48.8mW Multi-cell InP HBT Amplifier with on-wafer power combining at 220GHz

Thomas Reed, Mark Rodwell
University of California, Santa Barbara

Zach Griffith, Petra Rowell, Miguel Urteaga, Mark Field, Jon Hacker
Teledyne Scientific & Imaging, LLC

treed@ece.ucsb.edu

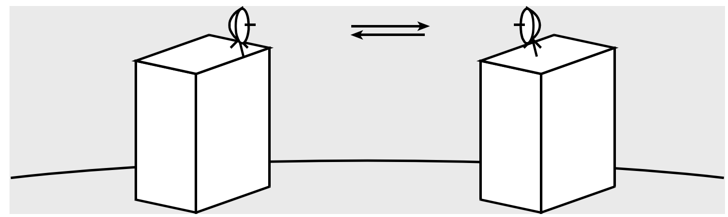
220 GHz InP HBT Power Amplifier

- mm-Wave Power in Communications and Imaging
- 250nm Indium Phosphide HBT Technology
- MMIC Power Amplifier Cells & Combiners
- Multi-cell Power Amplifier Results

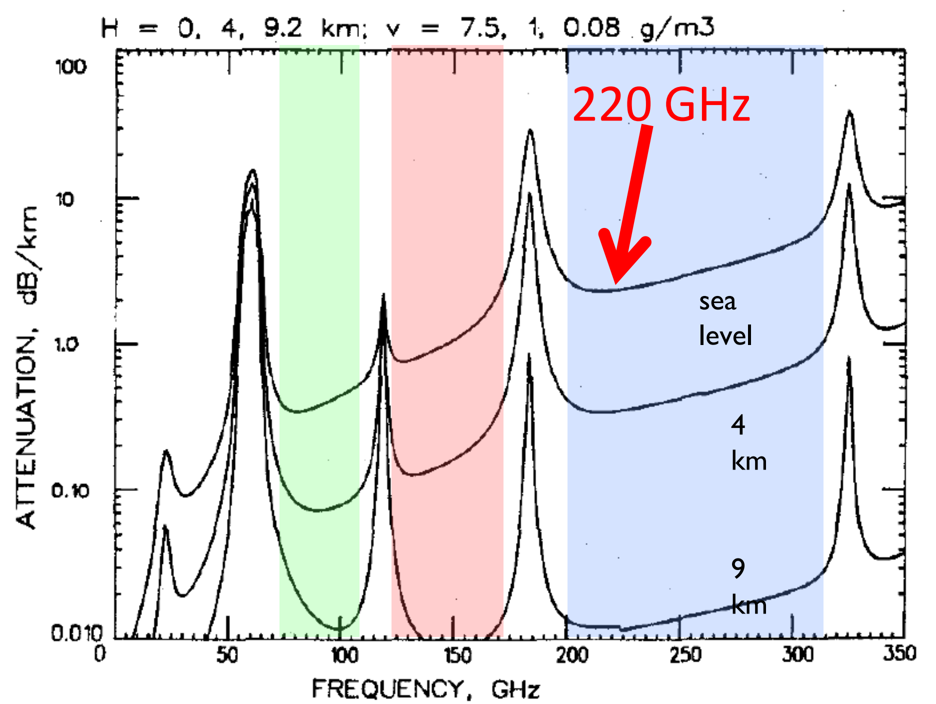
mm-Wave Power in Communications and Imaging

Systems at High Frequency

- High Bandwidth Communications
  - P_{Rec} decreases as $\dfrac{\lambda^2}{R^2}$
- High Resolution Imaging Systems
  - P_{Rec} decreases as $\dfrac{\lambda^4}{R^4}$
- Tx/Rx Challenges:
  - Atmospheric Attenuation
    - ~2.5 dB/km @ 220 GHz
    - +3-30dB/km w/ Fog/Rain
  - High Noise Figure
    - ~10 dB(InP)



Wiltse, 1997 IEEE APS-Symposium,



mm-Wave Comm. requires large power

- Minimum Received Power

$$P_{rec,min} = kTFBQ^2$$

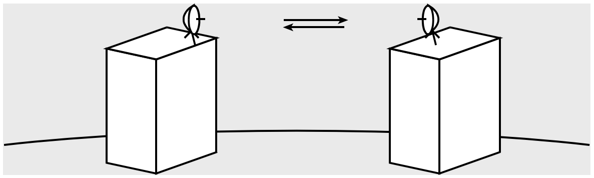
$$P_{rec,min} = -173.8\text{dBm/Hz} + 10\text{dB(NF)} + 90\text{dB(1Gbps)} + 3\text{dB}(Q^2) = -70.8\text{dBm}$$

- Transmission Losses 300m

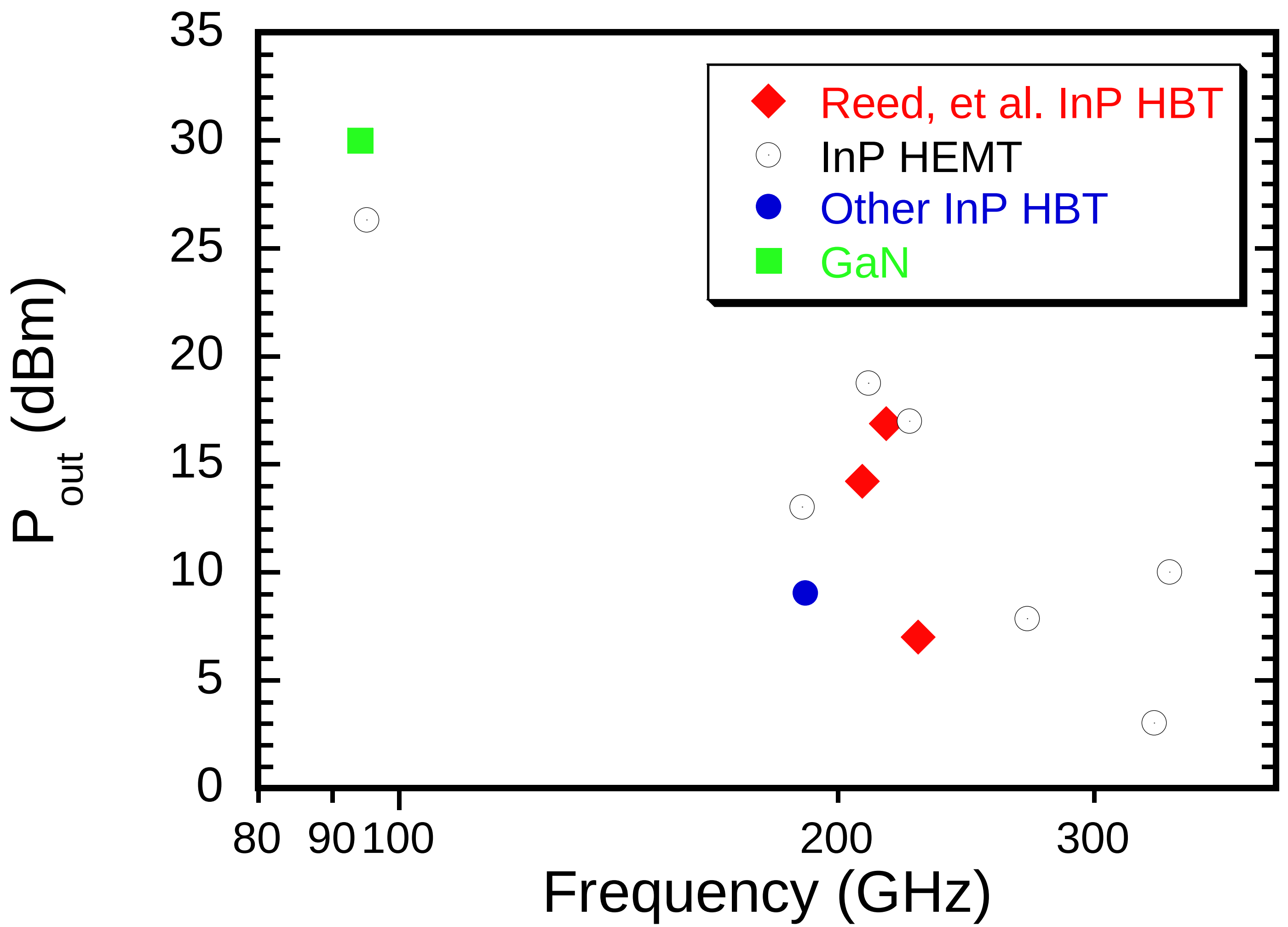
$$\frac{P_{rec}}{P_t} = e^{-\alpha R} G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 = -1\text{dB} + 20\text{dBi} + 20\text{dBi} - 139\text{dB} = -100\text{dB}$$

- Minimum Transmitted Power 29.2 dBm = 0.83 W

$$P_t = 29.2\text{dBm} = 0.83\text{W}$$



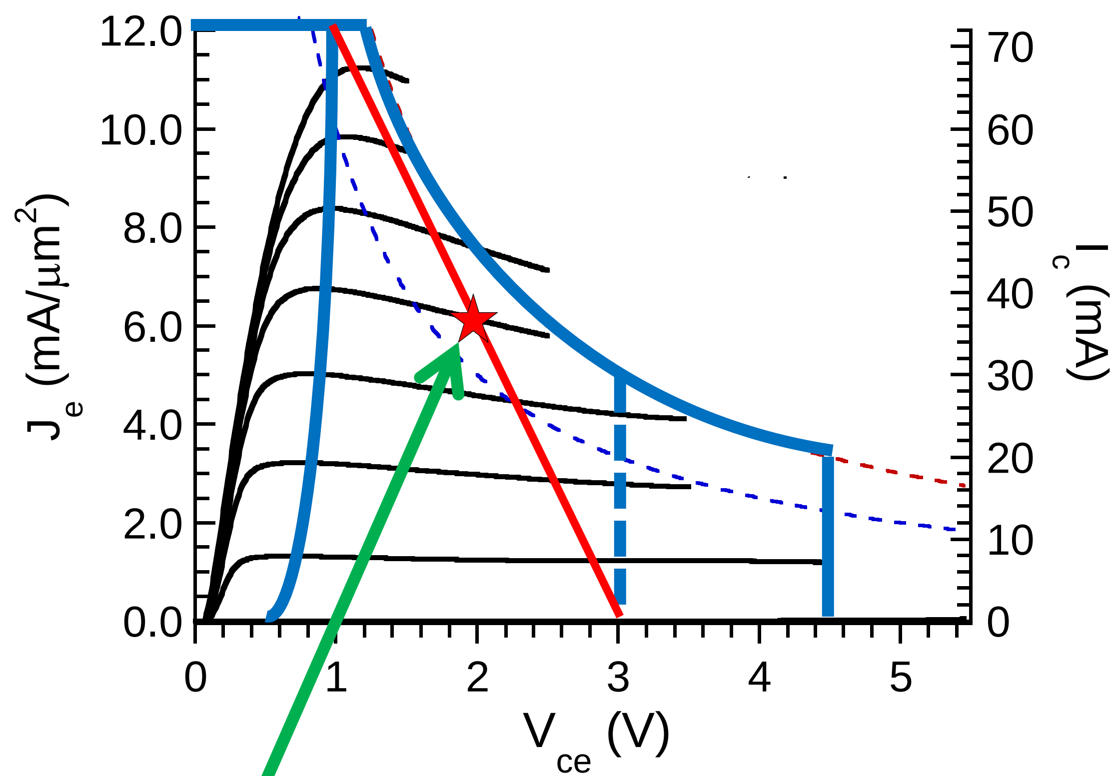
mm-Wave PA Results



250nm InP HBT Process

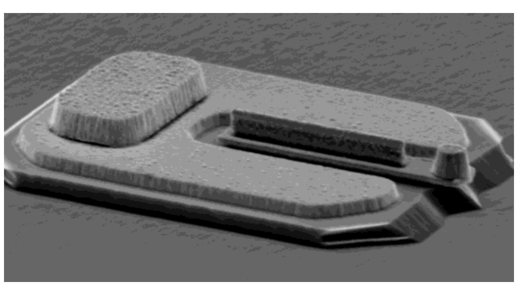
Device High Performance Operating Area

- J_{max} = 12mA/um^2
- $V_{be,on}$ = 0.85V
- VB_{cbo} = 4.5V
- P_{max} = 15mW/um^2
- $V_{ce,hf}$ = 3V
  high bandwidth



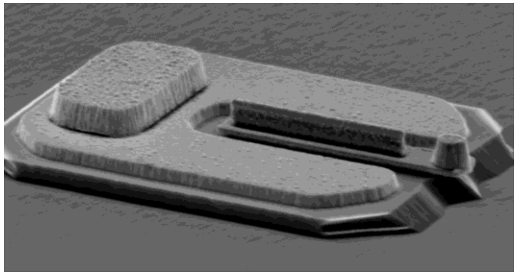
Quiescent Bias Point/
Class A load line

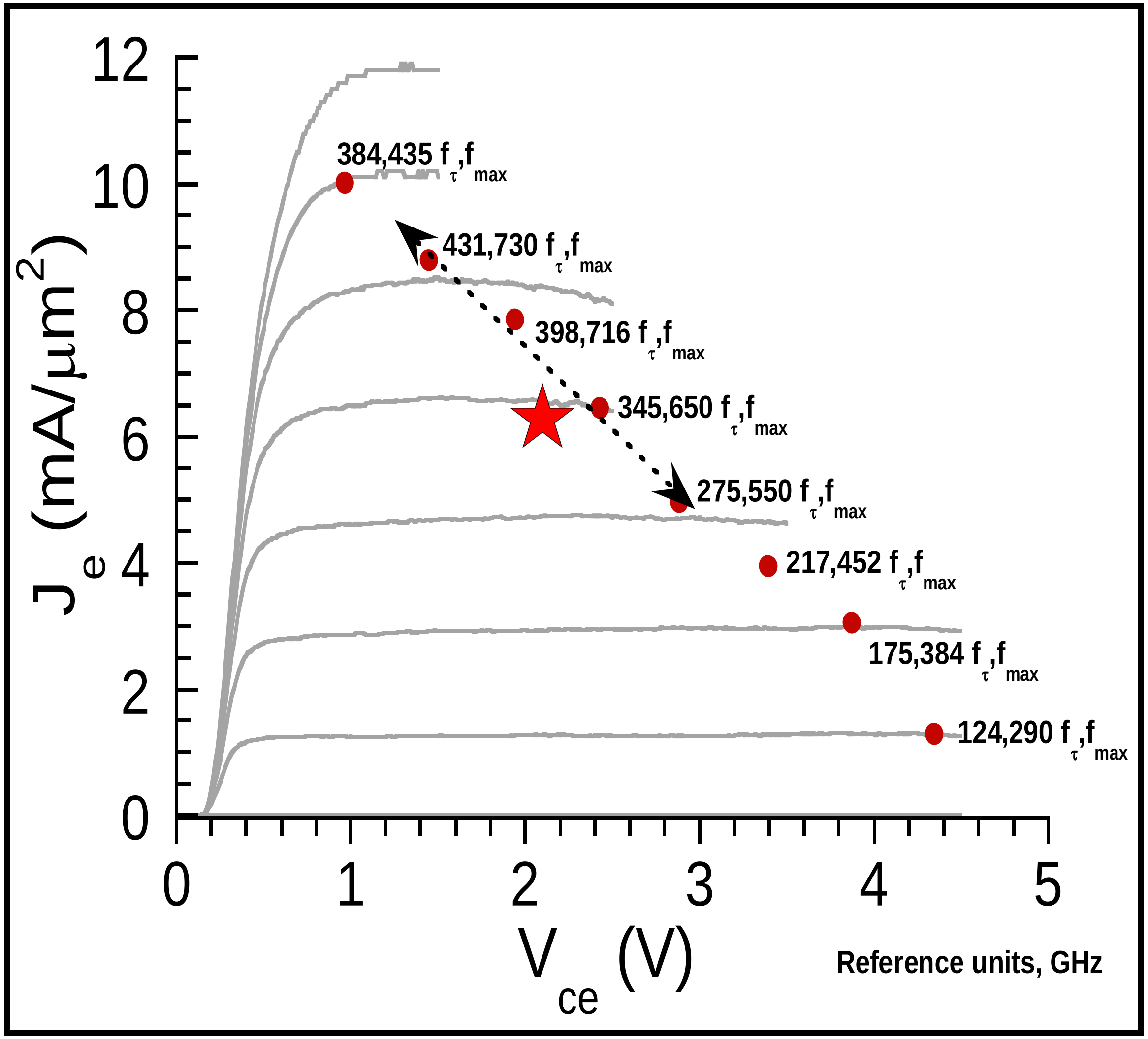
Data courtesy Zach Griffith



f_t,f_{max} varies with DC Bias

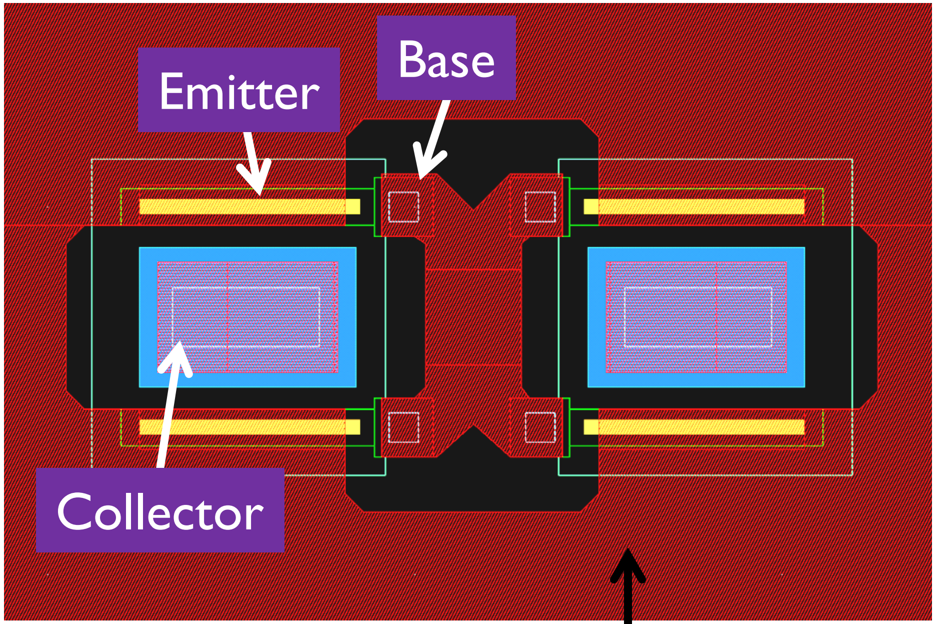
- ft/fmax peak = 400/700 GHz
- ft/fmax ★ = 350/590 GHz
- Highly degraded bandwidth above Vce=3V

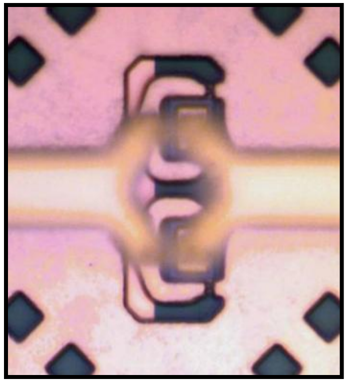




Multi-finger HBT Modeling

- Device Modeling
  - Hole in Ground Plane
  - Multi-finger HBT performance verified
- 4-finger HBT
  - $A_{emitter} = 4x\ 0.25x6\mu m^2$
  - ft/fmax = 333/530GHz
- 1-finger HBT
  - ft/fmax = 350/590GHz



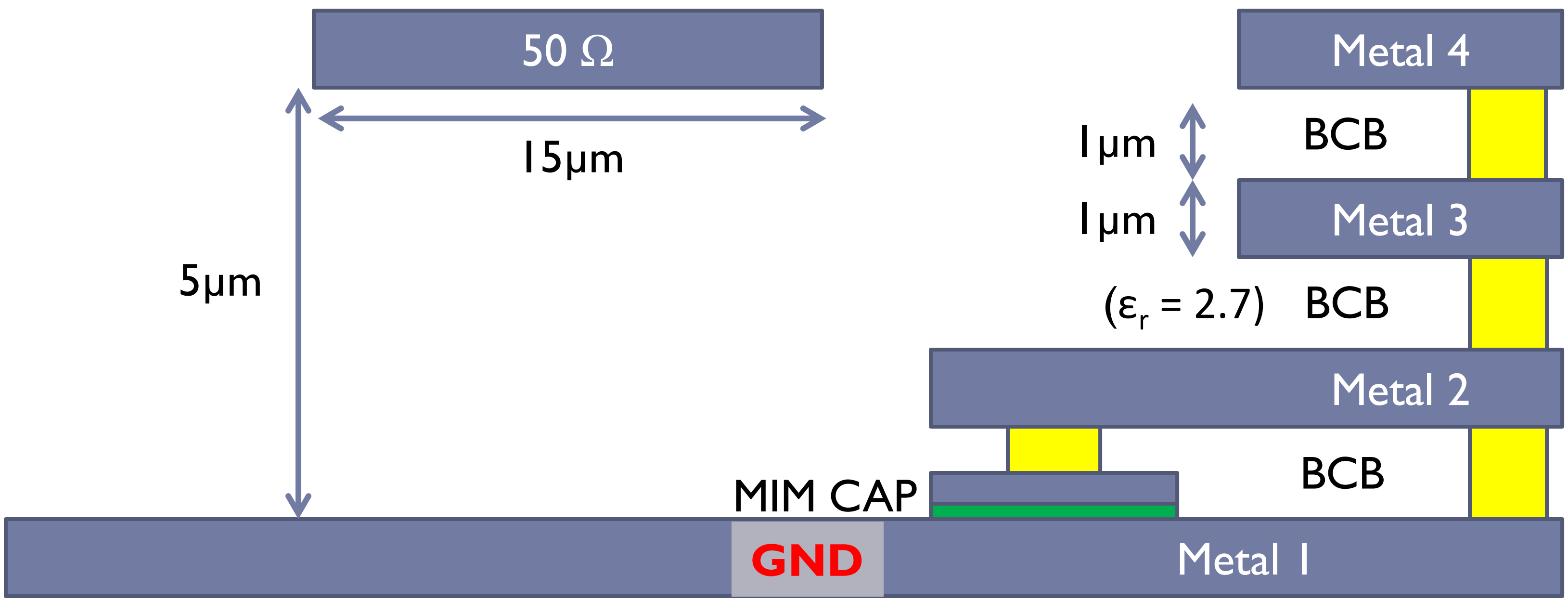


Another 4-finger cell

Non-Inverted Microstrip Wiring

- Local GND
- Wider 50Ω than inv. microstrip
- Must Model Holes in GND plane

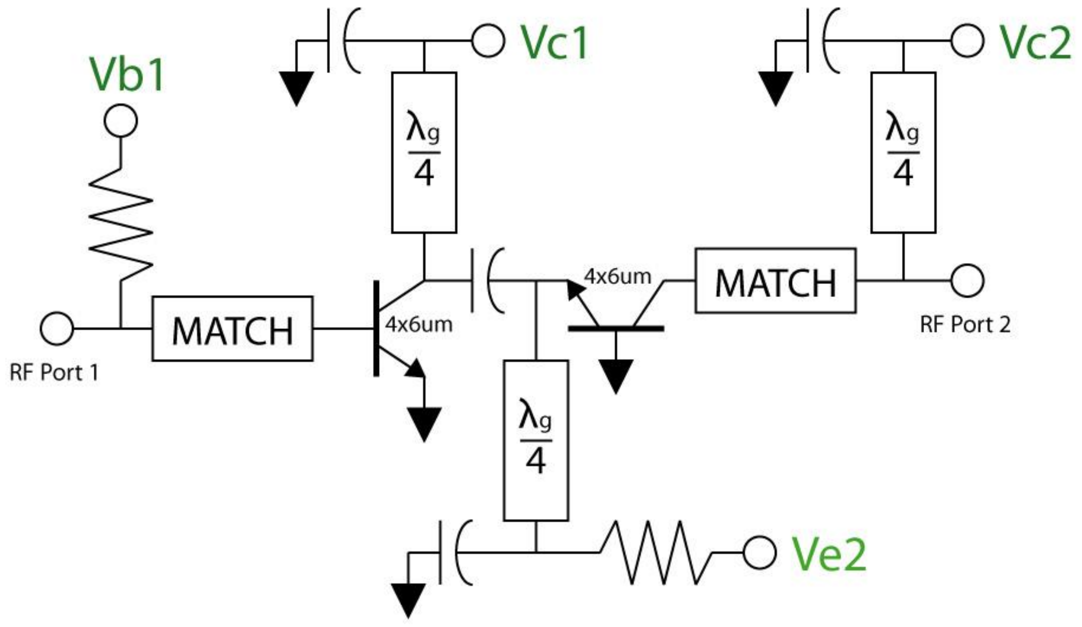
- MIM Capacitors, Thin-Film Resistors

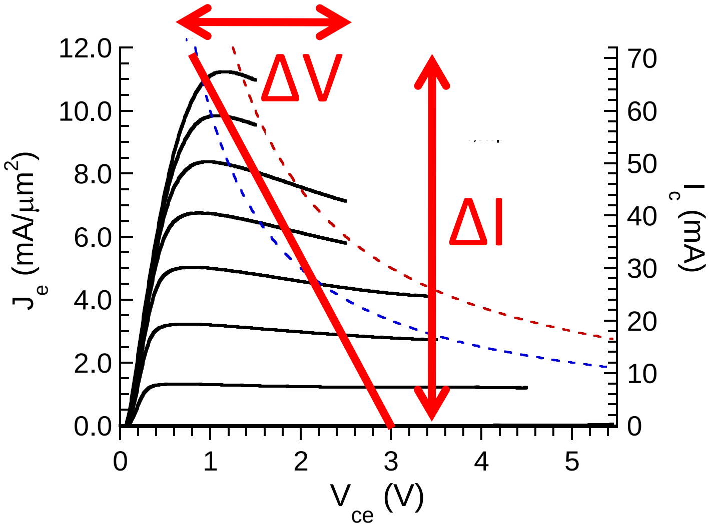


MMIC Power Amplifier Cells & Combiners

MMIC Power Amplifier Cell Design

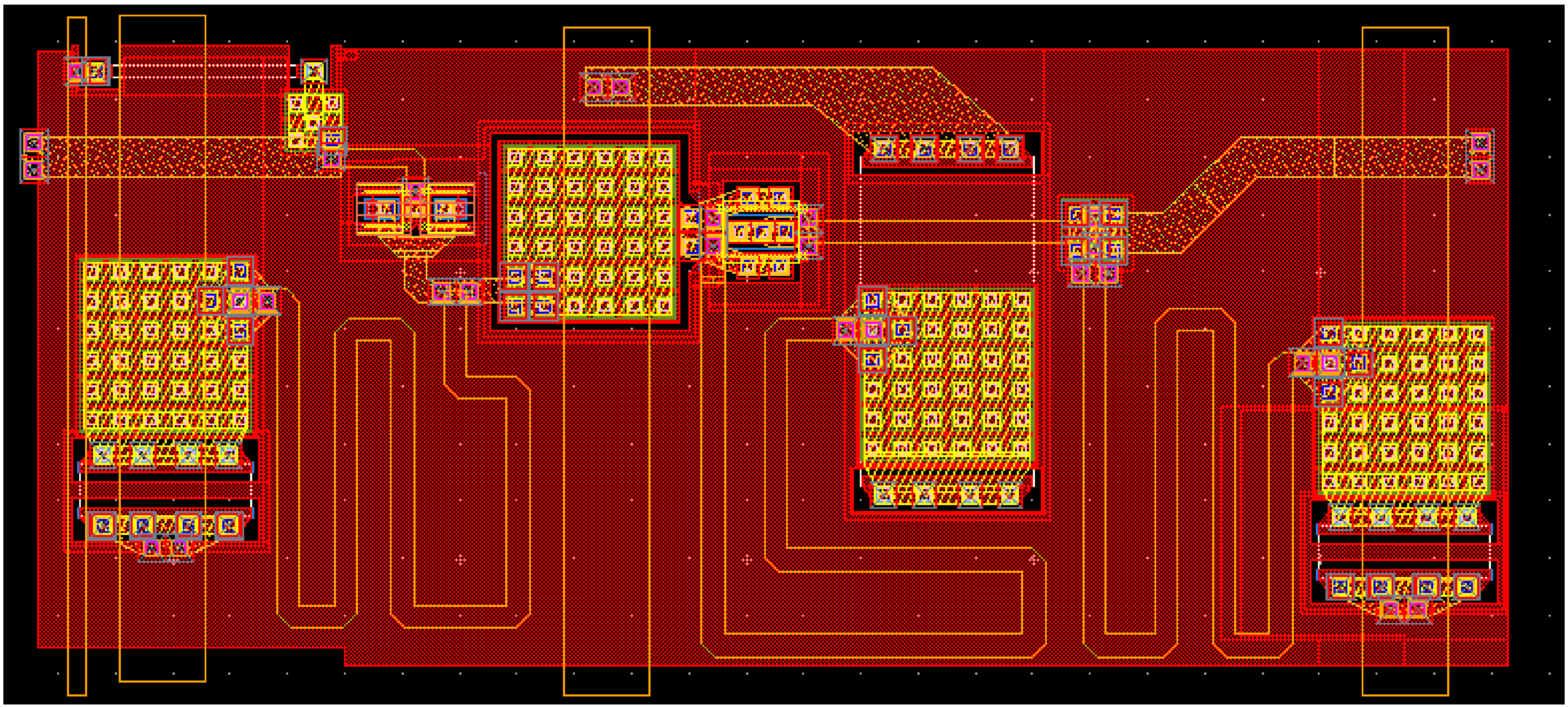
- Cascode Amplifier Topology
    - Gain, Input/Output Isolation,
    - Interconnects: ADS Momentum



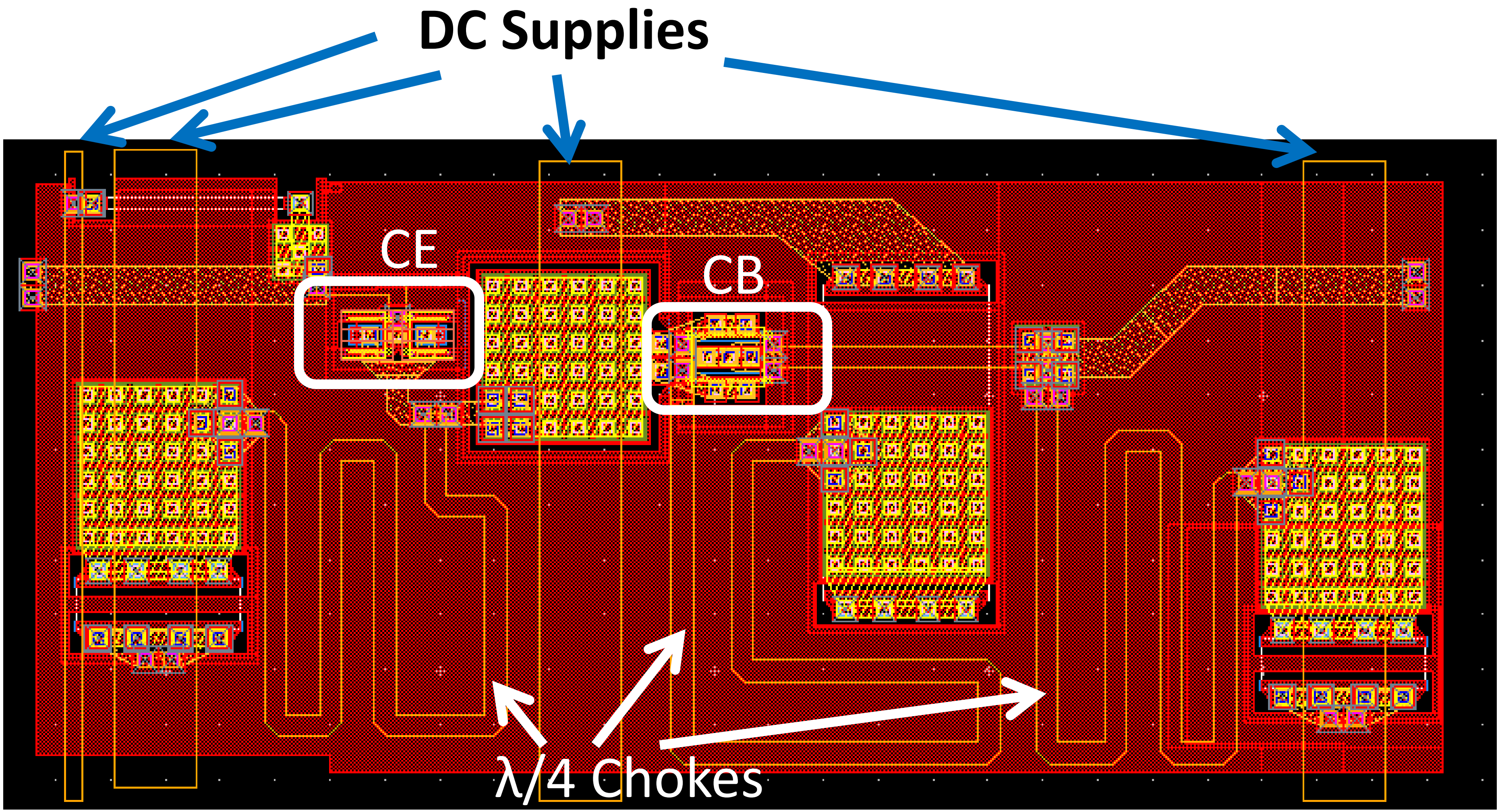


$$\frac{\Delta V}{\Delta I} = \frac{2V}{18mA} = 111\Omega/\text{finger}$$

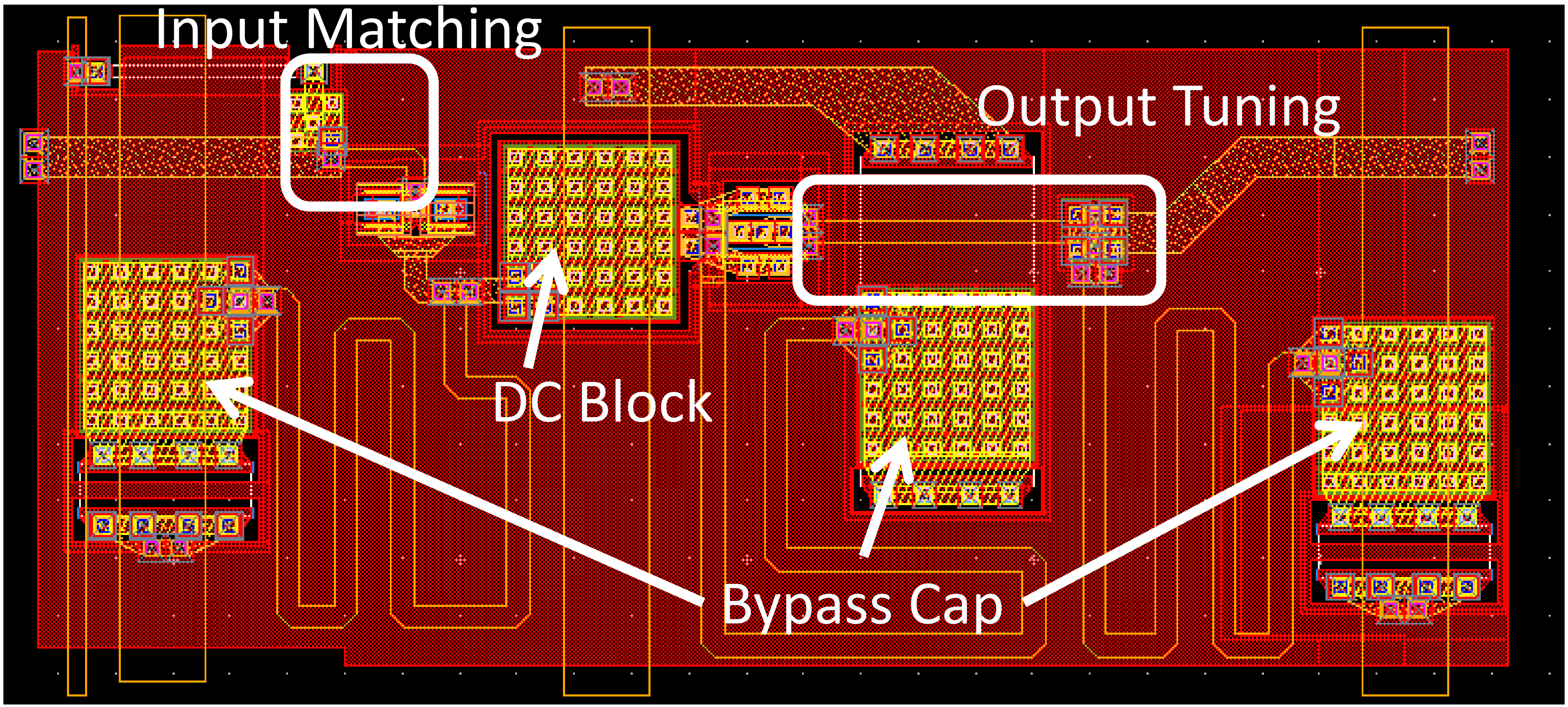
A 4-finger Amplifier Cell



A 4-finger Amplifier Cell

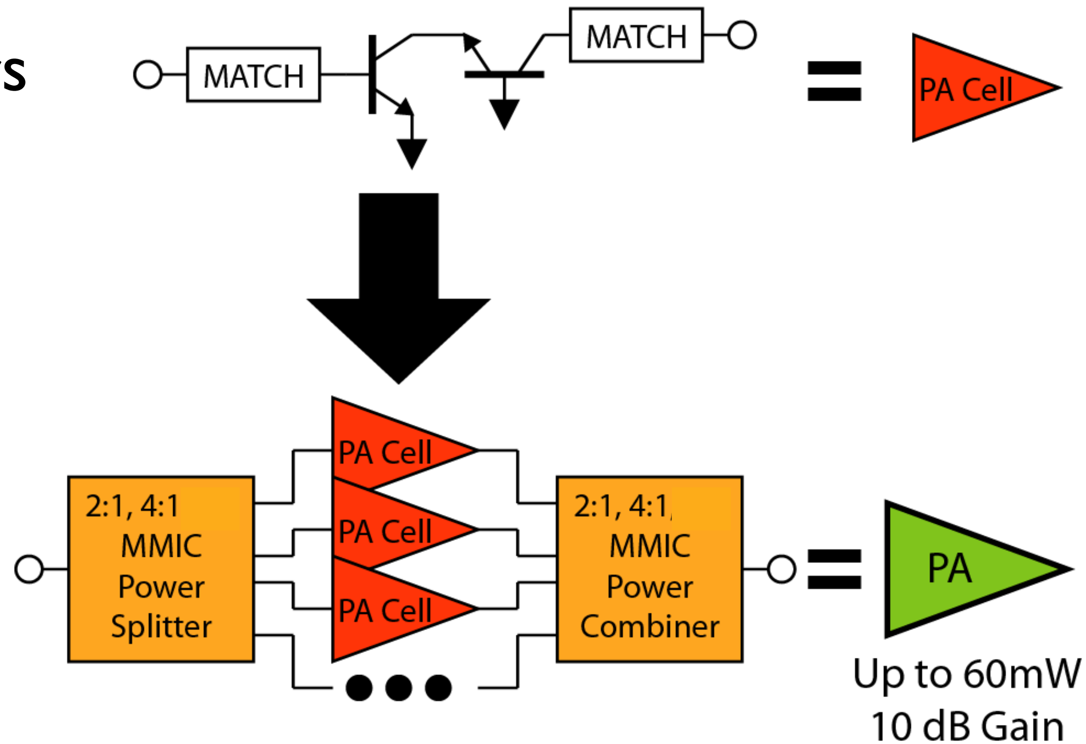


A 4-finger Amplifier Cell

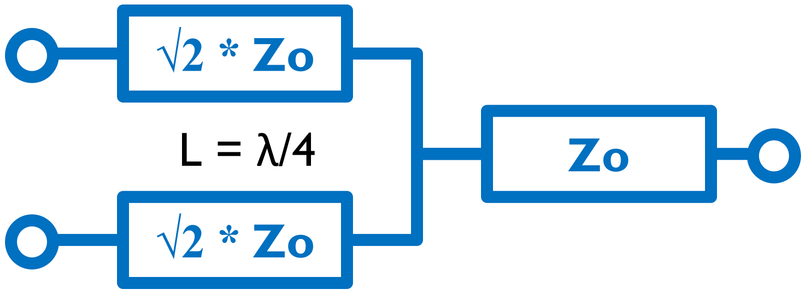


Combining for High MMIC Power

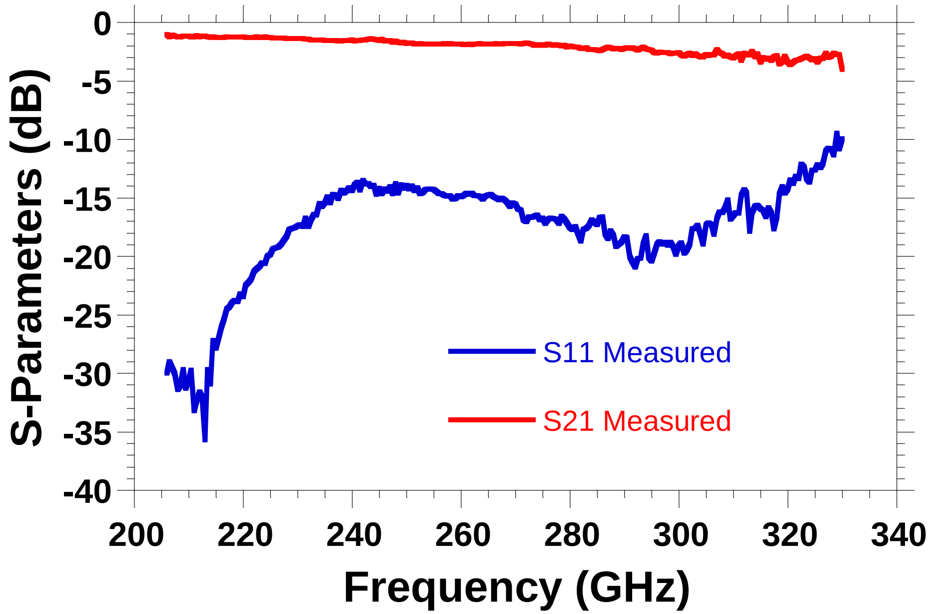
- Combine 4:1 and 2:1 for larger total power
- Limits to combiners
  - Large IL at L ≥ $\lambda_g/4$

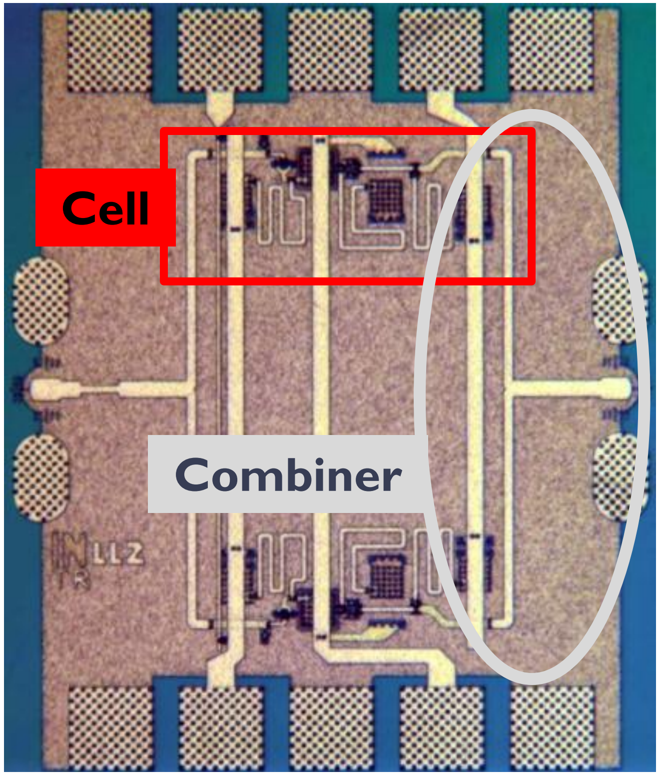


2:1 Power Combiner



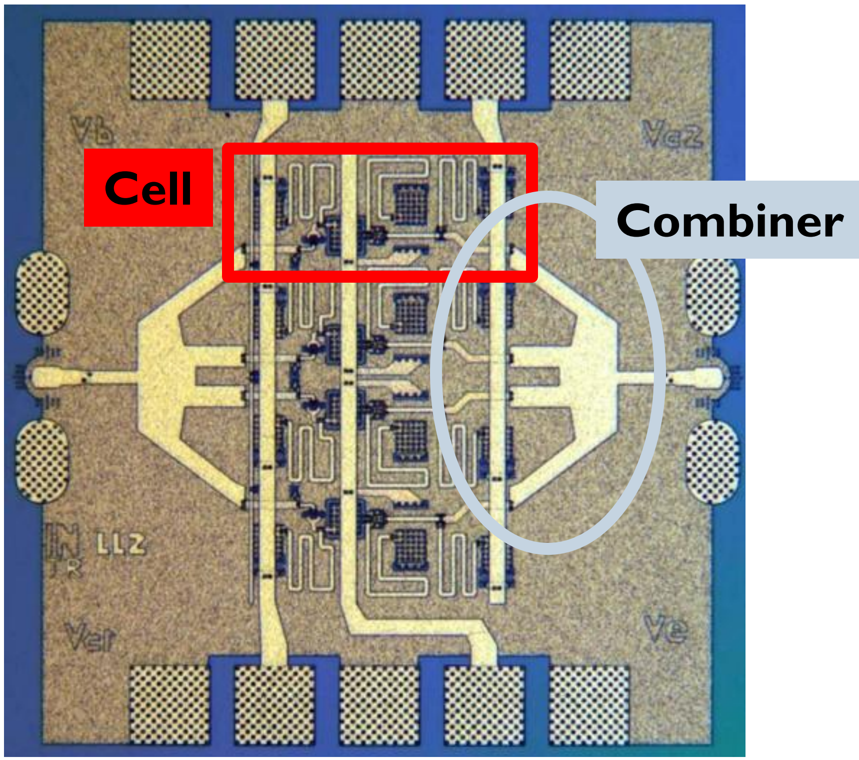
Measured 1.25dB insertion loss for Back-to-back Combiners





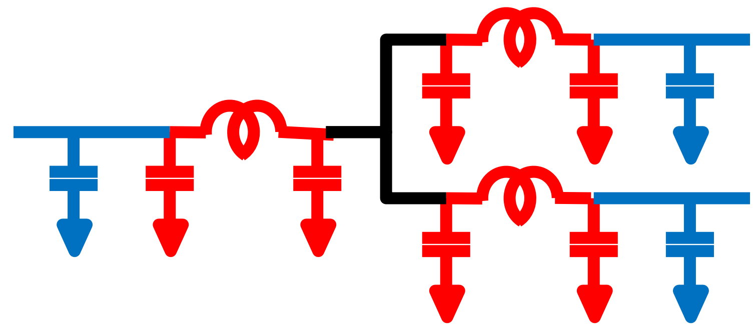
2-Cell Power Amplifier with 2:1 power combining. The die is 0.7x0.58 mm^2.

4:1 Power Combiner

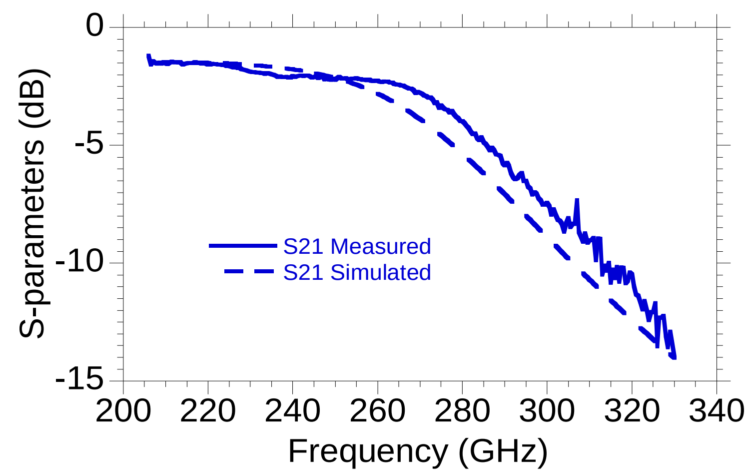


4-cell InP HBT amplifier with 4-1 power combiners. The die is 0.7x0.65 mm^2.

- Reduced to Lumped L/C for design



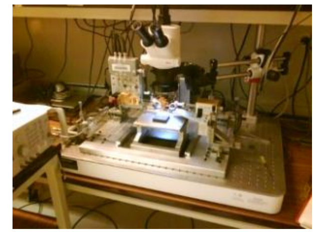
Measured 1.3 dB Insertion Loss for Back-to-back 4:1 power Combiners.

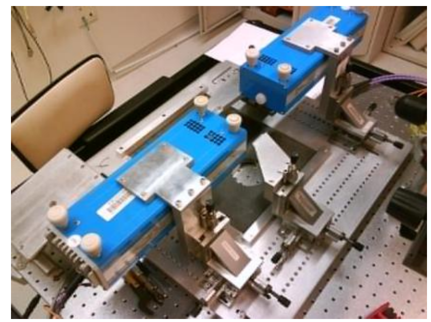


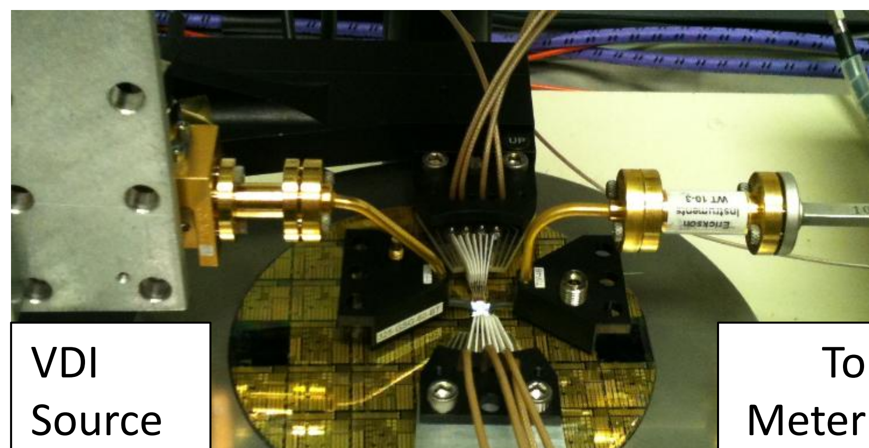
48.8 mW 4-finger Power Amplifiers

MMIC Measurements and Data

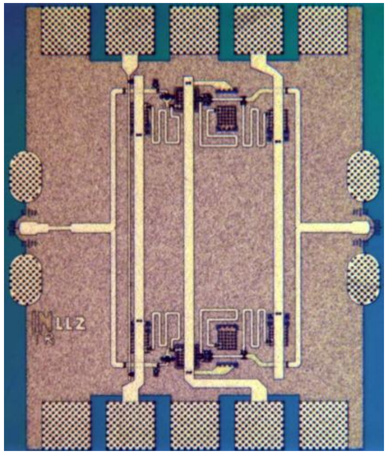
- Small Signal Measurement
  - VNA with 206-340 GHz frequency extender heads
  - SOLT calibration for circuits
- Power Sweep Measurement
  - 200 & 220 GHz frequency multiplier chains and sub-mm wave power meter
  - Insertion Loss Calibration

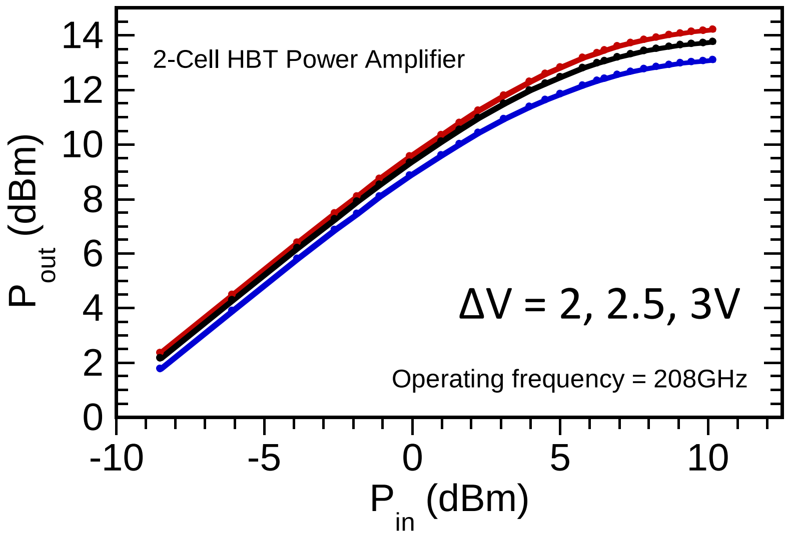




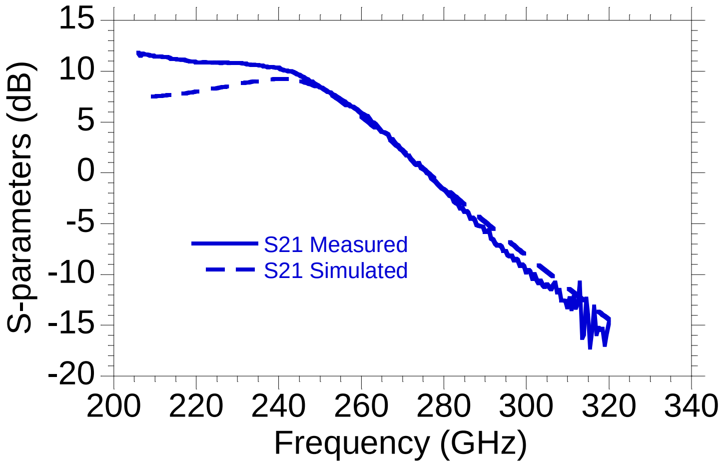


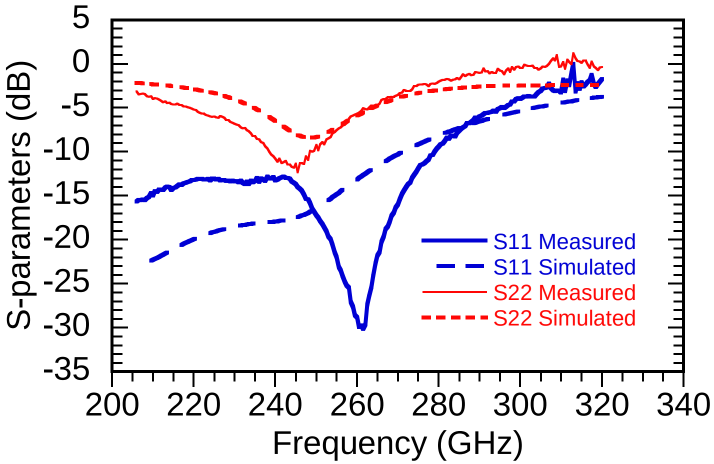
2-Cell PA Results



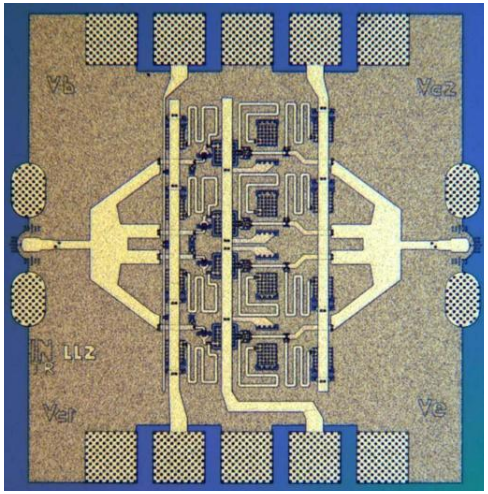


S_{21}=10.9 dB @ 220GHz
$P_{out,max}$=26.3mW @ 208GHz

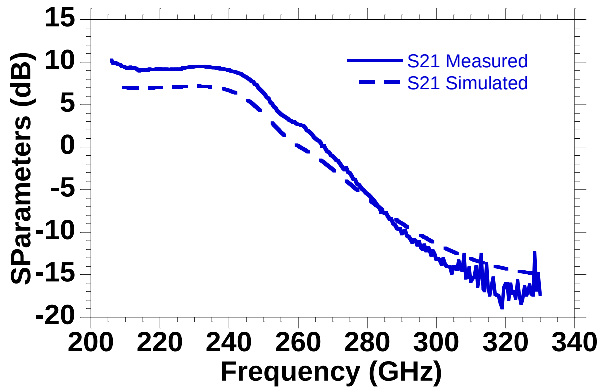


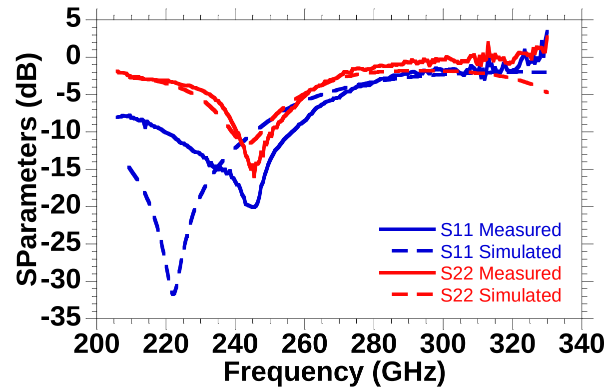


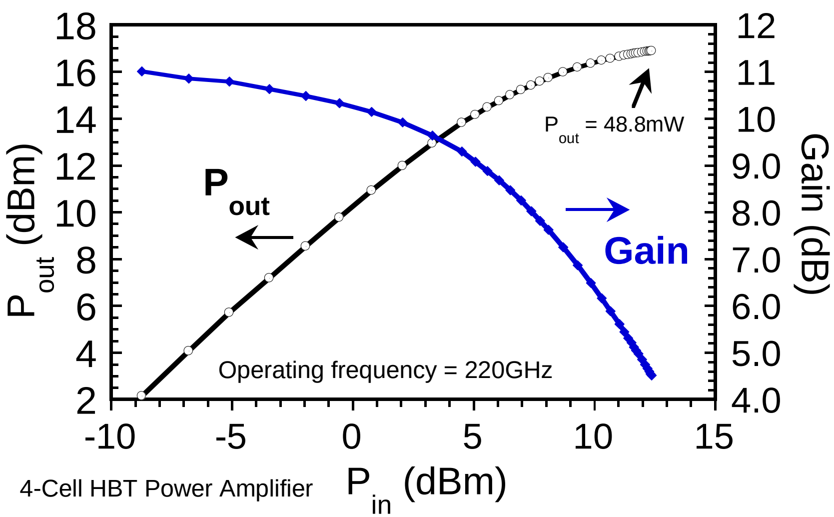
4-Cell PA Results

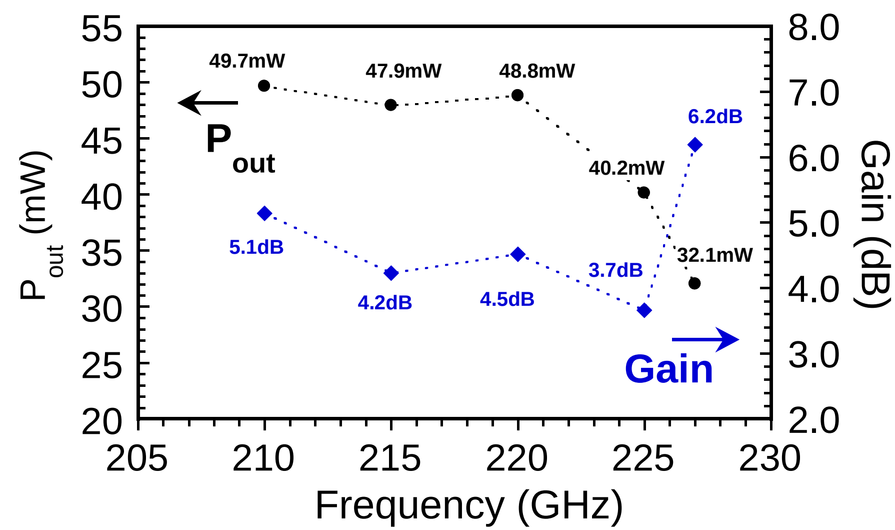


S_{21} = 10.1 dB @ 220 GHz
P_{out} ≈ 48mW @ 210-220GHz





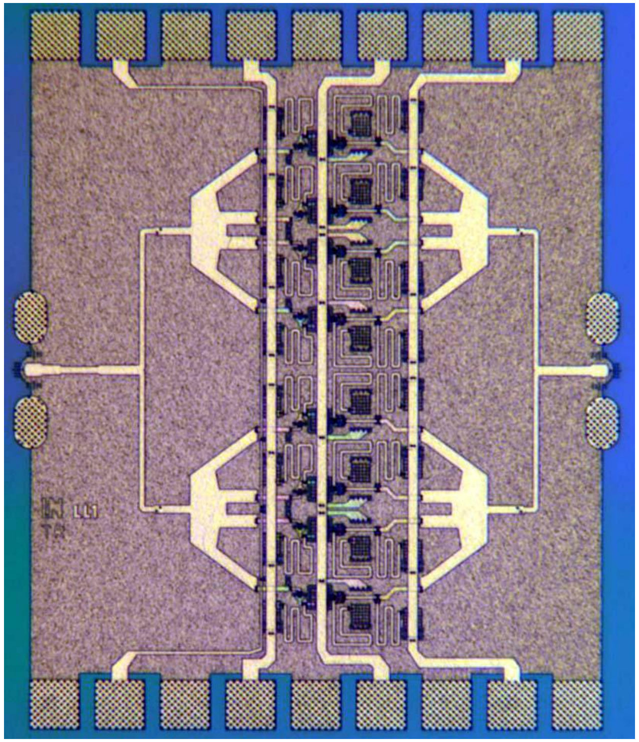


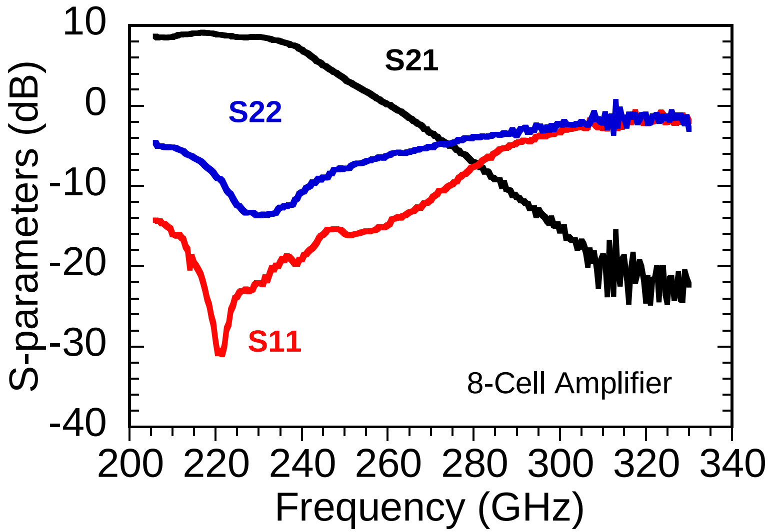


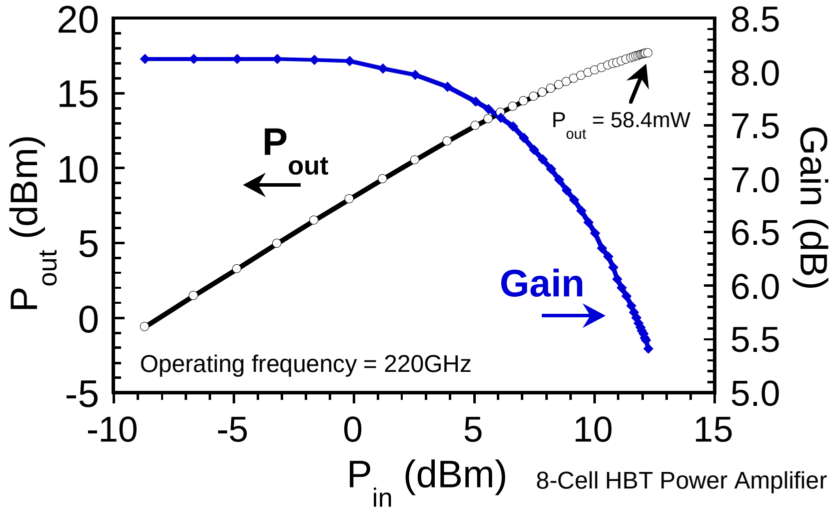
8-Cell Power Amplifiers

P_{out} = 66.1mW @ 215 GHz
$S_{21,max}$ = 9.1dB @ 217 GHz
3dB Bandwidth 206-242GHz

Measured P_{out} limited by 220GHz source power







Linear Power Density

$$P_{out,amp} = 48.8\text{mW}$$

$$P_{out,cell} = \frac{P_{out,amp}}{4\text{cells}} = 12.2\text{mW}$$

$$P_{out,finger} = \frac{P_{out,cell}}{4\text{fingers}} = 3.05\text{mW}$$

$$\text{Linear Power Density} = \frac{P_{out,finger}}{6\mu\text{m}} = 0.51\frac{\text{W}}{\text{mm}}$$

- InP HBT process is a competitive high power-density technology.

Recapitulation

- Modular amplifier cells have been designed to have high gain and high output power.
- 4-cell amplifiers show 48.8 mW saturated output power at 220 GHz using InP HBTs.
- 8-cell amplifiers show 58 mW output power at 220 GHz but measurements were limited by source power.

THANK YOU!

- CSICS Technical Committee
- Zach Griffith, Mark Rodwell, and Mark Field
- UCSB Rodwell Group Members
- DARPA MTO HiFive Program

Questions?

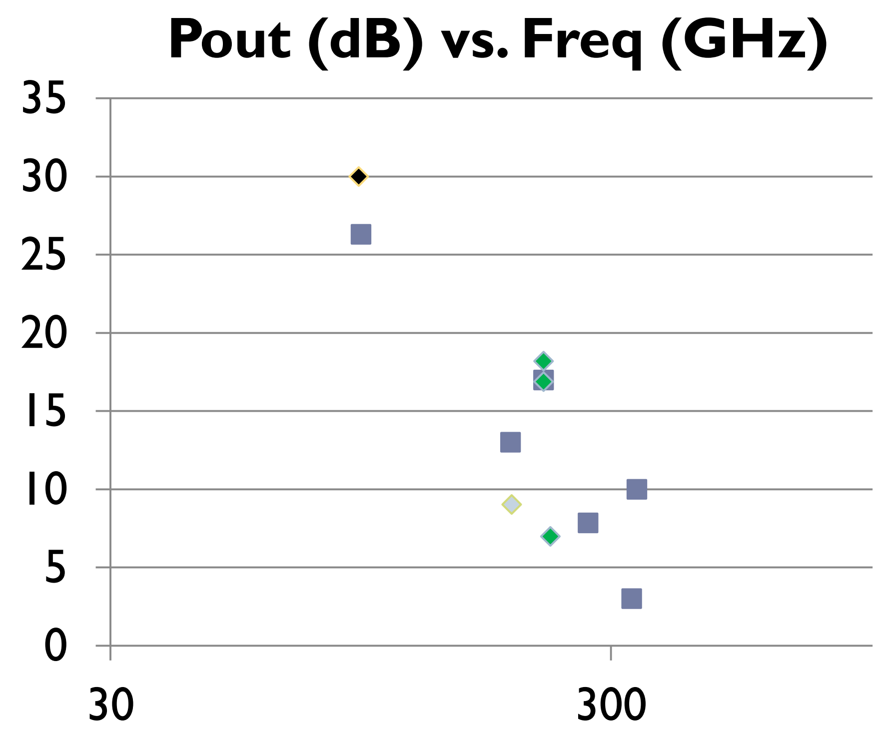
Bonus Slides

mm-Wave Power Amplifiers

Current Power Amplifier Results

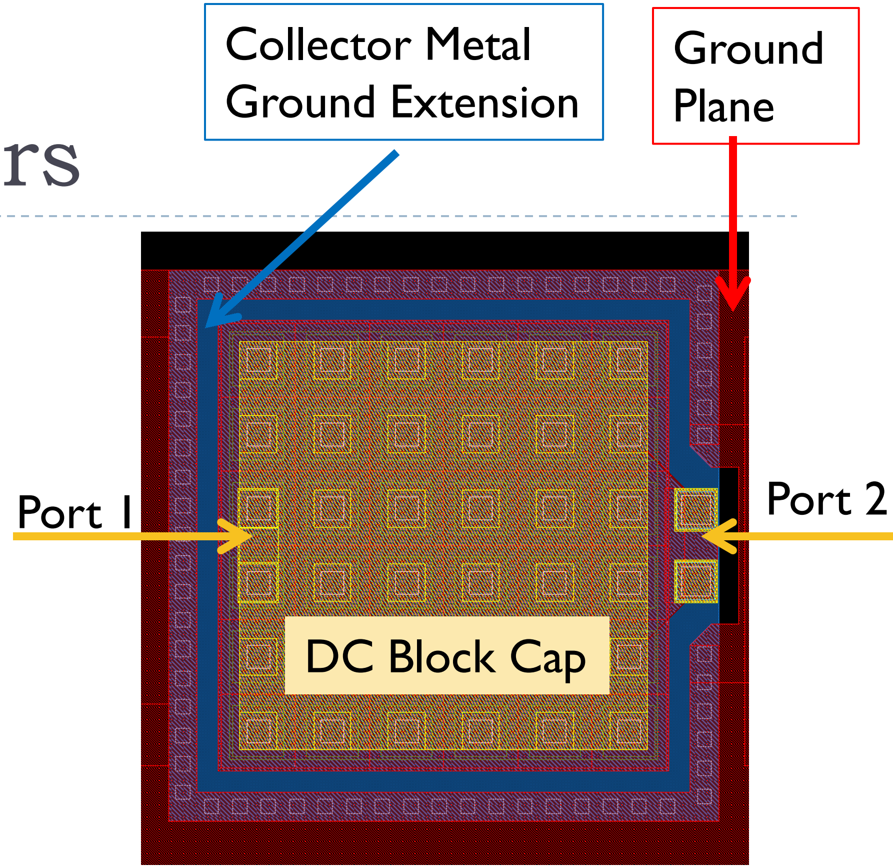
Key
Black – GaN
Red – InP HEMT
Green – My InP HBT Results
Yellow – Other InP HBT Results

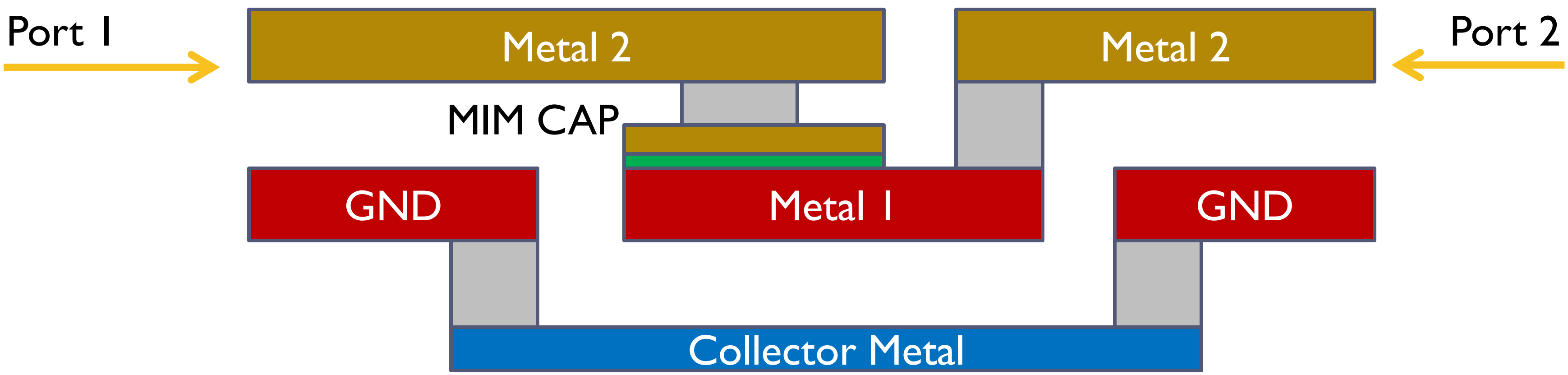
Fab	Author	Paper	Journal/Conference
Raytheon	Brown, A.	W-band GaN amplifier MMICs	IMS 2011
UCSB	Reed, T.	66.1 mW InP HBT Power Amplifier	* Not Published Yet
UCSB	Reed, T.	48.8 mW Multi-cell InP HBT Amplifier with on-wafer power combining at 220 GHz	CSICS 2011
NGST	Radisic, V.	A 50mW 220GHZ Power Amplifier Module	IMS 2010
NGST	Huang, P.P.	A 20mW G-band monolithic driver amplifier using 0.07-um InP HEMT	IEEE MTT-S 2006
UCSB	Paidi	G-band (140-220GHz) and W-band (75-110GHz) InP DHBT medium power amplifiers	IEEE Trans. Microwave Theory Tech Feb 2005
NGST	Deal, W.R.	Development of Sub-Millimeter-Wave Power Amplifiers	IEEE Trans. Microwave Theory Tech Dec 2007
NGST	Chen, Y.C.	A 95-GHz InP HEMT MMIC amplifier with 427-mW power output	IEEE Microwave and Guided Wave Letters Nov 1998
UCSB	Reed, T.	3.0 mW Common Base Power Amplifier with 3 dB Small Signal Gain at 221 GHz in InP DHBT Technology	Lester Eastman Conference 2010
NGST	Mei, X.B.	Sub-50nm InGaAs/InAlAs/InP HEMT for sub-millimeter wave power amplifier applications	IPRM 2010
NGST	Deal, W.R.	A balanced sub-millimeter wave power amplifier	IMS Digest 2008



DC Blocking Capacitors

- Ground Plane hole
  - Large enough to represent a short at 220GHz.
  - Blocking Caps create a hole in the ground plane
    - Inductance (Think Slot Antenna)





System Components at High Frequency

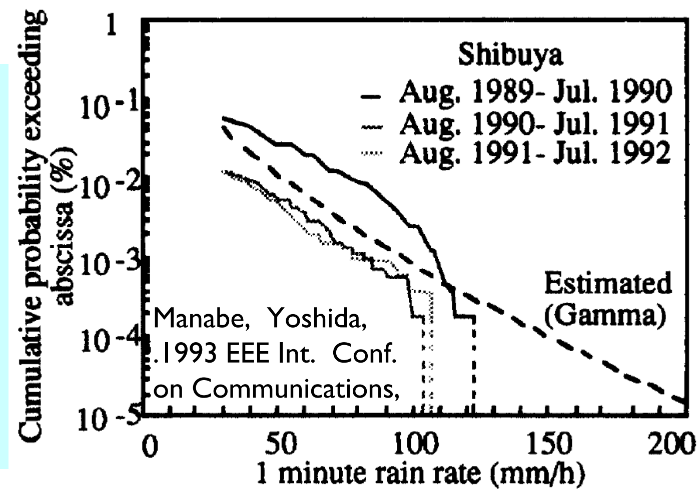
- High Frequency LNAs
  - 94 GHz InP mHEMT: 3dB NF
    - (Mikko Karkkainen, et al. *Coplanar 94 GHz Metamorphic HEMT Low Noise Amplifiers*. CSICS 2006.)
  - 150-215 GHz InP HBT: 5-12dB NF
    - (Samoska, L. *Towards Terahertz MMIC Amplifiers: Present Status and Trends. MTT-S 2006.)*
  - 300 GHz InP HBT LNA: 11.2dB NF
    - (J. Hacker, et al. *THz MMICs based on InP HBT Technology*. IMS 2010.)
  - 670 GHz InP HEMT: 13dB NF
    - (Deal, W.R., et al. *Low Noise Amplification at 0.67 THz Using 30nm InP HEMTs*. Microwave and Wireless Components Letters July 2011.)

Rain, Fog, & Humidy Reduce Range and Reliability

rain 50 mm/hr: 20 dB/km, 30-1000 GHz
150 mm/hr : 50 dB/km, 30-1000 GHz

Clouds, heavy fog:
~(25 dB/km)x(frequency/500 GHz)

90% Humidity: >30 dB/km above 300 GHz
nondominant below 250 GHz (Rosker 2007 IEEE IMS)



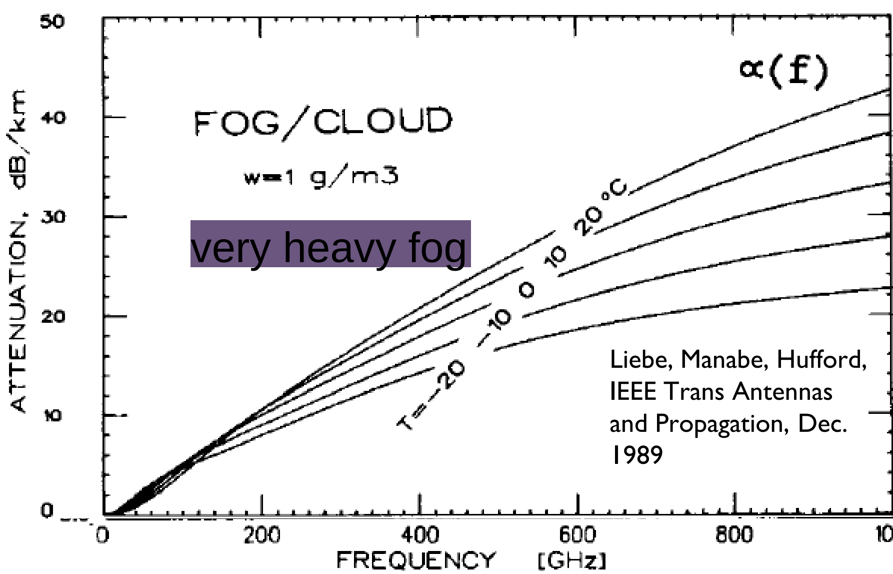
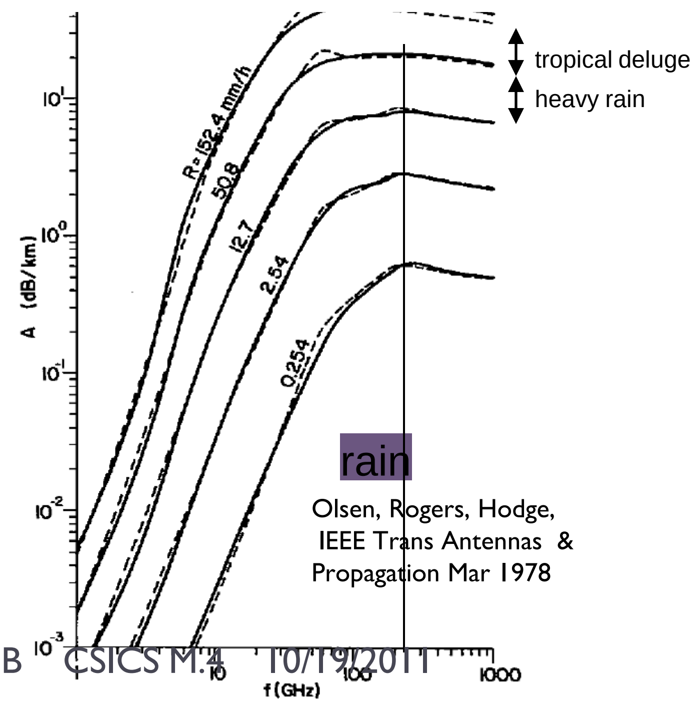
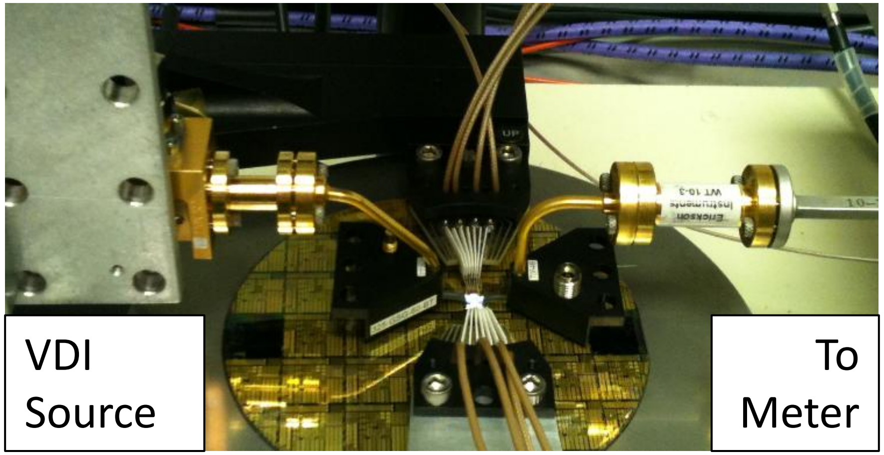


Fig. 1. SWD model predictions of attenuation $\alpha(f)$ and delay $\tau(f)$ for frequencies up to 1000 GHz assuming a water content, $w = 1$ g/m^3, and temperatures from -20 to $+20$°C (numerical examples are listed in Table I).



MMIC Measurements and Data

- "Load Pull" Station
  - Power Sweep using VDI 200 GHz and 220GHz Multiplier Chain
  - Calorimeter—Erickson sub-mm wave power meter
- Calibration
  - Insertion Loss calibration with the reference plane at the probe tips
  - Waveguide flange to probe tip insertion loss ~1.7dB



Above Photo Courtesy Zach Griffith