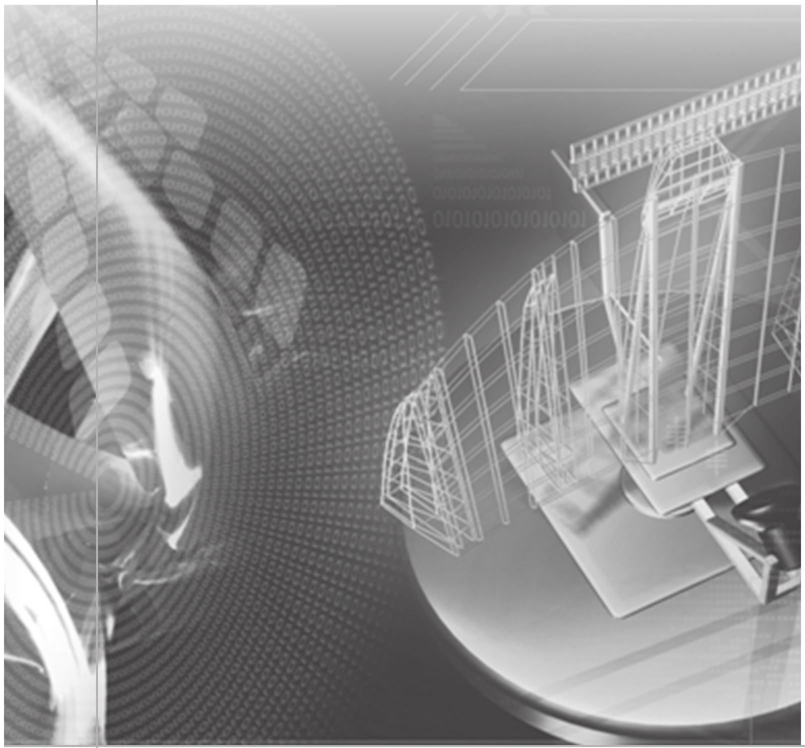


A 180mW InP HBT Power Amplifier MMIC at 214 GHz

Thomas Reed

CSICS 2013
Paper D.2
10/14/2013

InP HBT Power Amplifier MMICs at 220GHz

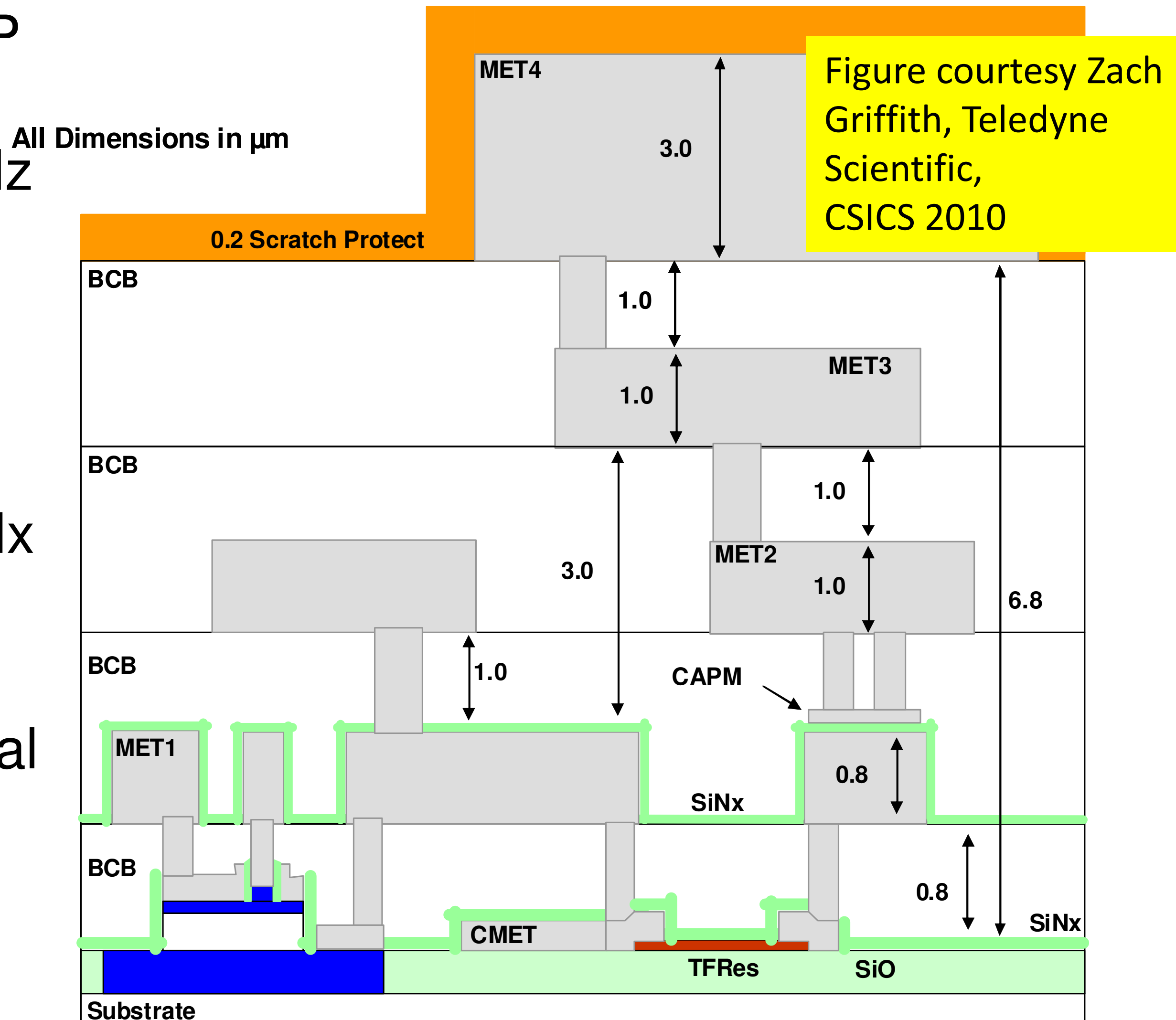
- Abstract: Sub-THz systems designers have shown interest in the 220GHz, low-loss free-space propagation window for future synthetic aperture radars, scanners, and weapons systems. Multi-HBT power amplifier cells were designed to leverage strong RF power densities and high 220GHz available gain in the 250nm InP HBT technology. On-wafer power combiners were designed to double and quadruple output power at each stage of combining. For large output peripheries, multi-stage PAs were developed to drive the final stage fully into compression. A novel design approach is used to increase periphery within a single cell. Using this approach a record single-MMIC Pout of 180mW was demonstrated at 220GHz.

- Co-authors/Collaborators: Dr. Zach Griffith (Teledyne Scientific Co.), Prof. Mark Rodwell (UC Santa Barbara)

220GHz InP HBT PAs demonstrate >100mW

250nm InP HBT Technology Description

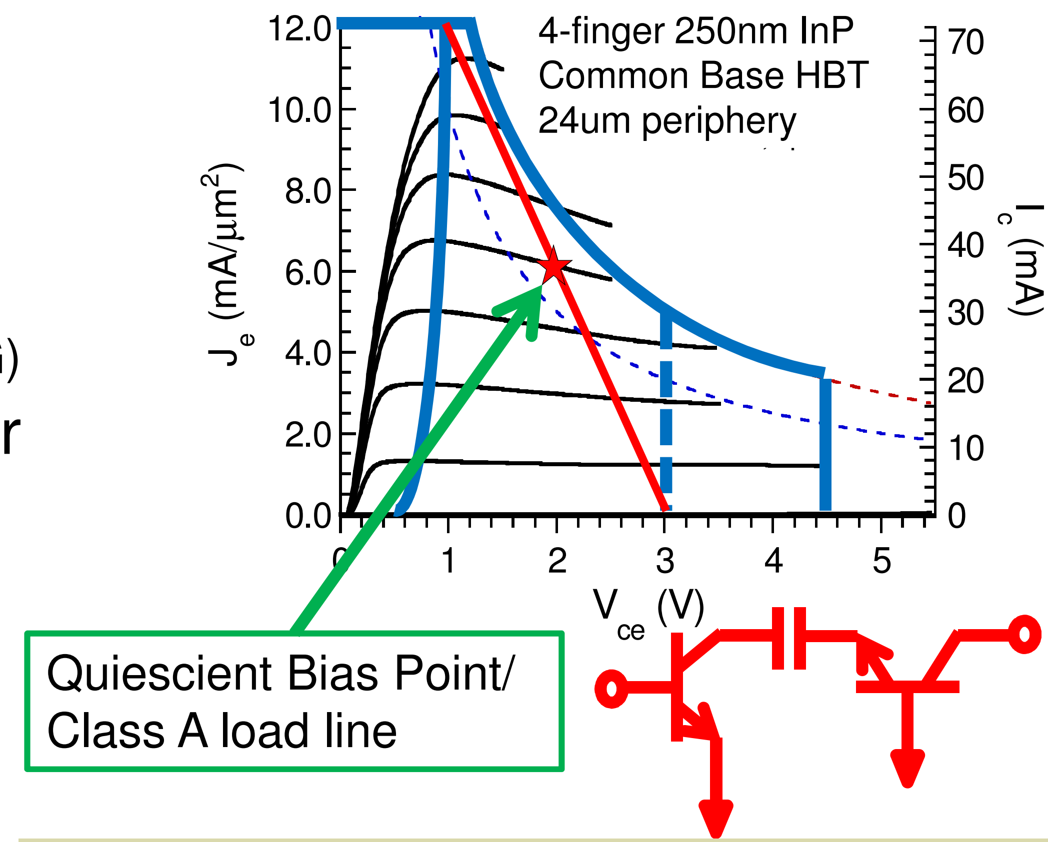
- DHBT InP/InGaAs/InP process with peak fT/fmax = 400/700GHz
- 4-finger HBT (24x0.25μm²) shows f_T/f_{MAX} = 333/533GHz at PA bias point.
- Au interconnects, SiNx MIM Caps, NiCr Thin Film Resistor
- Microstrip MET1 signal and MET4 ground



HBTs with 220GHz gain & versatile interconnects

PA Cell Topology

- Load line shown for 4x6um HBT.
  - J_{max} = 12mA/um^2
  - $V_{be,on}$ = 0.85V
  - VB_{cbo} = 4.5V
  - P_{max} = 15mW/um^2
  - $V_{ce,hf}$ = 3V (low large-signal MAG)
- Cascode chosen for higher 220 available gain
- AC coupled cascode for CE/CB HBT grounding & higher gain
- Class A LL in high ss gain region

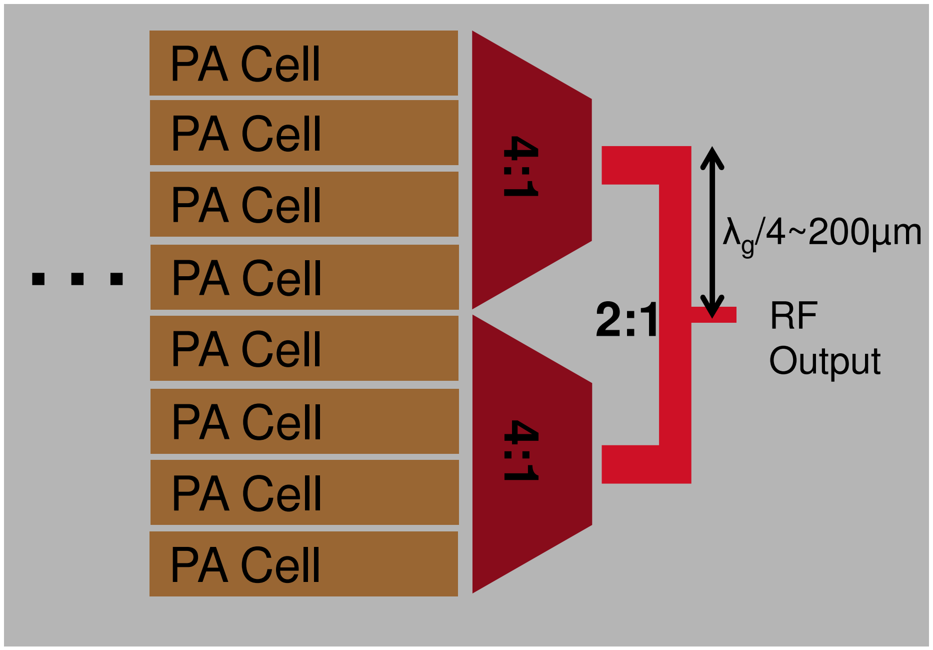


Conversion: Area to Linear current density
10mA/um^2 = 2.5mA/um = 2500mA/mm

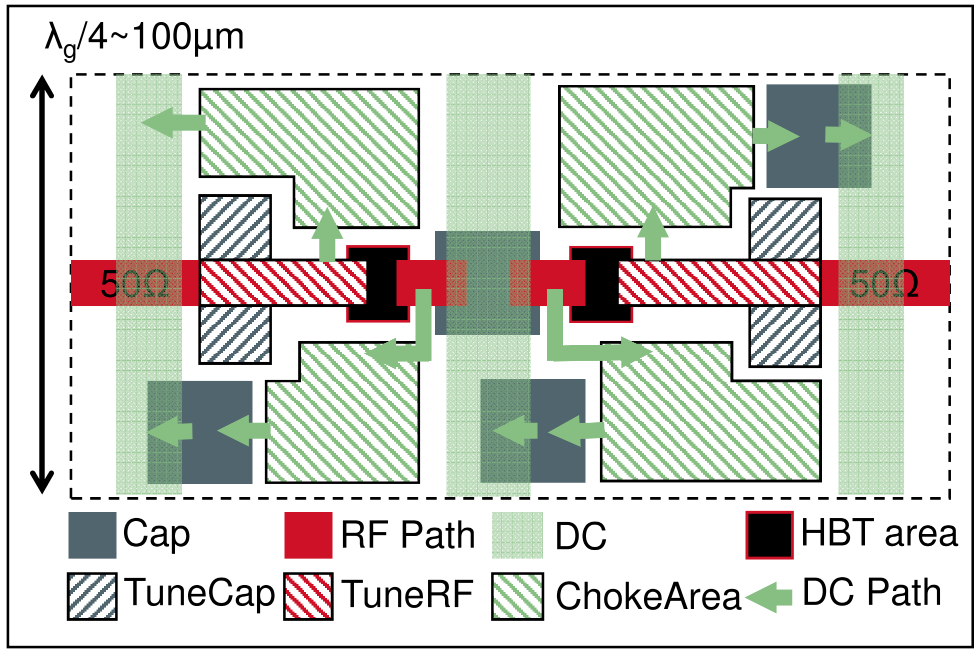
15dB MAG @ 220GHz, 1.125mW/um Loadline

Multi-PA Cell Layout Floorplanning

- To minimize 2:1 combiner size, the PA Cell height was $\lambda_g/8$ ~ 100µm



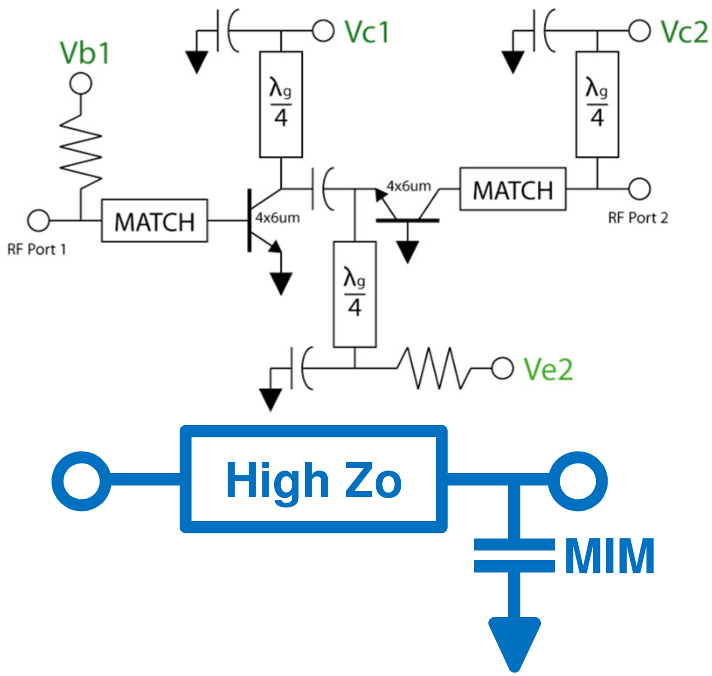
- Given the DC routing needs of the PA Cell, the PA Cell is floorplanned.



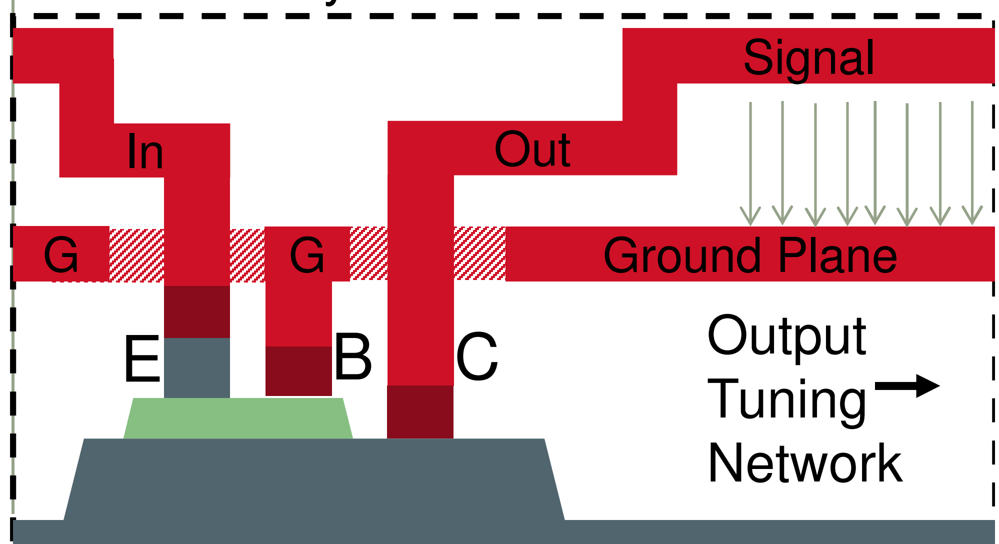
FP adds top-level perspective to PA Cell design

Ideal Circuit Simulation/Component EM

- ADS Circuit Simulation
  - Cap and MLIN models for SiNx, 3 & 5um BCB MSUB
  - DC, S-parameters, Harmonic Balance (Load Line)



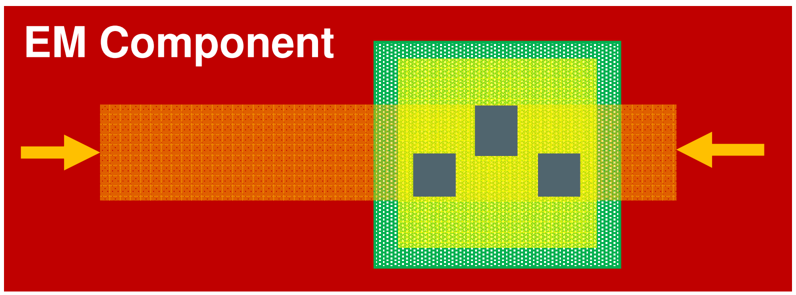
- ADS Momentum
  - Characterize the Environment
    - Range of Zo, R,C possible
    - Identify parasitics in Passives
  - Individual Components
    - Tune Cap, Res, TL, DCChokes
    - Heavy EM sim near HBT area



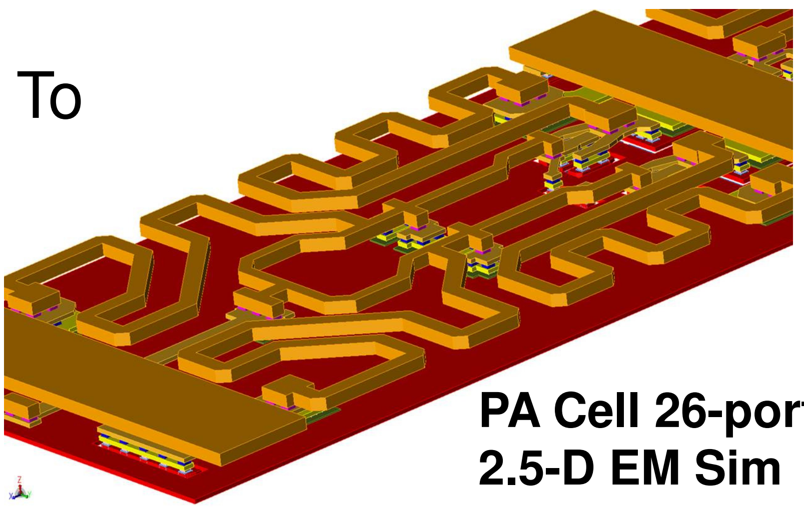
Coarse tune at cell (circuit sim) and component (EM sim)

PA Cell Large Multi-port EM simulation

- From

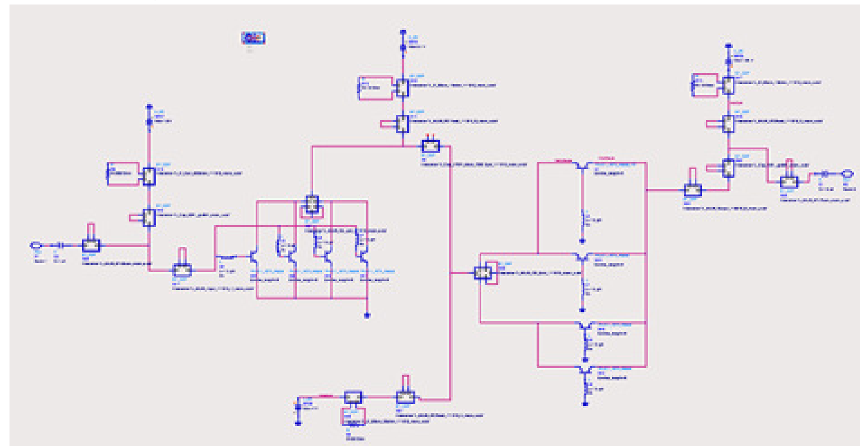


- To

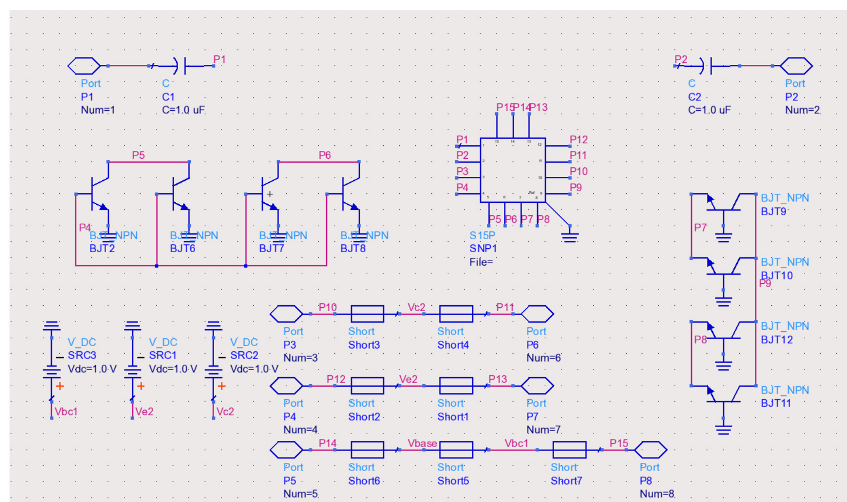


PA Cell 26-port
2.5-D EM Sim

- From

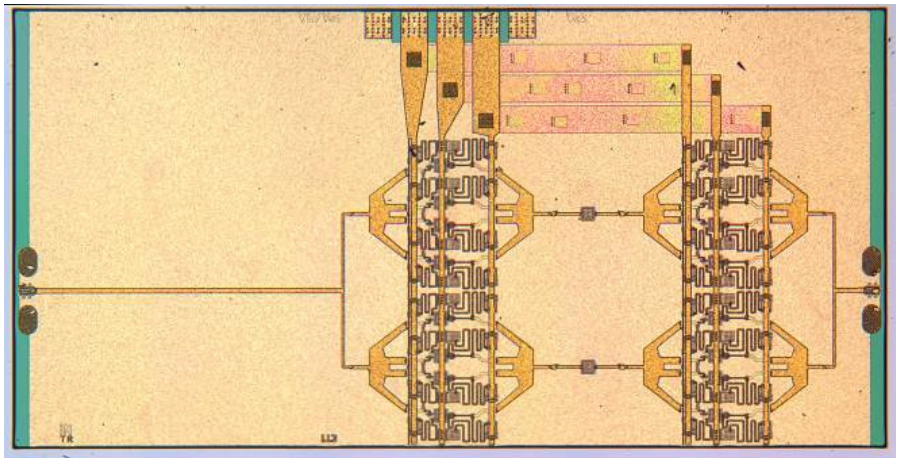


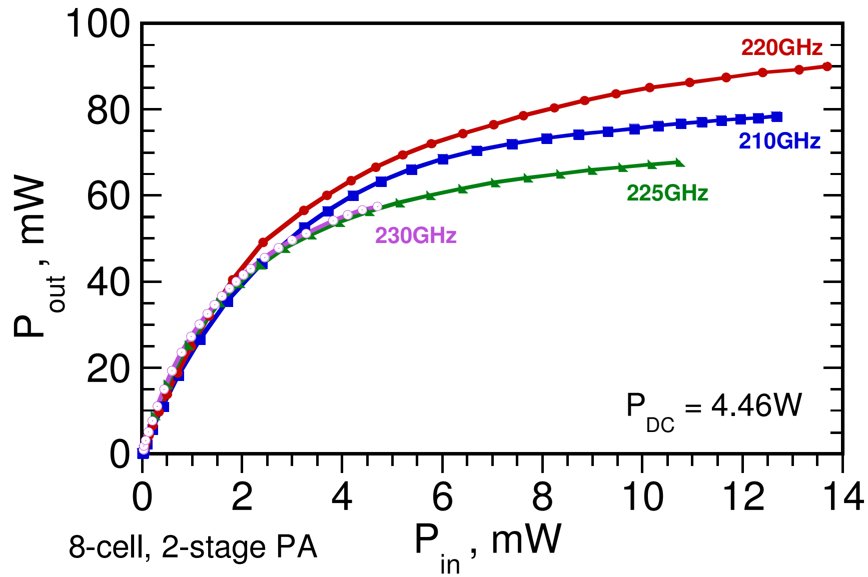
- To

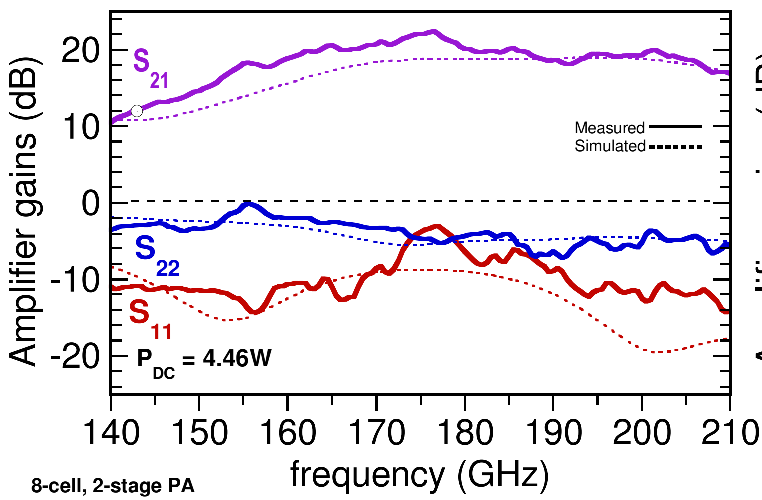


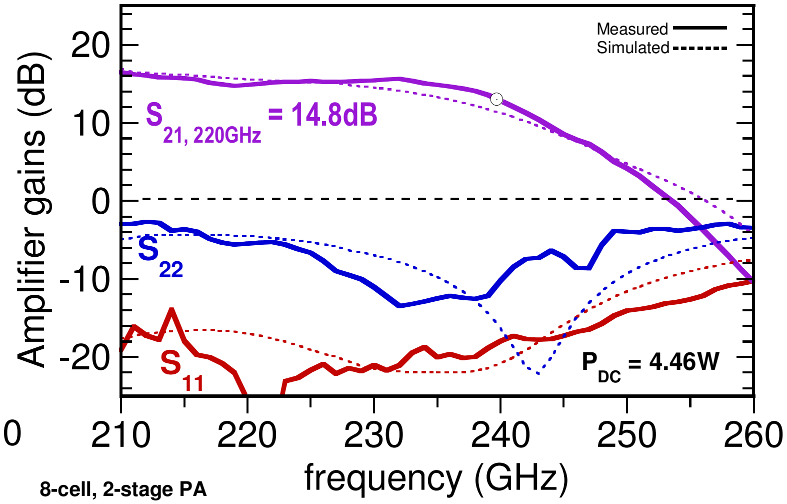
Fine tune at MMIC (Circuit), Network (EM), & Cell (EM)

Past 8-Cell 2-Stage PA Results (CSICS 2012)









8mW Pin -> 80mW Pout

Total MMIC Power

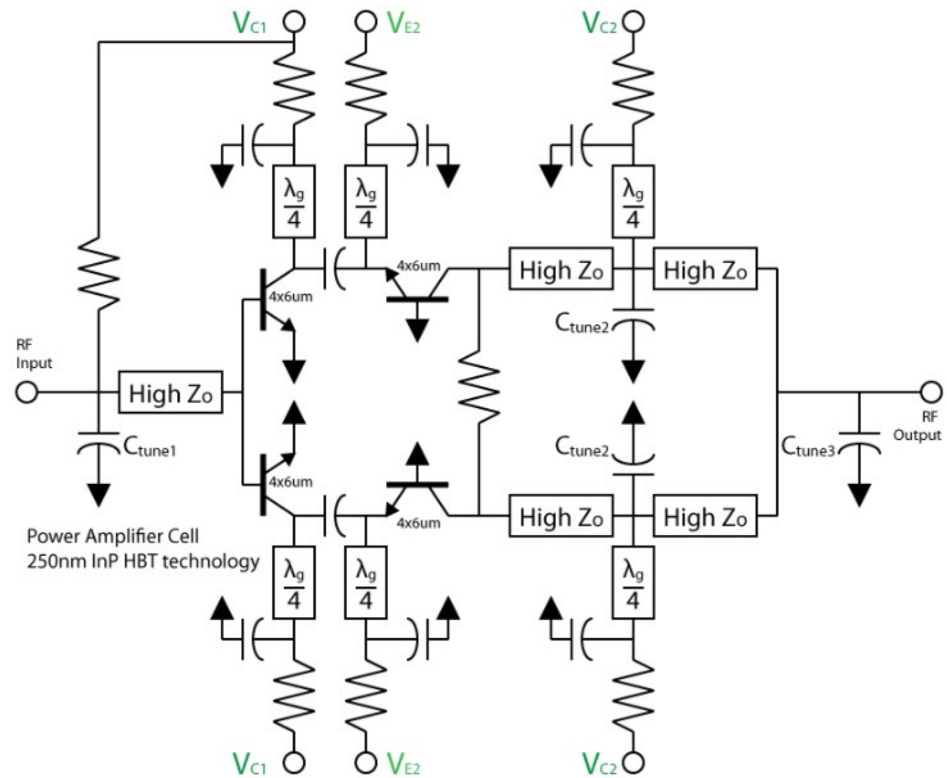
- Depends on
  1. Total HBT periphery (Periphery/PA Cell, Chip Size)
  2. HBT matching network design (Load Power Target)
  3. Losses due to power combining (Limit to Chip Size)

- To increase power
  – Increase HBT periphery per PA Cell (1, but requires a new 2)
  – Combine more PA Cells (1, but requires a new 3)

PA Cell Design Methodology

- Considerations/Lessons:
  1. Longer HBT = low MAG* at 220GHz
  2. Larger multi-finger HBTs = low MAG at 220GHz
  3. Close HBTs under DC bias interact thermally.
  4. 5um of delay is significant
  5. 4-finger HBTs worked when spaced ~100um (CSICS, IMS)

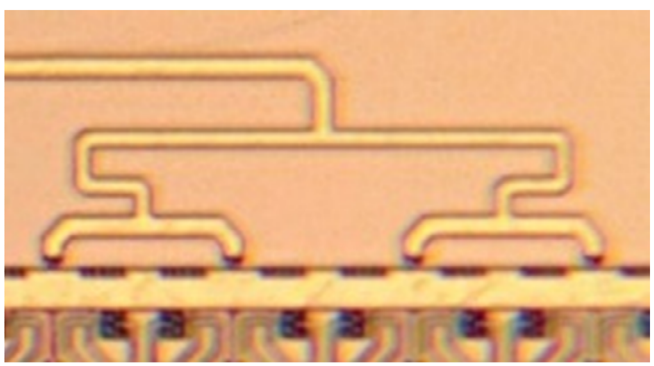
*I'm using the term "MAG" as min(MAG,MSG)

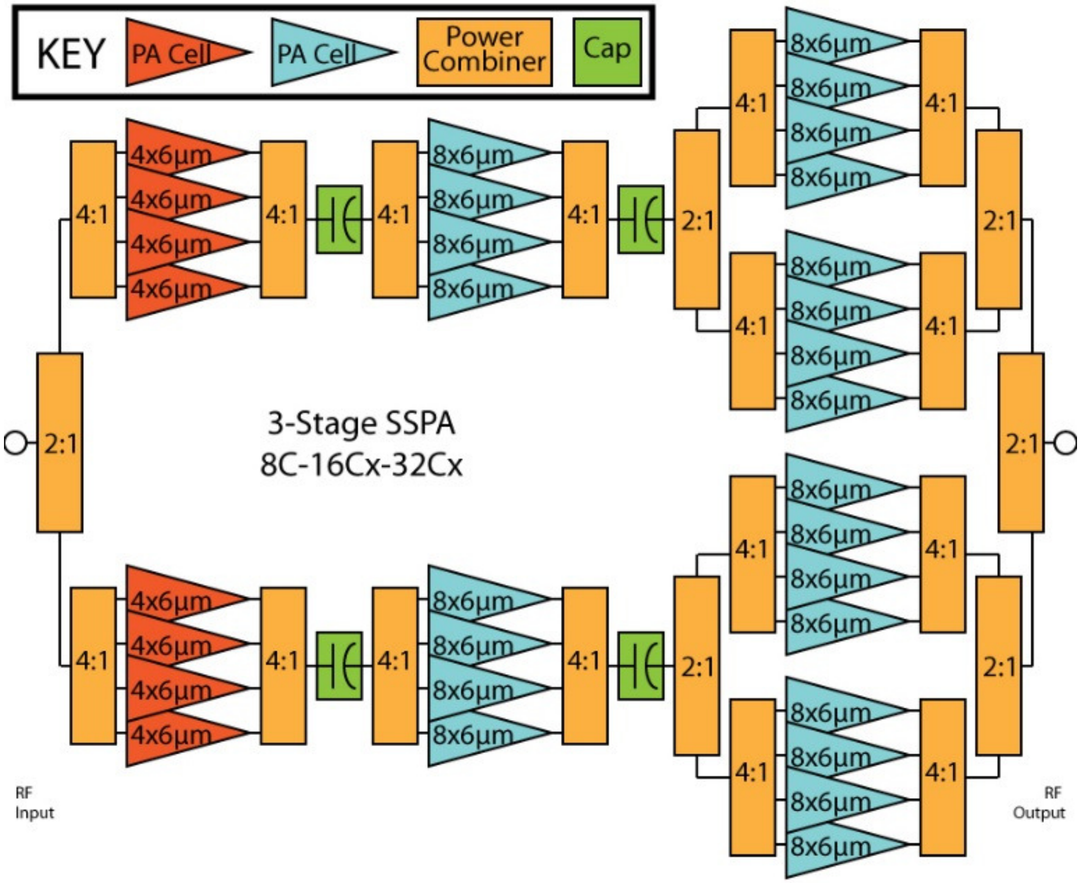


Design as a 3-port network—using HBT Zout as port Zo
Symmetric Tuning—achieve load target tuned to 50ohms
Near HBTs Spaced 40um center-to-center.

PA MMIC Design Methodology

- Final Stage PA cells have 2x HBT periphery (compare CSICS 2012)
- PA Cells combined 16x on the output (8x combiner CSICS 2012)
- Lower-loss interstage DC Block designed
- New 4:1 combiner

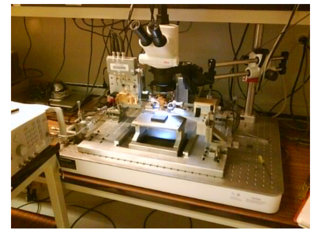


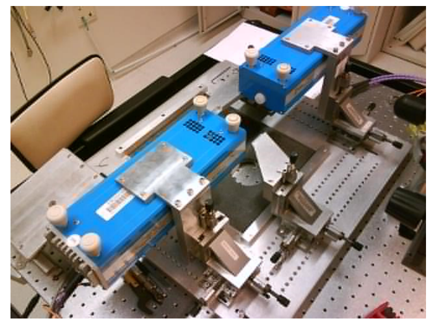


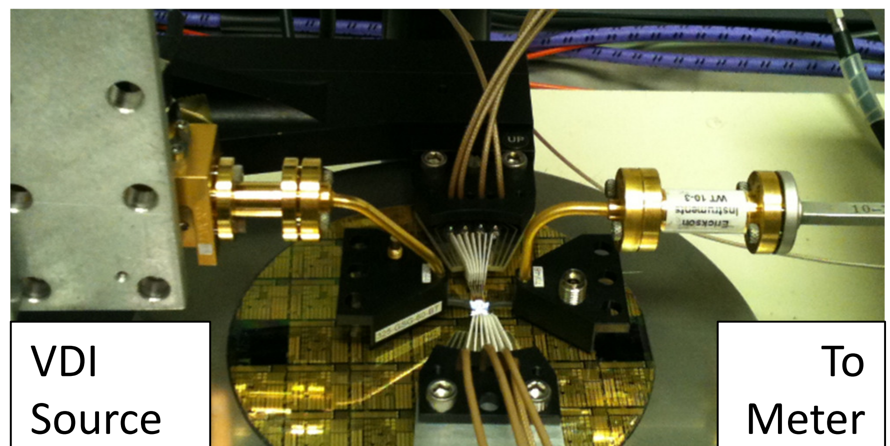
A top-level schematic of the SSPA MMIC.

220GHz Measurement

- Small Signal Measurement
  - VNA with 140-220 and 206-340 GHz frequency extender heads
  - LRRM Probe-tip Calibration
- Power Sweep Measurement
  - 220 GHz frequency multiplier chains and sub-mm wave power meter
  - Insertion Loss Calibration
  - Forced Air cooling





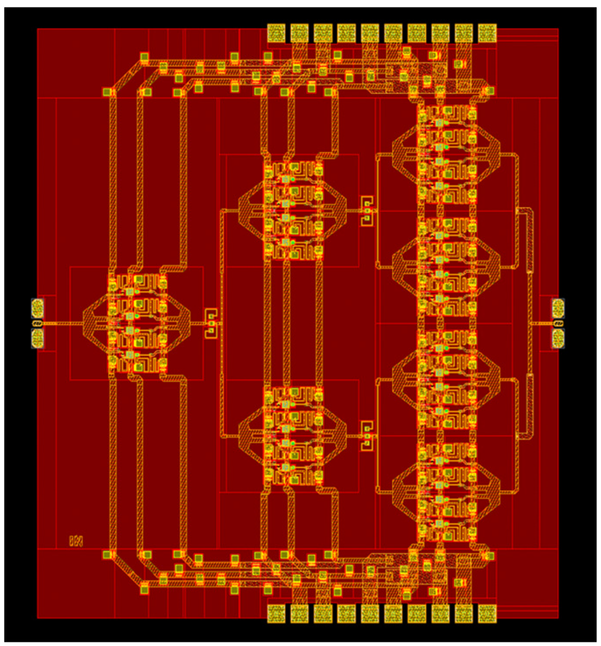


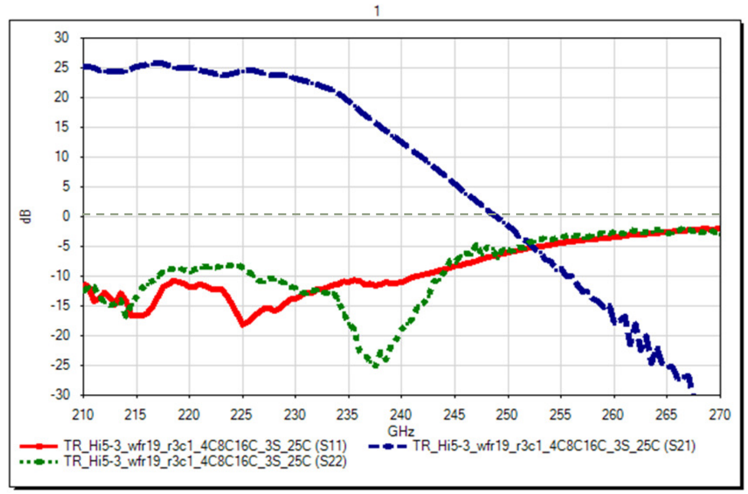
Calibration data validates amplifier data

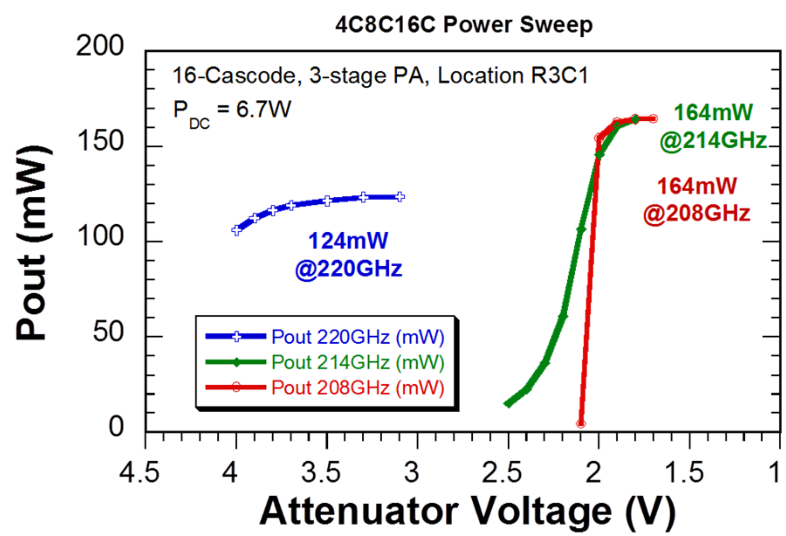
4C8C16C PA (Baseline Design 2x)

- 25dB S21 Gain at 220GHz
- 164mW at 208 & 214GHz
- 0.427W/mm

DC power: 6.7W
Physical Size: 2.5x2.1mm^2



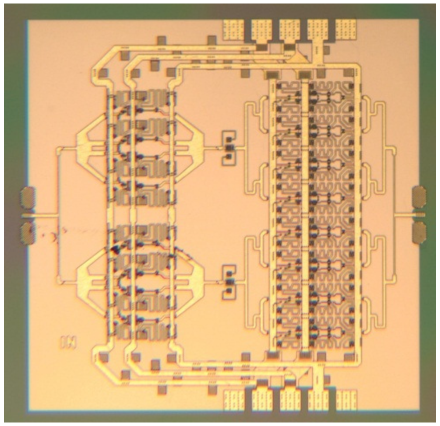


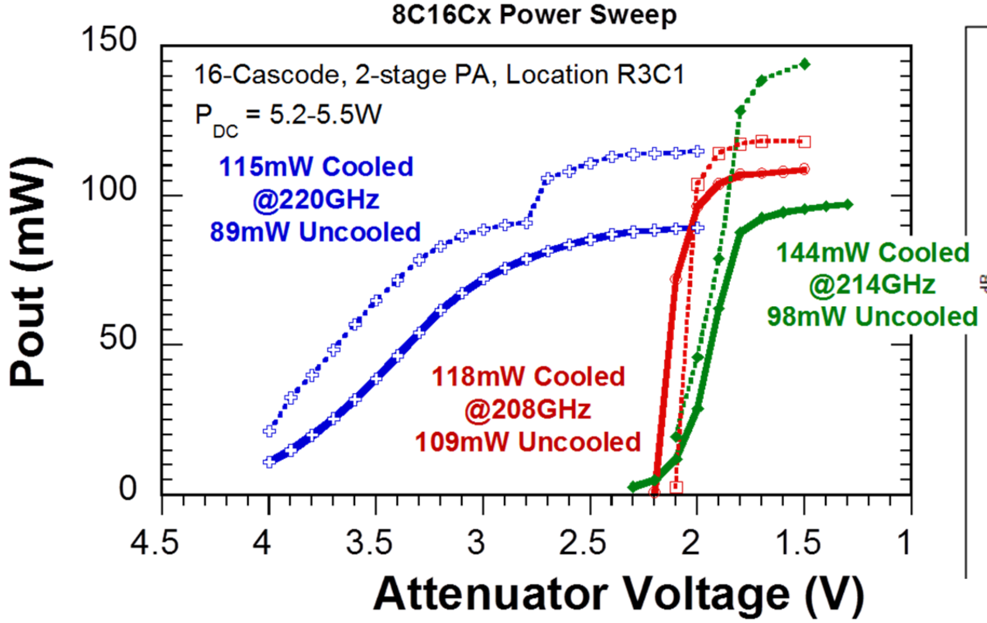


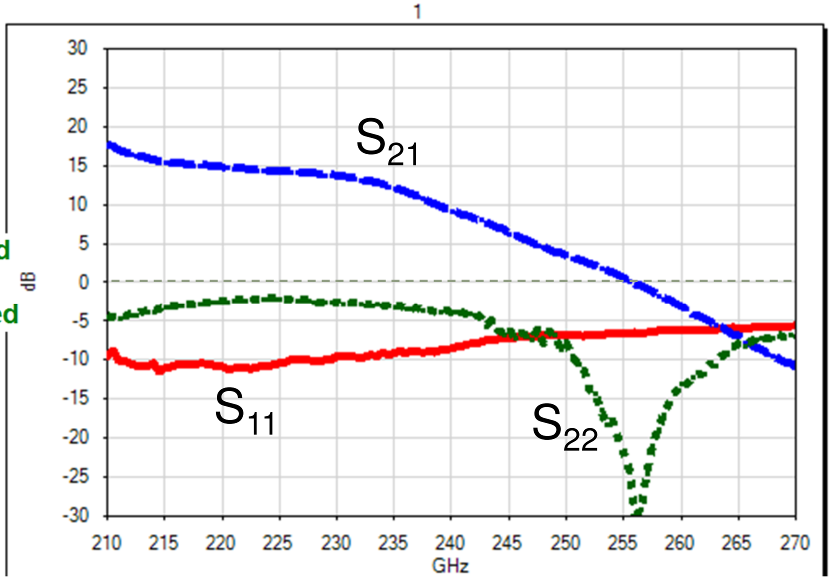
8C16Cx PA

DC power: 5.5W
Physical Size:
1.4x1.4mm^2

- 144mW @ 214GHz Cooled
- 14.9dB S21 gain at 220GHz
- 0.374 W/mm
- Forced Air increase P_{OUT} 10-40%



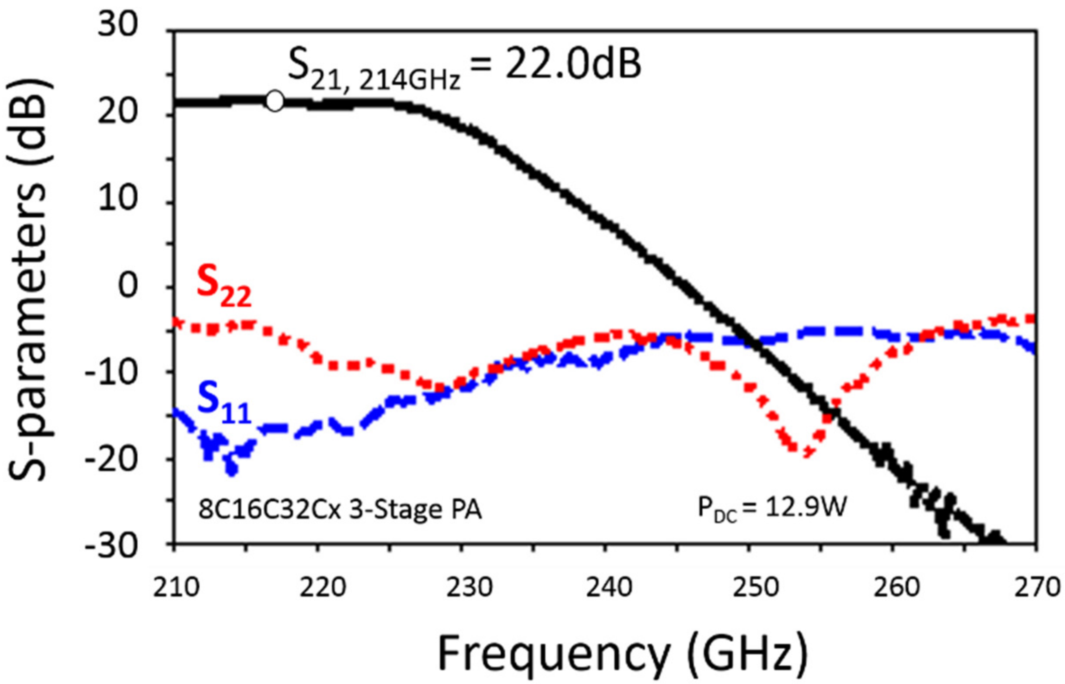




32Cx 3-Stage PA S-parameters

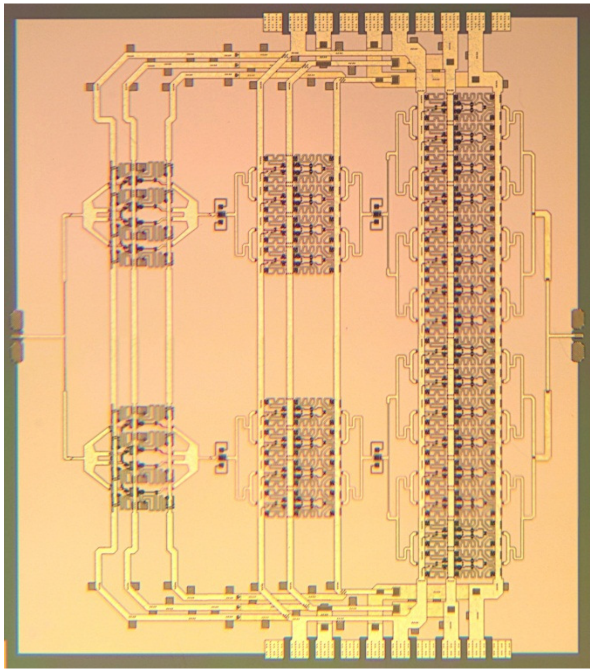
- S-parameters of the 3-stage, 8C16C32Cx SSPA. Gain at 214 and 220GHz is 22dB. 3dB bandwidth extends up to 230GHz. Measured with Forced Air Cooling

0.768mm emitter periphery



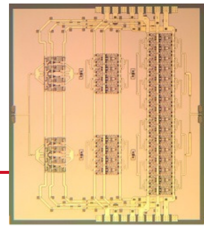
DC power: 12W

Physical Size: 2.5x2.2mm^2

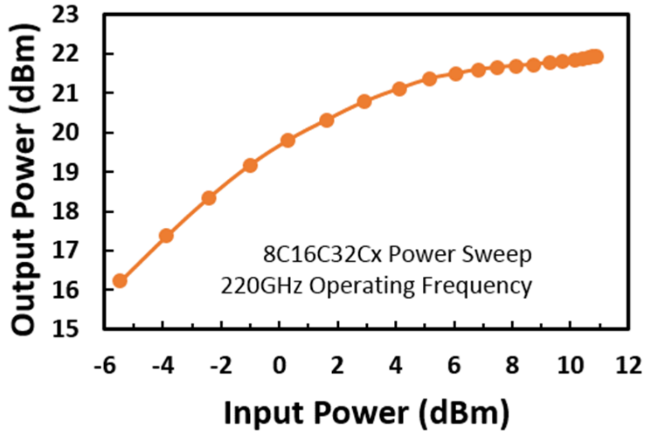


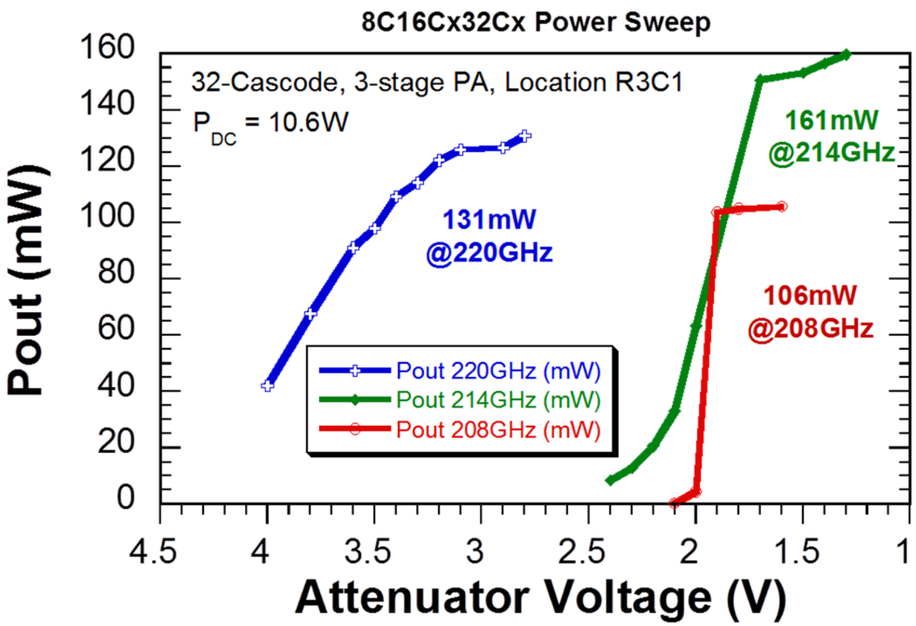
Micrograph of an 8C16Cx32Cx

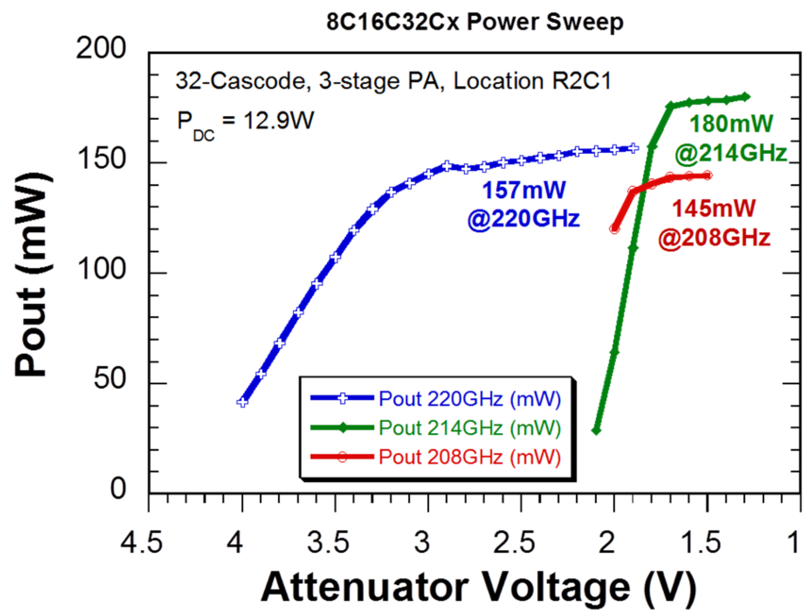
8C16C32Cx & 8C16Cx32Cx Power



- 8C16C32Cx
  $P_{OUT,SAT}$=180mW @214GHz
- 8C16Cx32Cx
  $P_{OUT,SAT}$=161mW @214GHz
- Results measured with
  Cooled forced air







Recapitulation

- First pass design success on InP Tapeouts
- Design method focuses on EM modeling of at component, network, and Cell level.
- Design method shows multiport output matching network
- 250nm InP HBT demonstrates a high power density technology at 220GHz with versatile backend interconnect stack
- A high power SSPA MMICs designed for 220GHz was demonstrated to show a compressed power level of 180mW at 214 GHz.

220GHz design methods demonstrate 180mW MMIC

BACK UP SLIDES

Table of 220 GHz Power Results

Operating Frequenc y	MMIC or Module*	Technology	Output Power	Output Power Density (RF Pout/Device Perihpery)**	Reference
220 GHz	MMIC	250nm InP HBT	49mW	2.03 (mW/μm²)	Reed et al., CSICS 2011 [3]
210 GHz	1 MMIC Module	sub-50nm InP HEMT	75 mW	78 (mW/mm)*	Radisic et al., CSICS 2011 [6]
220 GHz	MMIC	250nm InP HBT	90 mW	1.88(mW/μm²)	Reed et al., CSICS 2012 [1]
210 GHz	4 MMIC Module	sub-50nm InP HEMT	185 mW	48 (mW/mm)*	Radisic et al., JSSC 2012 [9]
220 GHz	MMIC	250nm InP HBT	60 mW	2.50 (mW/μm²)	Griffith et al., IMS 2013 [4]
214GHz	MMIC	250nm InP HBT	180mW	0.94(mW/μm²)	[This Work]

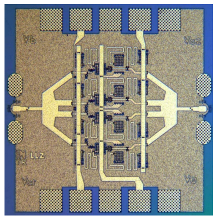
A Table of Recent PA Results near 220 GHz.

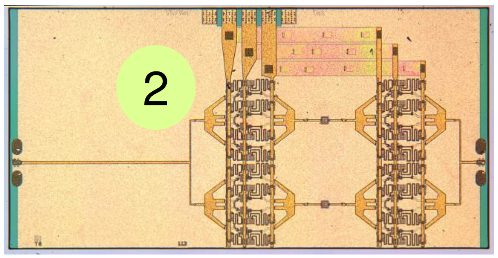
* Modules incur additional RF transition loss.

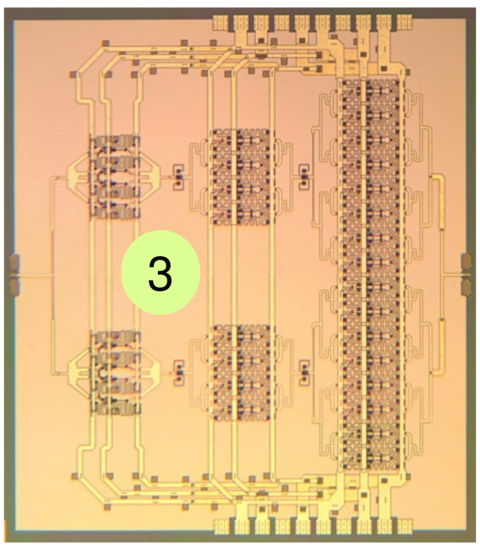
** HBT power density is typically reported per unit HBT area whereas for HEMTs, linear power density is typically reported.

Timeline of 220 GHz InP HBT PA results

1







4-Cell PA, 24um/Cell
0.7x0.7mm^2
PDC=1.15 W
(Reported CSICS 2011)

1

4-Cell PA, 24um/Cell
S_{21} @220 GHz = 10.1 dB
$P_{out} \approx$ 48mW
@ 210-220GHz

8-Cell, 2-Stage, 24um/Cell
2.4x1.2mm^2
PDC=4.5W
(Reported CSICS 2012)

2

8-Cell, 2-Stage, 24um/Cell
S_{21} @220 GHz = 14.8dB
P_{out} = 90mW @ 220 GHz
P_{out} > 65mW for 210-225 GHz

16-Cell, 3-Stage, 48um/Cell
2.5x2.2mm^2
(Reported CSICS 2013)

3

16-Cell, 3-Stage, 48um/Cell
Pout=180mW @ 214GHz
w/ Forced Air Cooling
Thinning/heat removal?

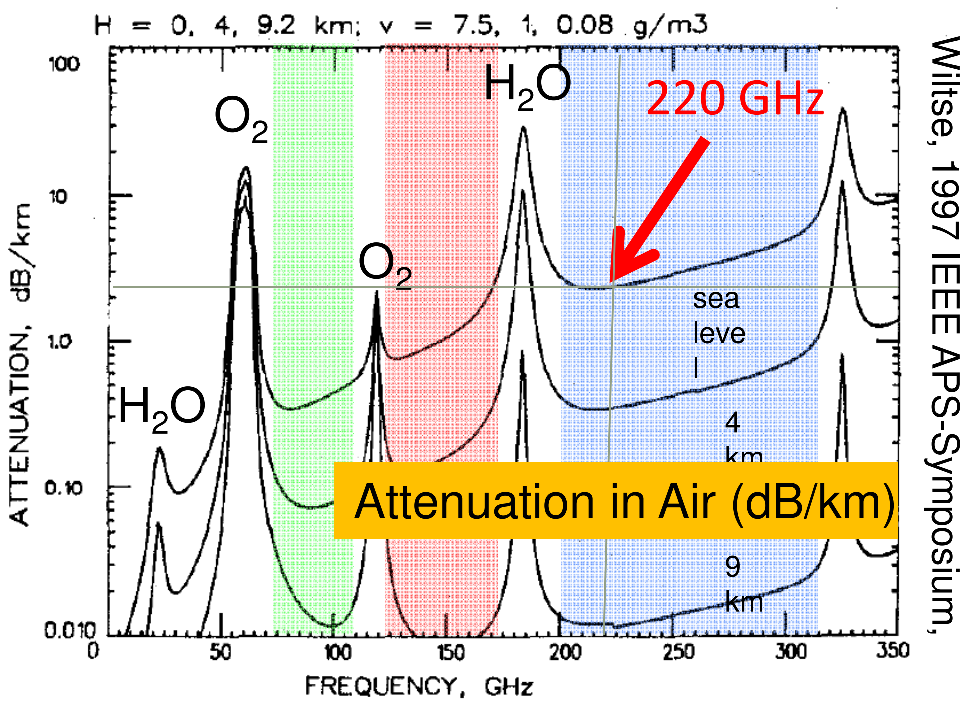
High power densities demonstrated with InP HBT MMICs

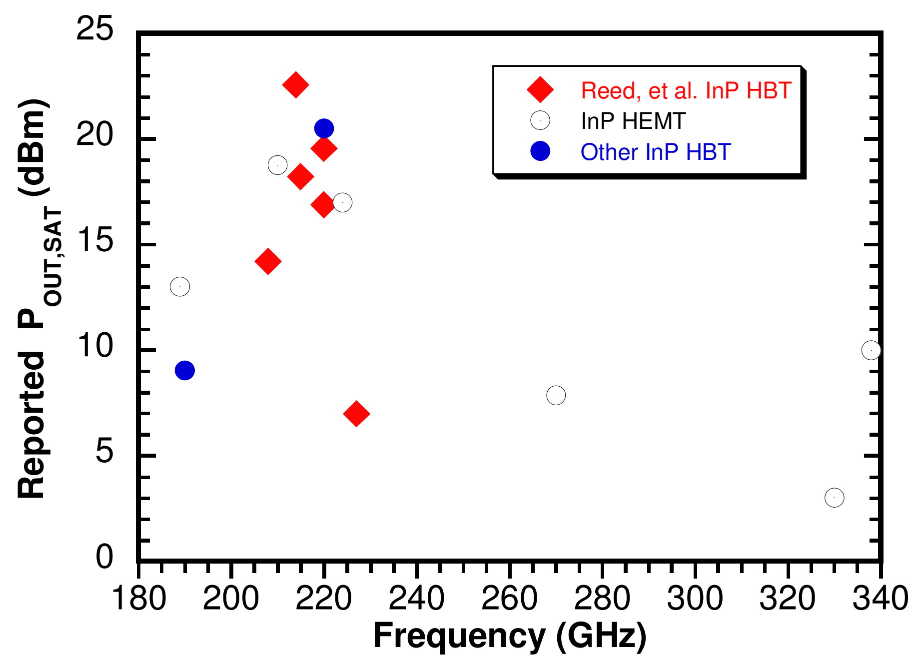
Thanks

- UCSB and Teledyne Scientific
- Mark Rodwell (UCSB), Zach Griffith(TSC)
- Rodwell Group Members
  – Hyunchul Park, Saeid Daneshgar, Vibhor Jain, and many others.
- DARPA MTO for funding this work under the Hi-FIVE program

mm-Wave Wireless Systems

- Free-Space Propagation Loss Minimum ~2.5dB/km @ 220GHz
- Avg. LNA result 8-11dB NF near 220GHz…
- Example: 1GHz BW system, clear day, 20dB antennas, 300m range, 3dB SNR (modulation scheme) requires 0.83W of Pout





220GHz is a local minima, but >1 Watt is desired