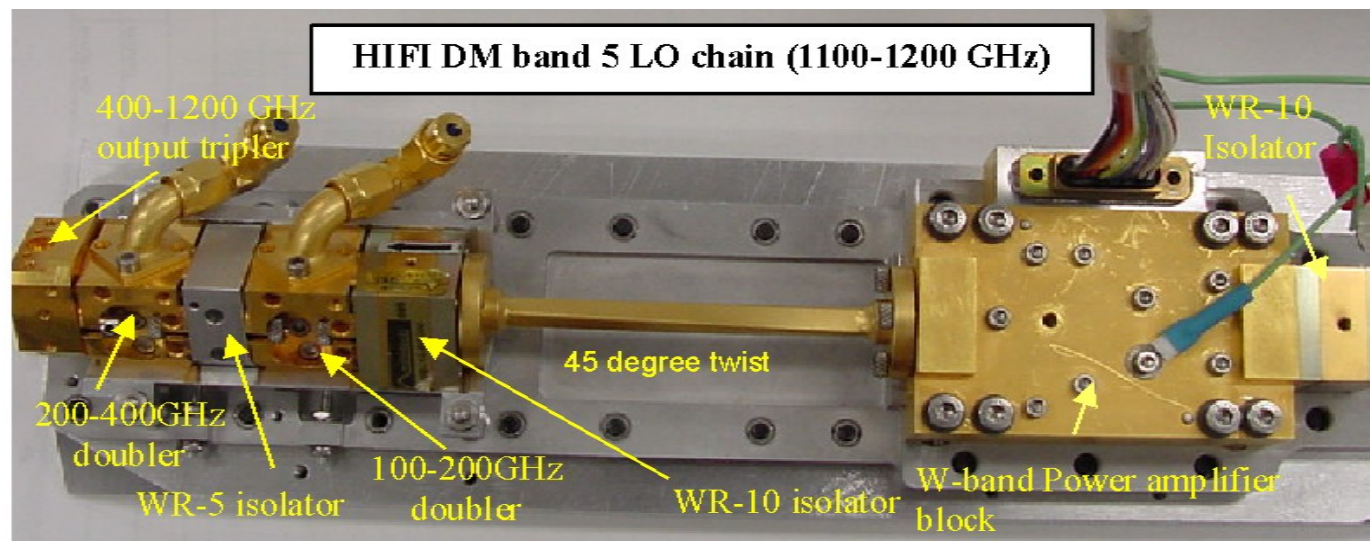
- 20-30 μ W at 1.46 THz
- Room temperature operation



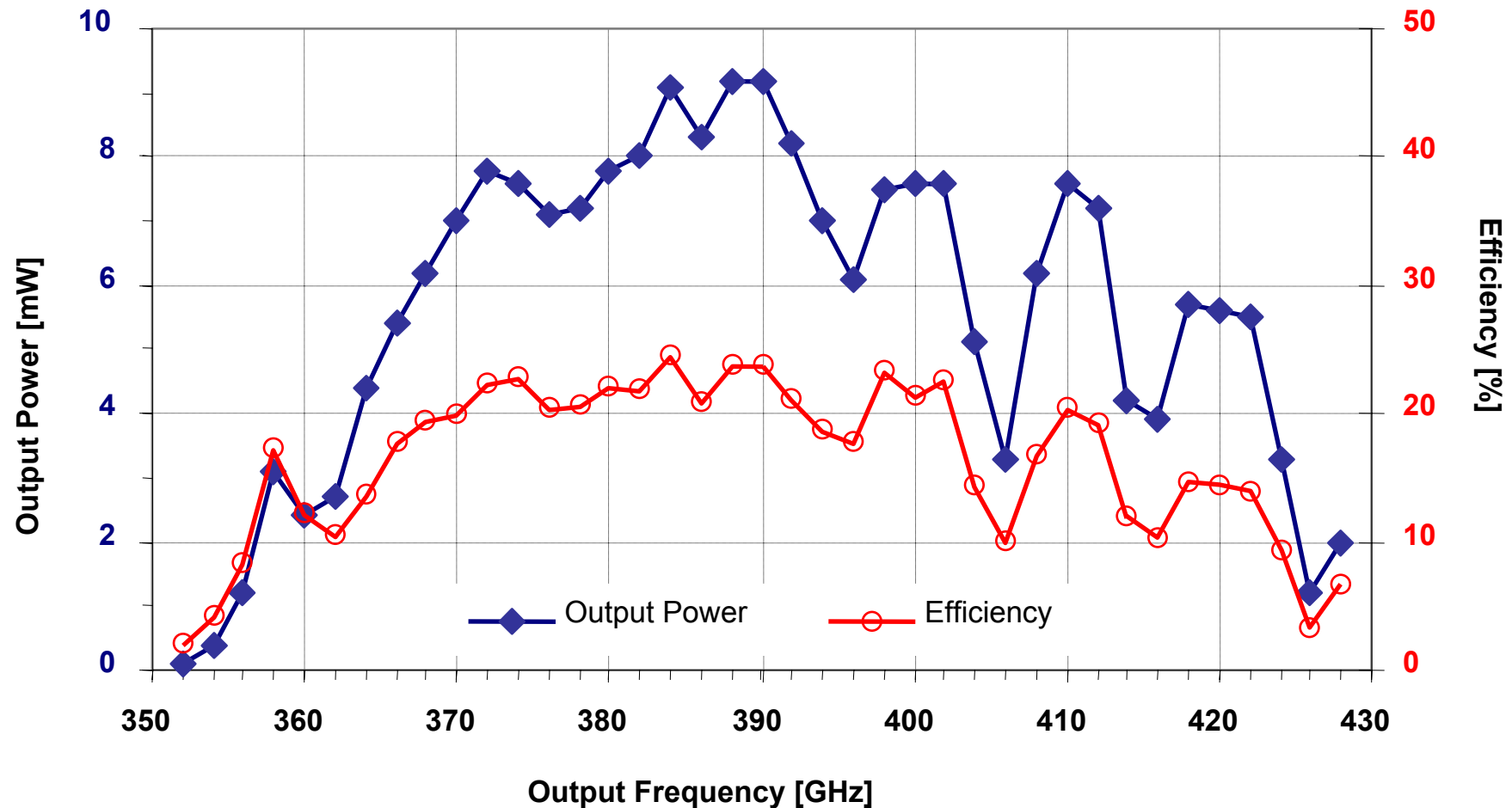
Schottky-Varactor Frequency Multiplier Chain (w/ amplification at W Band, Jet Propulsion Lab/NG Corp)



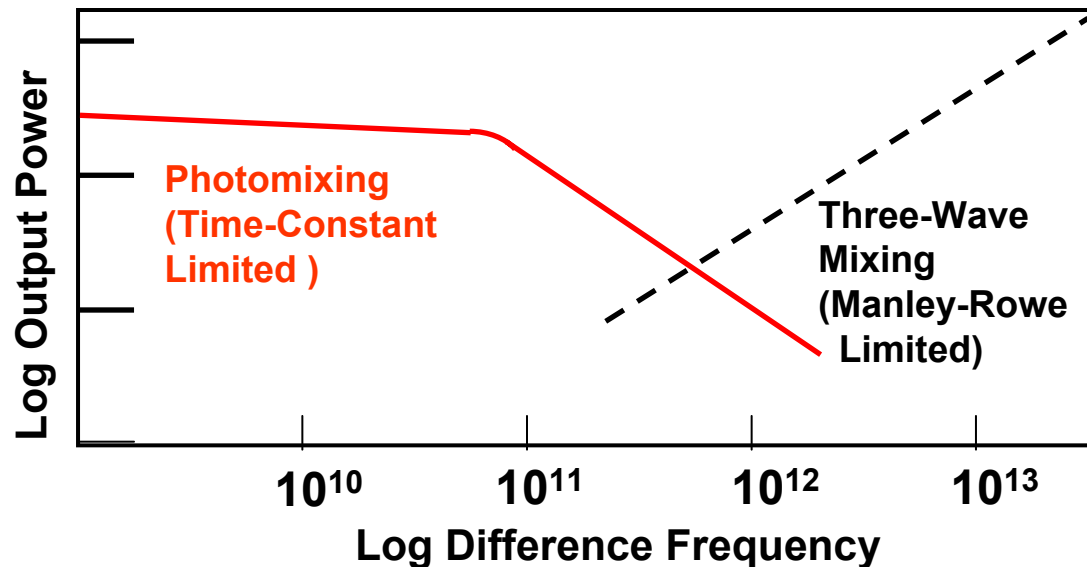
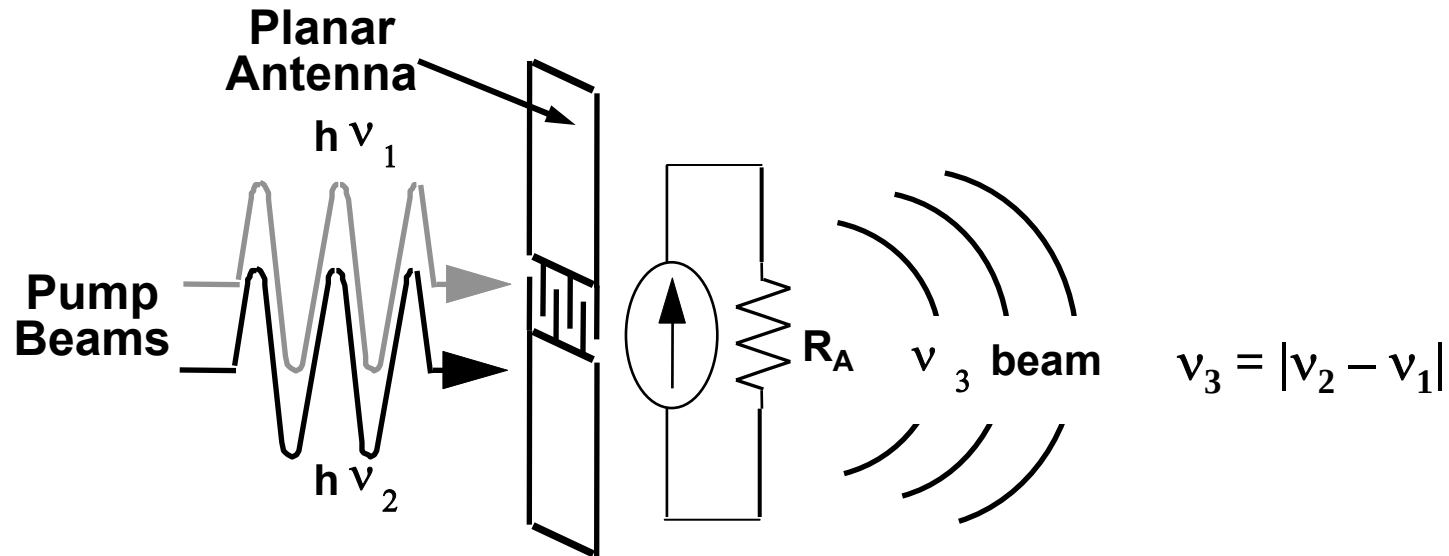
Block diagram of proposed electronically tuned transmitter based on a synthesized source followed by solid-state amplifiers and frequency doublers. Demonstrated output power is >5mW at 420 GHz.



JPL/NGC Varactor Multiplier Chain Performance



Photo(conductive) Mixing



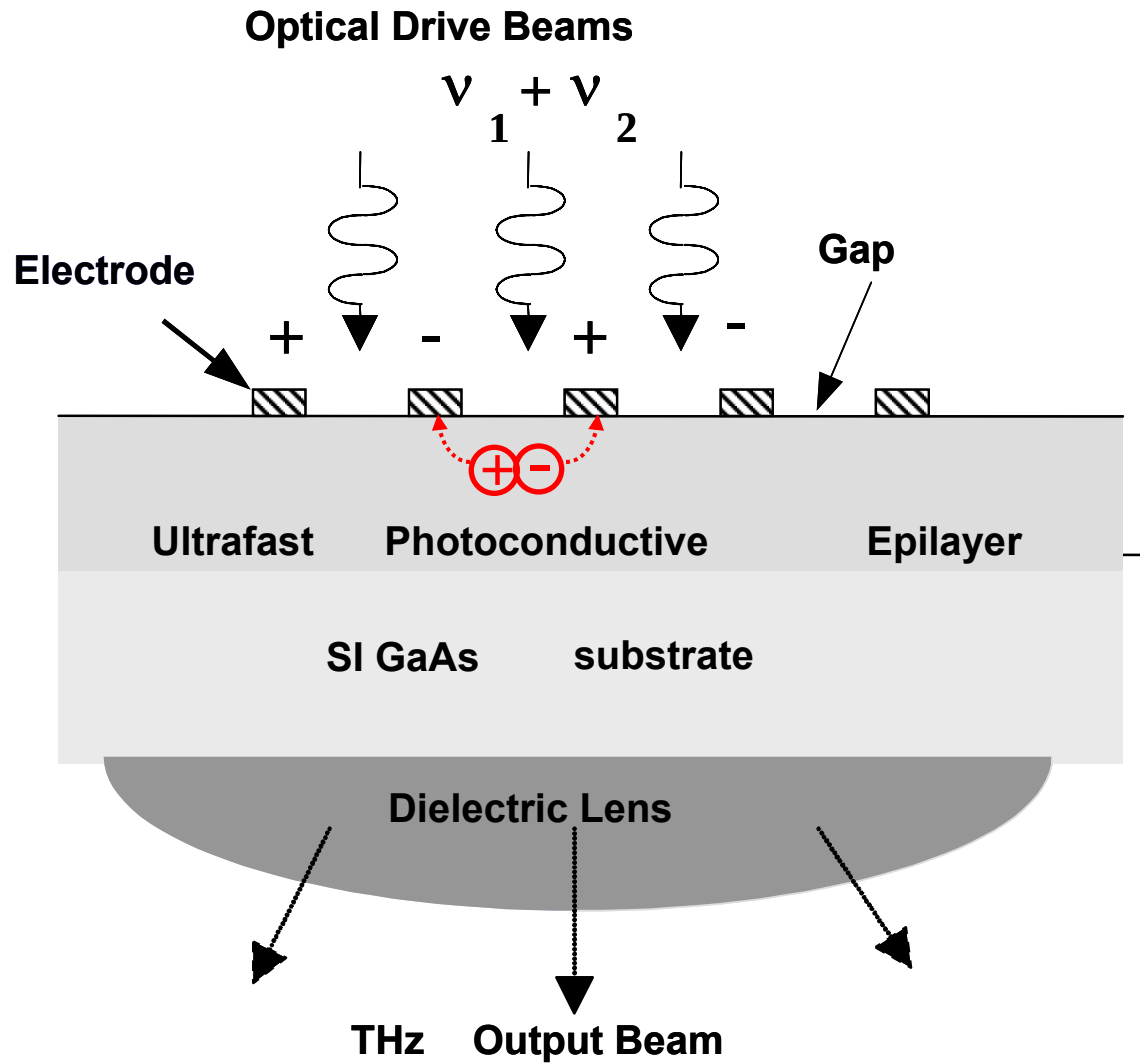
Recall Manley-Rowe Limit for Three-Wave Mixing:
No more than one photon out for two (pump) photons in $\Rightarrow$

Max Conversion Efficiency:

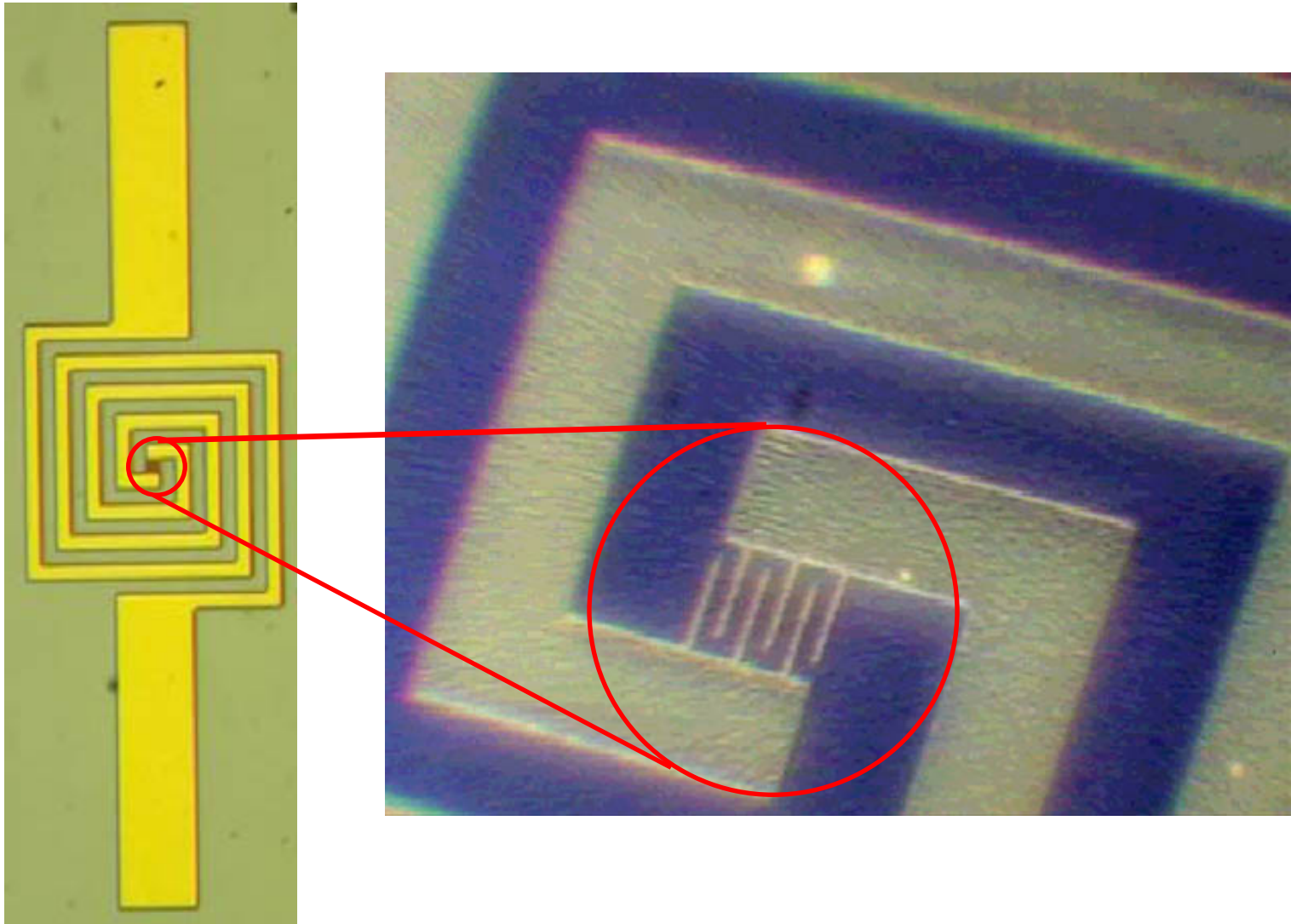
$$\eta = \frac{h\nu_3}{h\nu_1 + h\nu_2} \approx \frac{\lambda_P}{2\lambda_3}$$

Assuming both pump photons in near-IR or visible

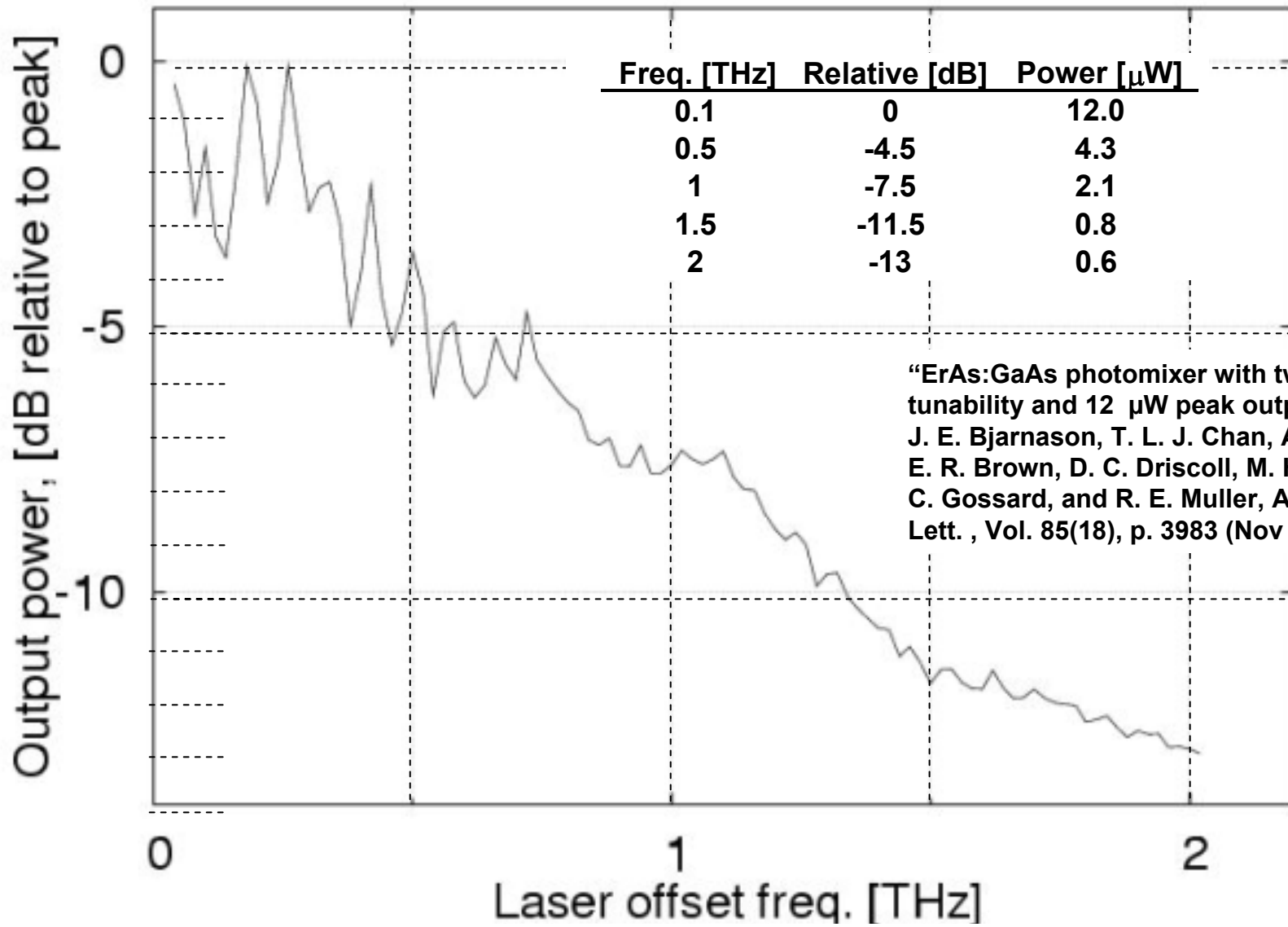
Low-Capacitance Interdigital-Electrode Structure



Self-Complementary Rectangular-Spiral THz Antenna



Calibrated CW Output Power from Square-Spiral Photomixer

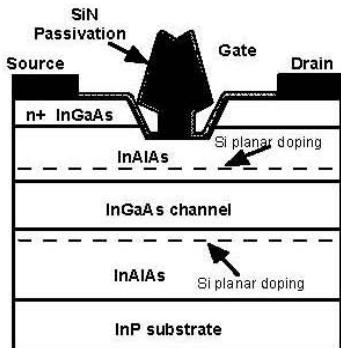


“ErAs:GaAs photomixer with two-decade tunability and 12 μ W peak output power,”
J. E. Bjarnason, T. L. J. Chan, A. W. M. Lee,
E. R. Brown, D. C. Driscoll, M. Hanson, A.
C. Gossard, and R. E. Muller, Appl. Phys.
Lett. , Vol. 85(18), p. 3983 (Nov 2004).

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



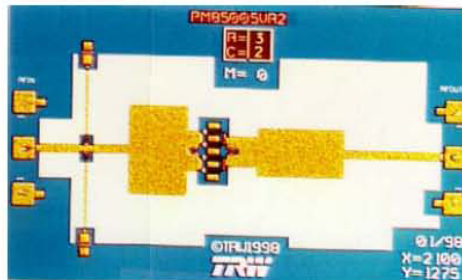
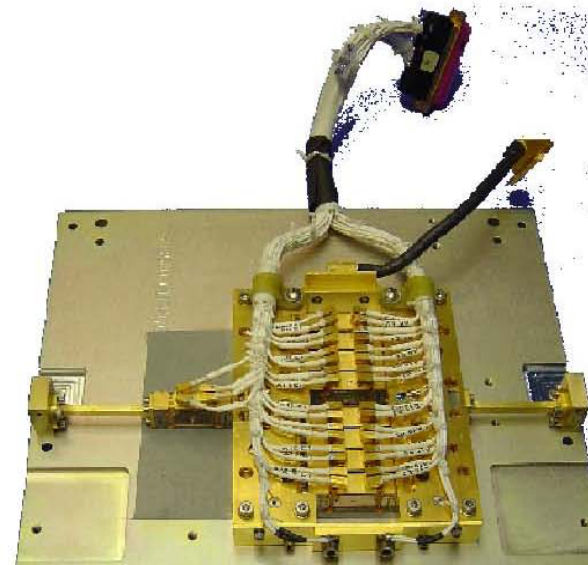
**GaAs and InP
HEMT**



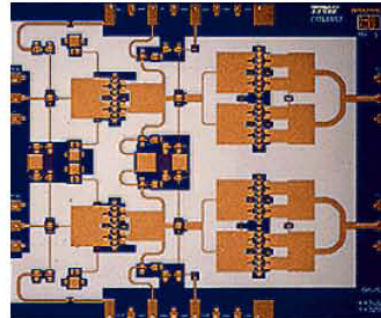
**0.1, 0.15
um gates**



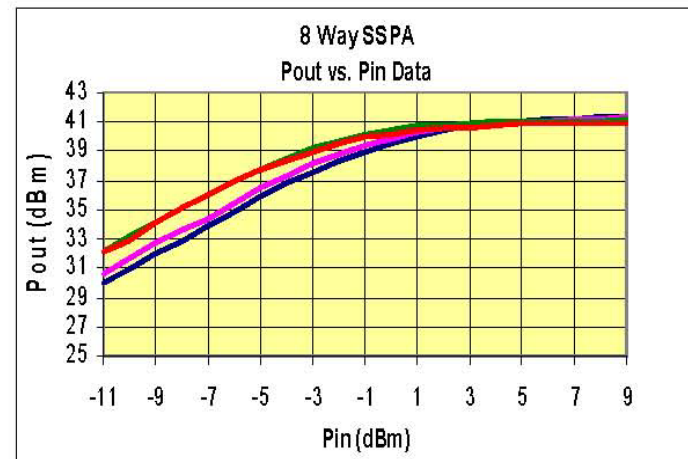
2-mil vias



**200 mW, 40% PAE
60 GHz InP HEMT**

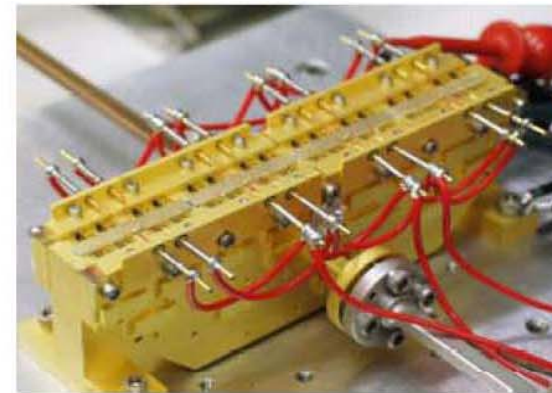
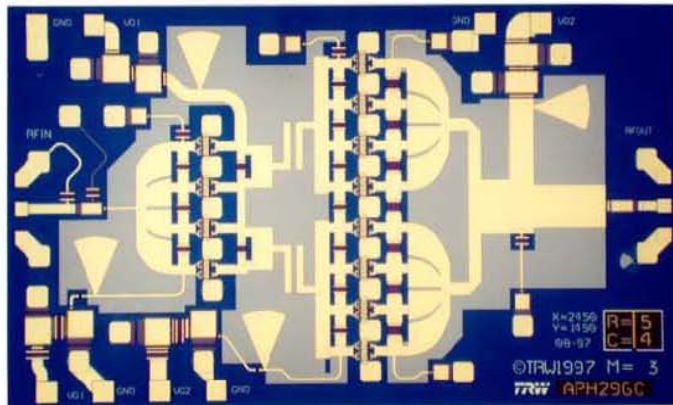


**>0.5W, 20% PAE
60 GHz GaAs HEMT**

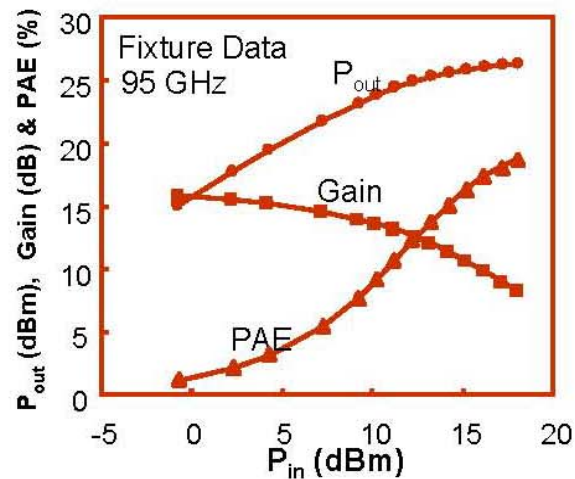


Courtesy: Dr. Rich Lai

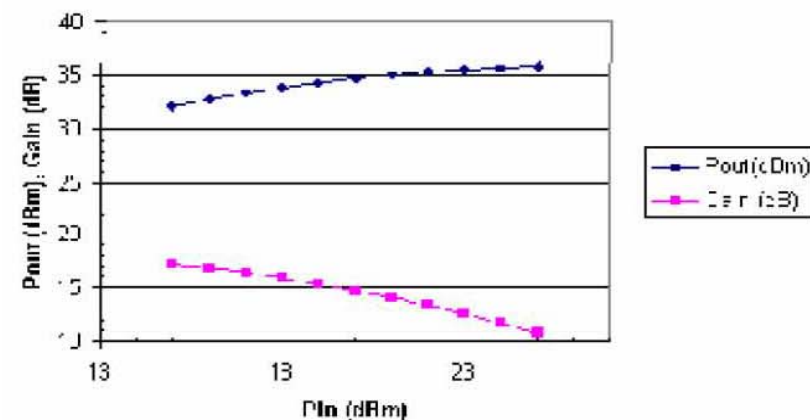
State-of-art W-band SSPA MMICs and Modules



Power Performance at 95 GHz

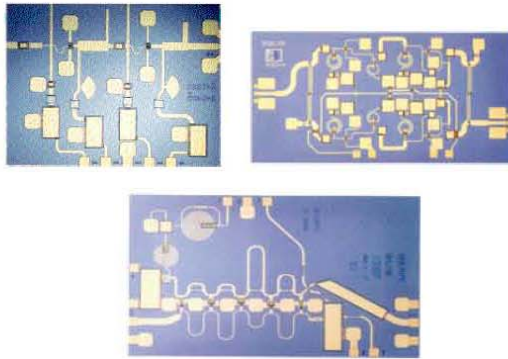


16-Way W-Band High Power Module Using GaAs HEMT

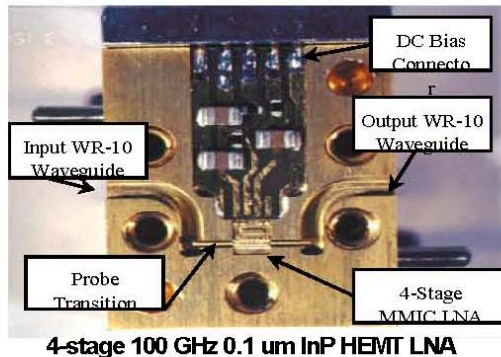
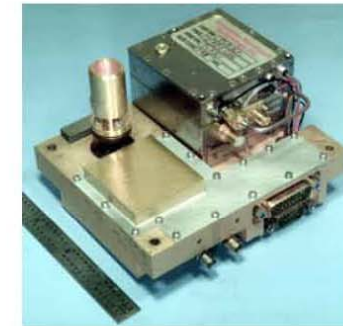


Courtesy: Dr. Rich Lai

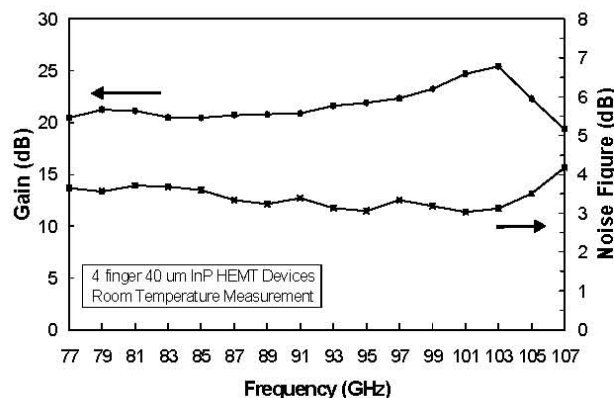
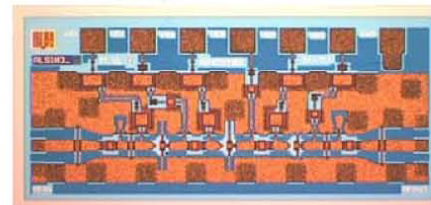
State-of-art MMW LNA MMICs



94 GHz LNA Receiver 112-118 GHz LNA Receiver

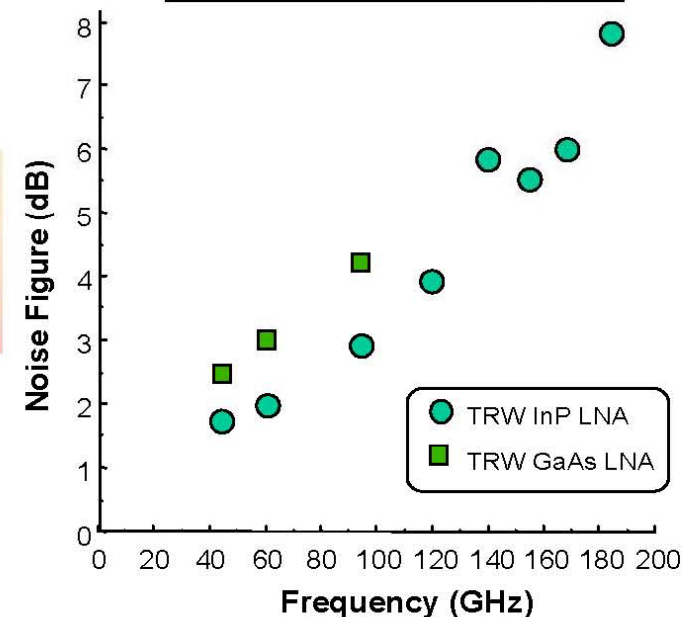


ABCS HEMT LNA
Gain: ~ 11 dB
DC Power: 1.8 mW
Noise Figure: < 5.4 dB



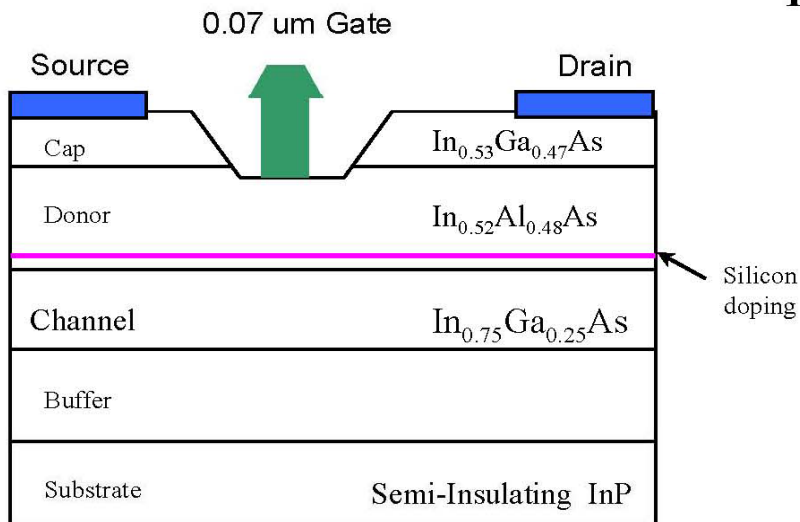
InP HEMT LNA
Gain: ~20 dB
Noise Figure: 3 dB

World Class LNA Performance to 200 GHz and Beyond

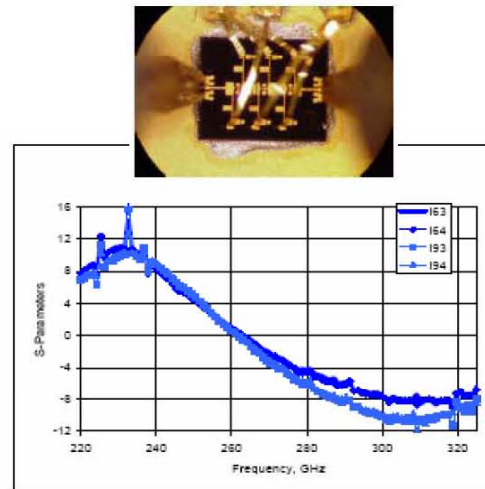


Courtesy: Dr. Rich Lai

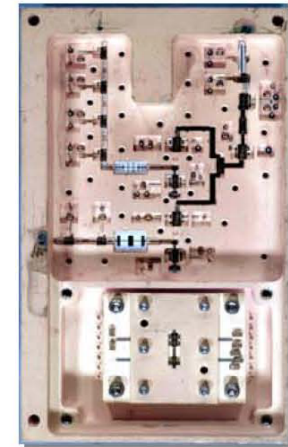
State-of-art High Frequency MMW MMICs



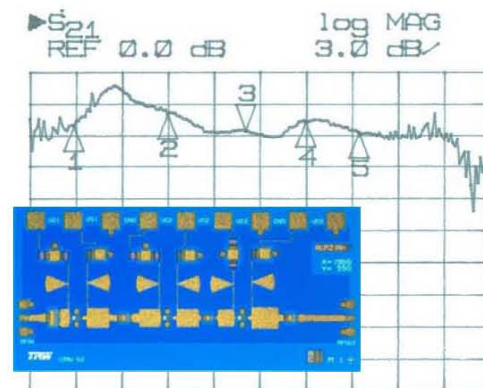
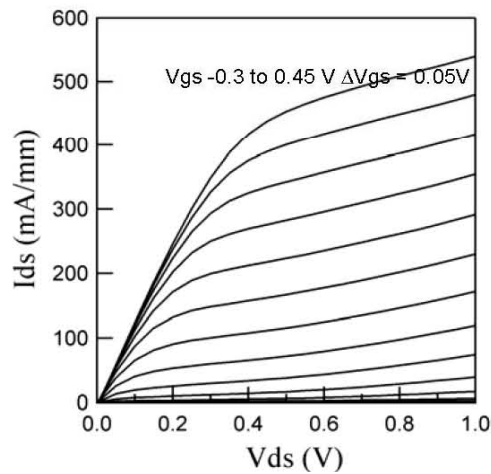
10 dB gain 3-stage LNA @235 GHz



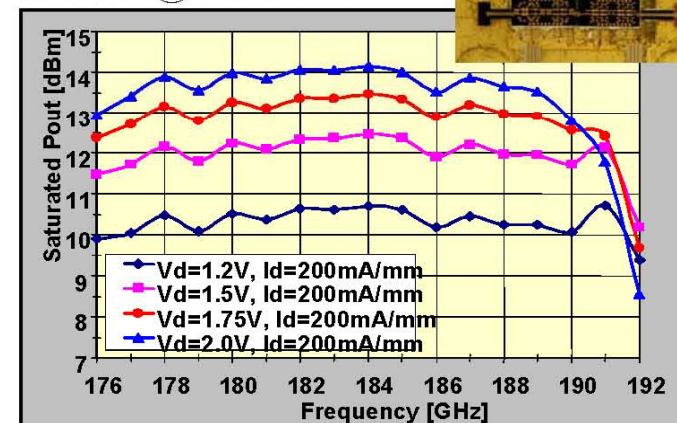
7.4 dB NF 183 GHz Radiometer



$G_{mp} \sim 1500 \text{ mS/mm}$; $f_T = 350 \text{ GHz}$



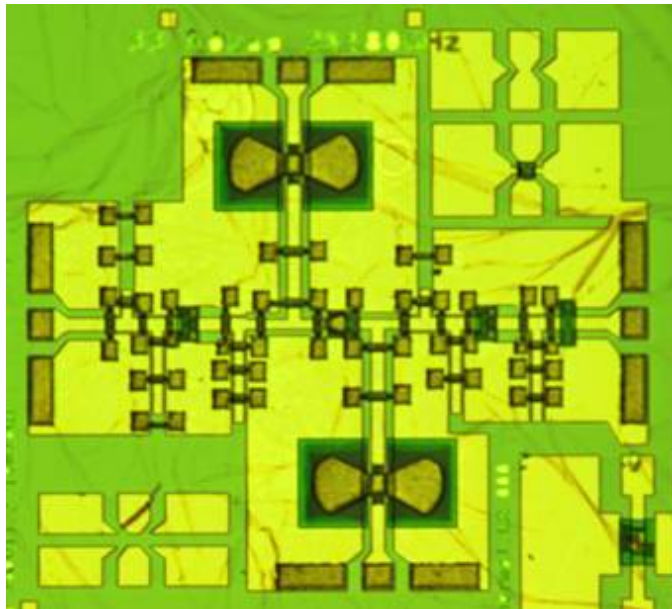
25 mW InP HEMT power module@184 GHz



Courtesy: Dr. Rich Lai

176 GHz Two-Stage HBT Amplifier

(Prof. Rodwell's Group, UCSB)

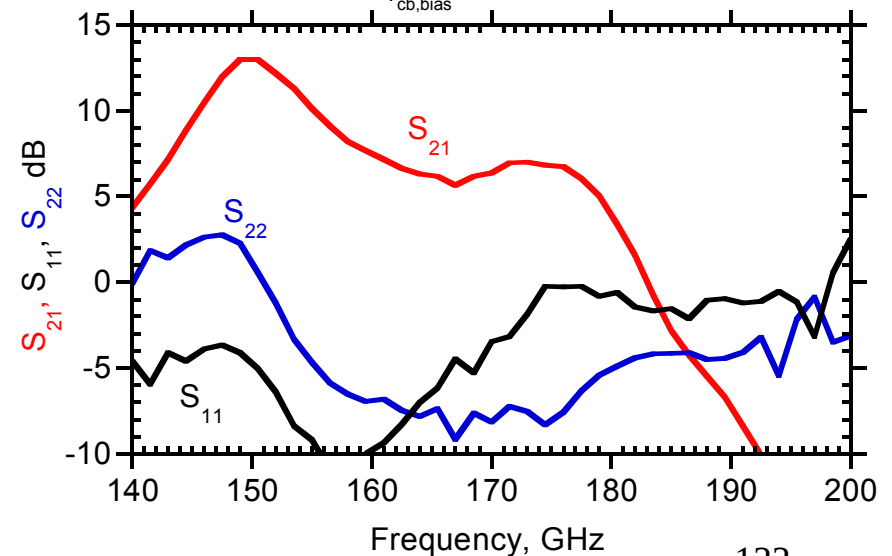
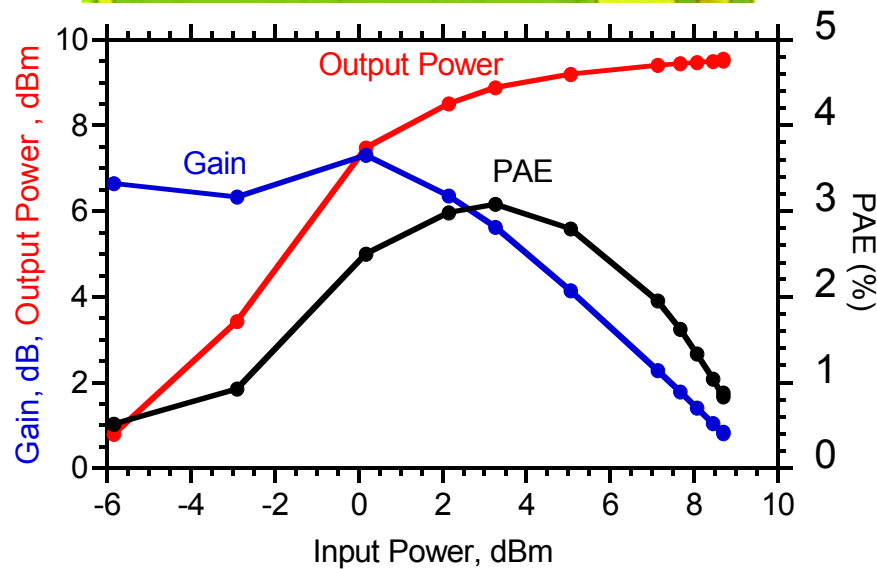
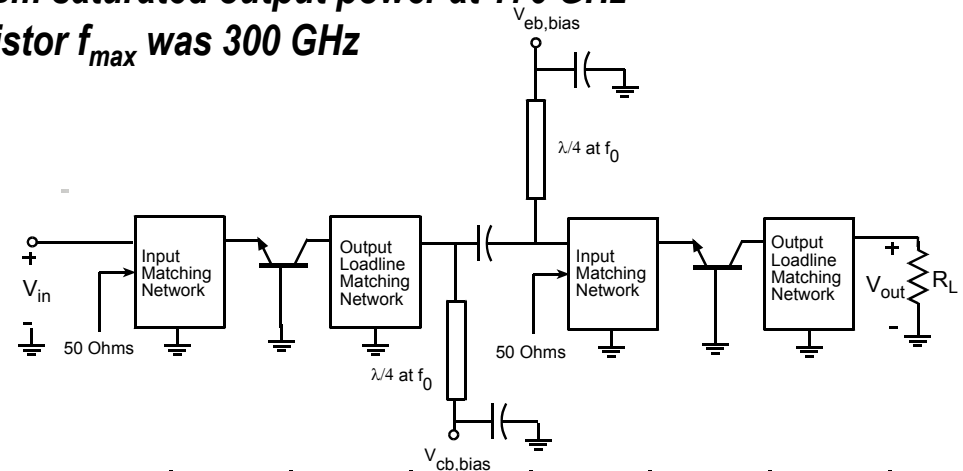


7-dB gain at 176 GHz

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

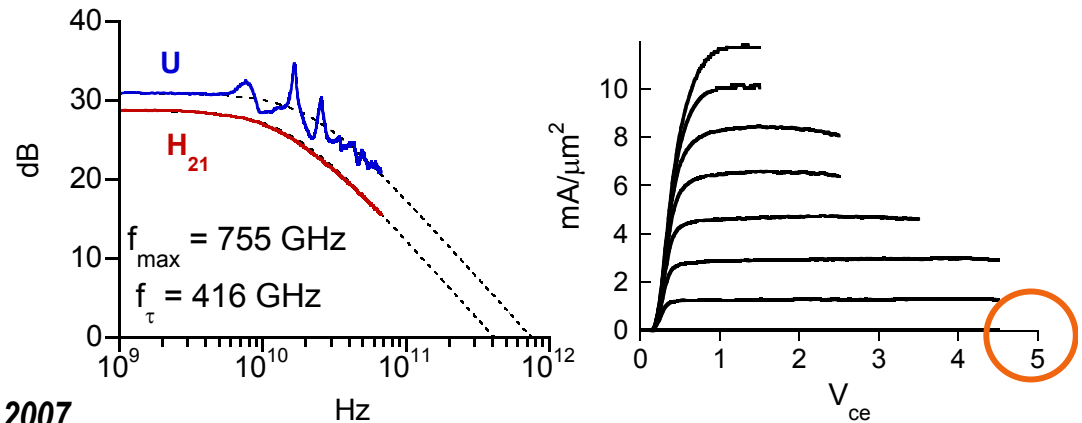


THz Transistors are Coming Soon

(Prof. Rodwell's Group, UCSB)

InP Bipolars: 250 nm generation: $\rightarrow 750 \text{ GHz } f_{\max}, 400 \text{ GHz } f_{\tau}, 5 \text{ V } BV_{CE0}$

**125 nm & 62 nm nodes
 $\rightarrow \sim \text{THz devices}$**



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

IBM IEDM '06: 65 nm SOI CMOS $\rightarrow 450 \text{ GHz } f_{\max}, \sim 1 \text{ V operation}$

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

$\rightarrow \text{continued rapid progress}$

