Millimeter Wave CMOS Power Amplifiers

Professor Ali M. Niknejad

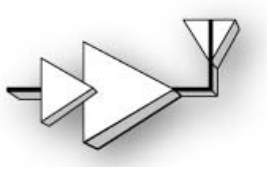
Berkeley Wireless Research Center

University of California, Berkeley

Berkeley Wireless Research Center

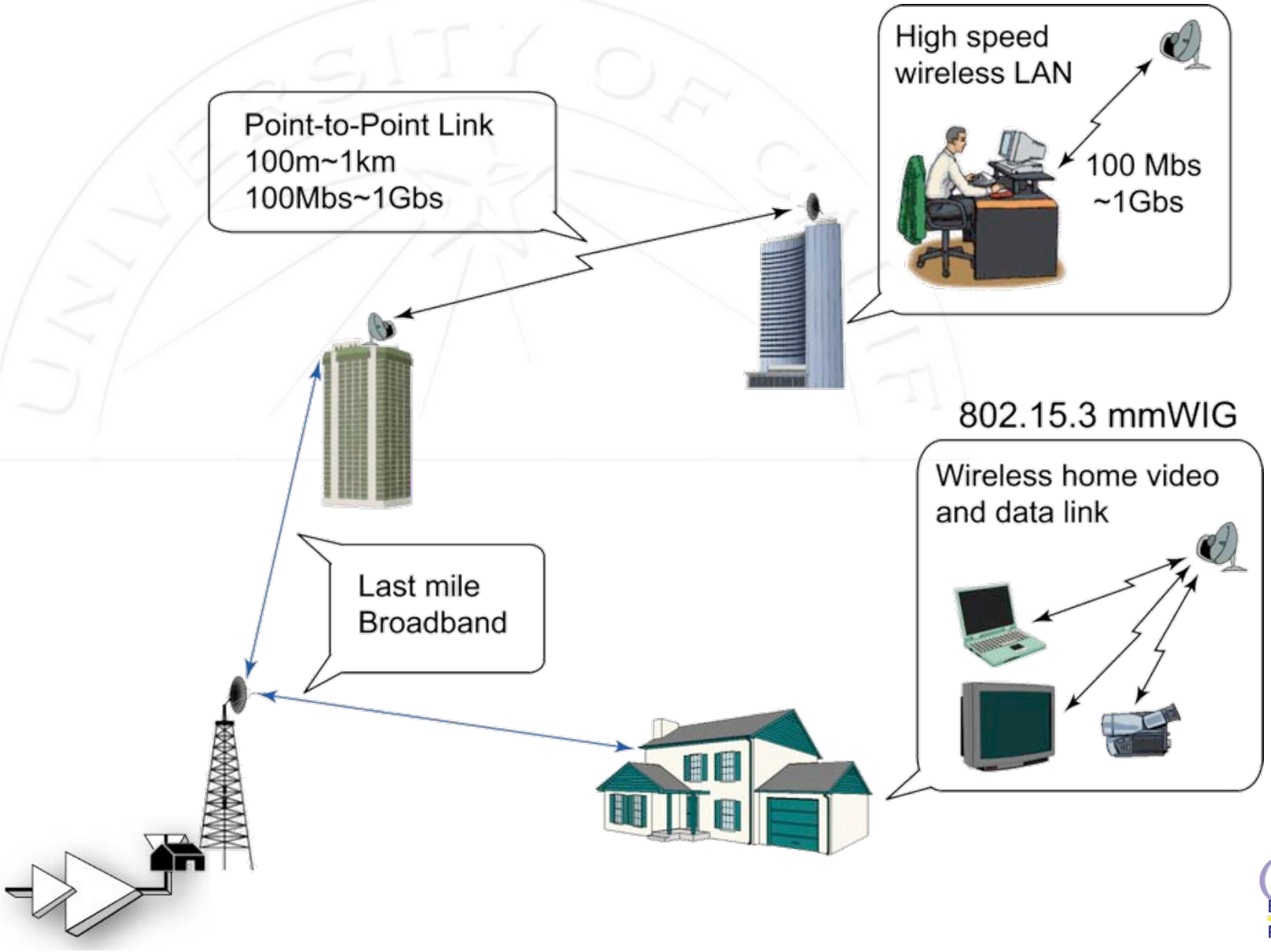
Outline

- Applications / Performance Requirements
- PA Amplifier Design Examples
- Complete “Digital” CMOS PA Transmitter



Berkeley Wireless Research Center

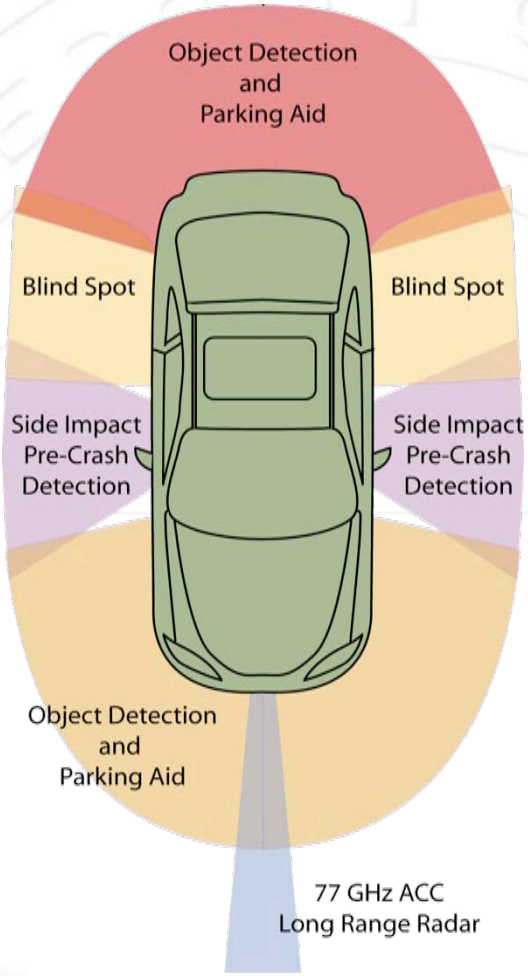
The “Last Inch”



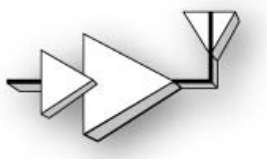
Berkeley Wireless
Research Center

Universal Mobility

Automotive Radar

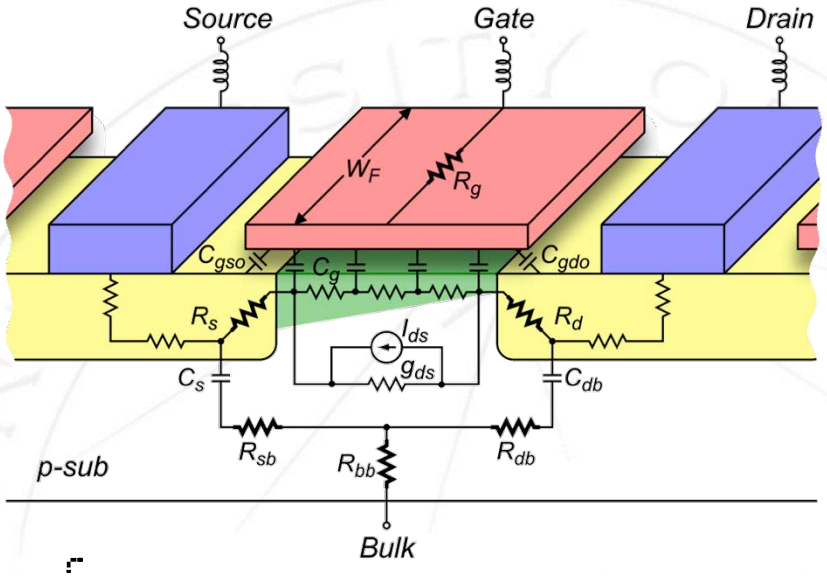


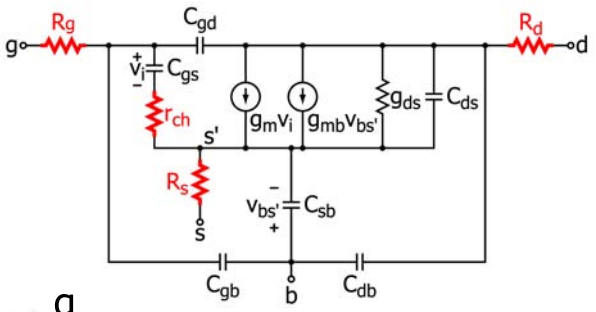
- Short range radar for parking assist, object detection
- Long range radars for automatic cruise control, low visibility (fog) object detection, impact warning
- Long range vision: automatic driver



Berkeley Wireless
Research Center

CMOS Technology Trends

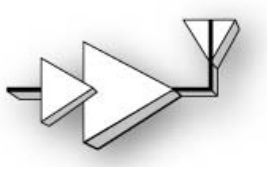




$$f_t \approx \frac{g_m}{2\pi C_{gg}}$$

$$f_{max} \approx \frac{f_t}{2\sqrt{R_g(g_m C_{gd}/C_{gg}) + (R_g + r_{ch} + R_s)g_{ds}}}$$

	130nm	90 nm	65nm	45nm
F_t	70 GHz	100 GHz	150 GHz	280 GHz
F_{max}	135 GHz	200-300 GHz	300 GHz	560 GHz
NF_{min} (60 GHz)	4-5 dB	3-4 dB	3 dB	2.3 dB

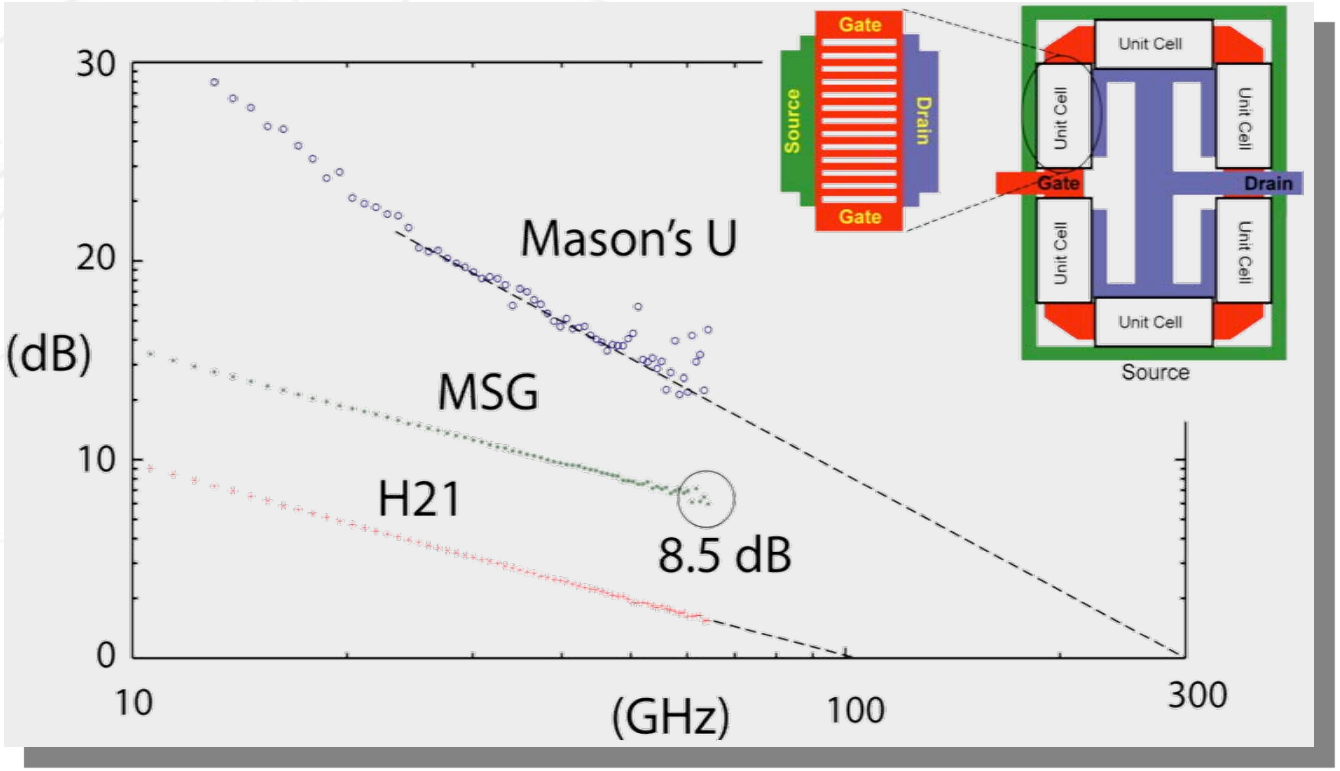


Measured

ITRS+projection

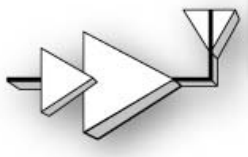
Berkeley Wireless Research Center

Layout Optimization (90nm)



Presented at ISSCC 2007

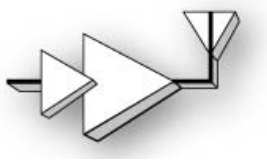
- MSG 60GHz = 8.5 dB, NFmin ~ 3-4 dB
- f_{max}= 300 GHz (*extrapolated*), f_T= 100 GHz
- Highest reported f_{max}/f_T=3 ratio for CMOS!



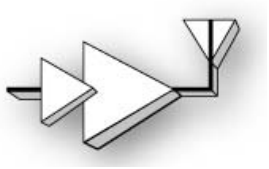
Berkeley Wireless Research Center

60 GHz Link Budget

Component	Contribution	Comment
Background Noise	-174 dBm/Hz	kT at room temp.
Noise BW	93 dB	2 GHz
Noise Figure	10 dB	RX noise figure
SNR at input	10 dB	Typ. Digital Mod.
Noise at input	-61 dBm	(-174 + 93 + 10 + 10)
Antenna Gain	-67 dBm	6 dBi
Path Loss	74 dB	2-m LOS
Other Loss	10 dB	Reflection from wall
Tx Power	17 dBm	-67 dBm + 84 dB
PA output power	11 dBm	6 dBi gain in antenna

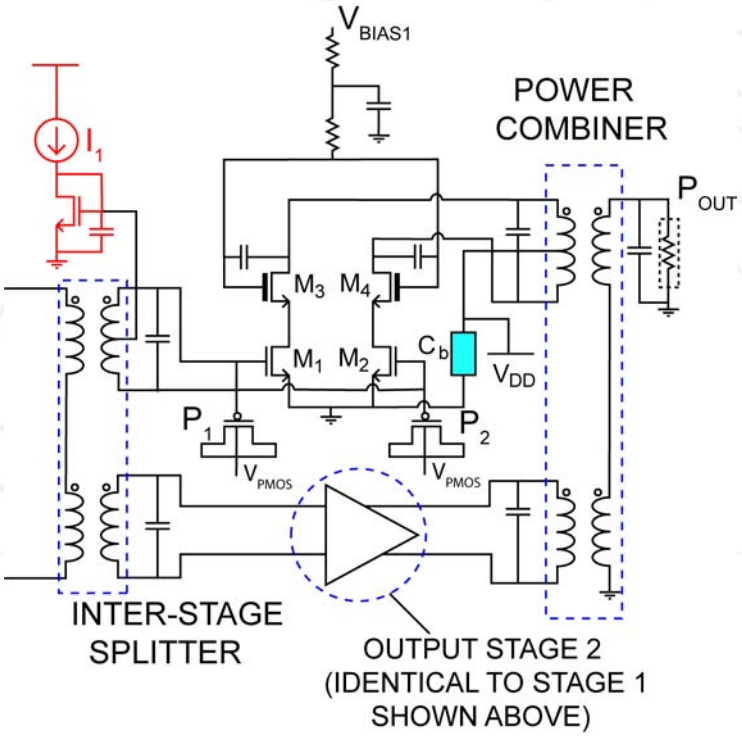


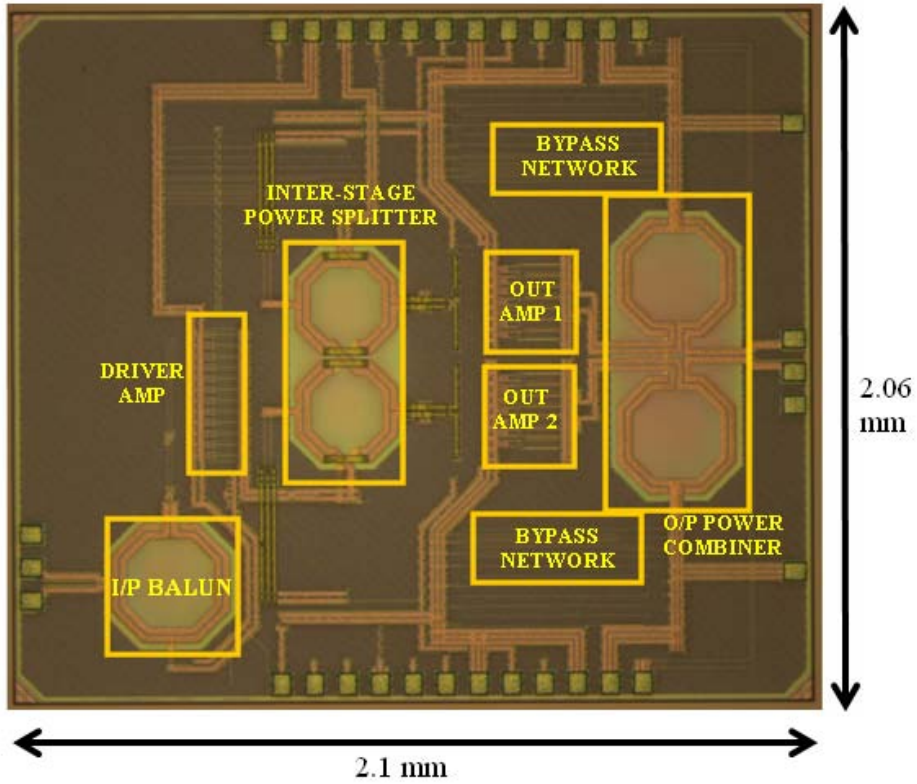
60 GHZ PA DESIGNS



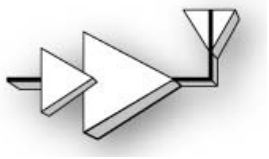
Berkeley Wireless
Research Center

24. GHz WiMAX CMOS PA's



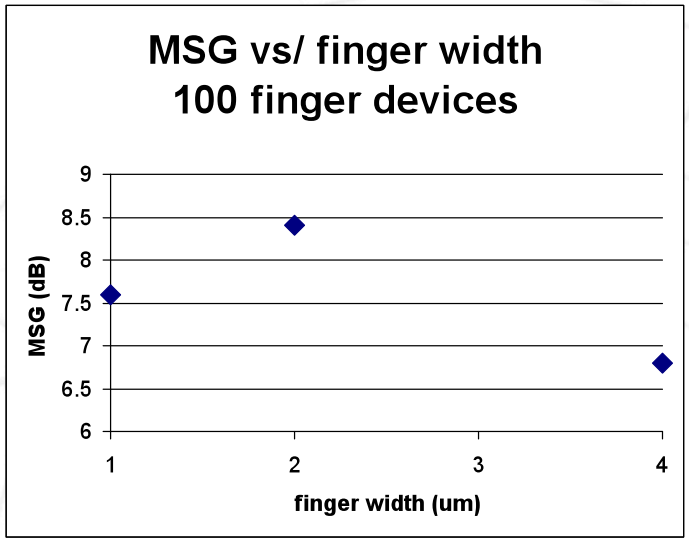


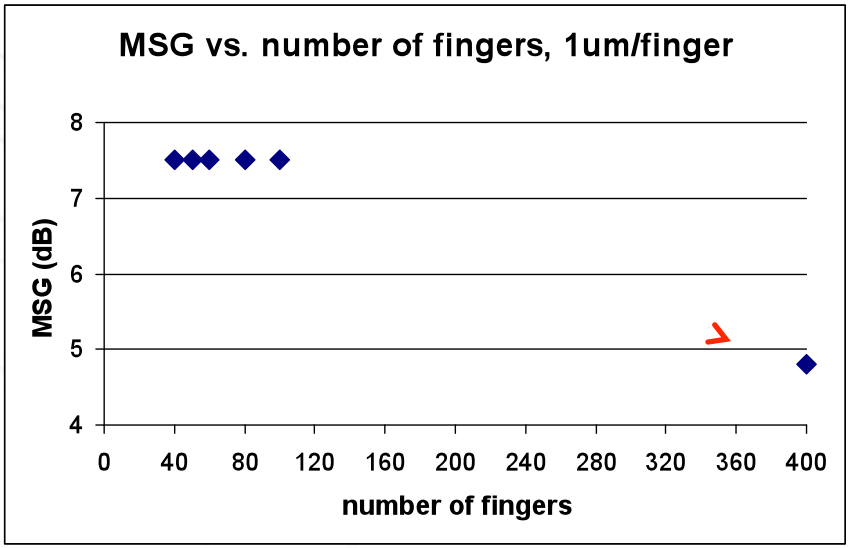
- Psat > 30 dBm, P-1dB > 27.7 dBm, PAE = 33%
- OFDM output EVM < -26dB with 22.7 dBm output power
- Fully FCC compliant, no external components



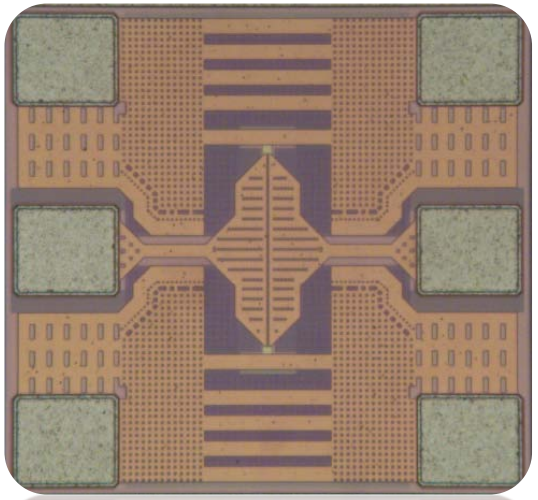
Berkeley Wireless Research Center

PA Device Selection

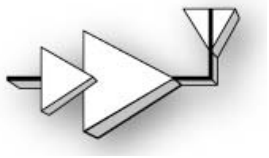




- Need a large device for high power → large parasitics → lower gain. Optimum finger size for stable gain.
- Using too many parallel devices leads to low gain

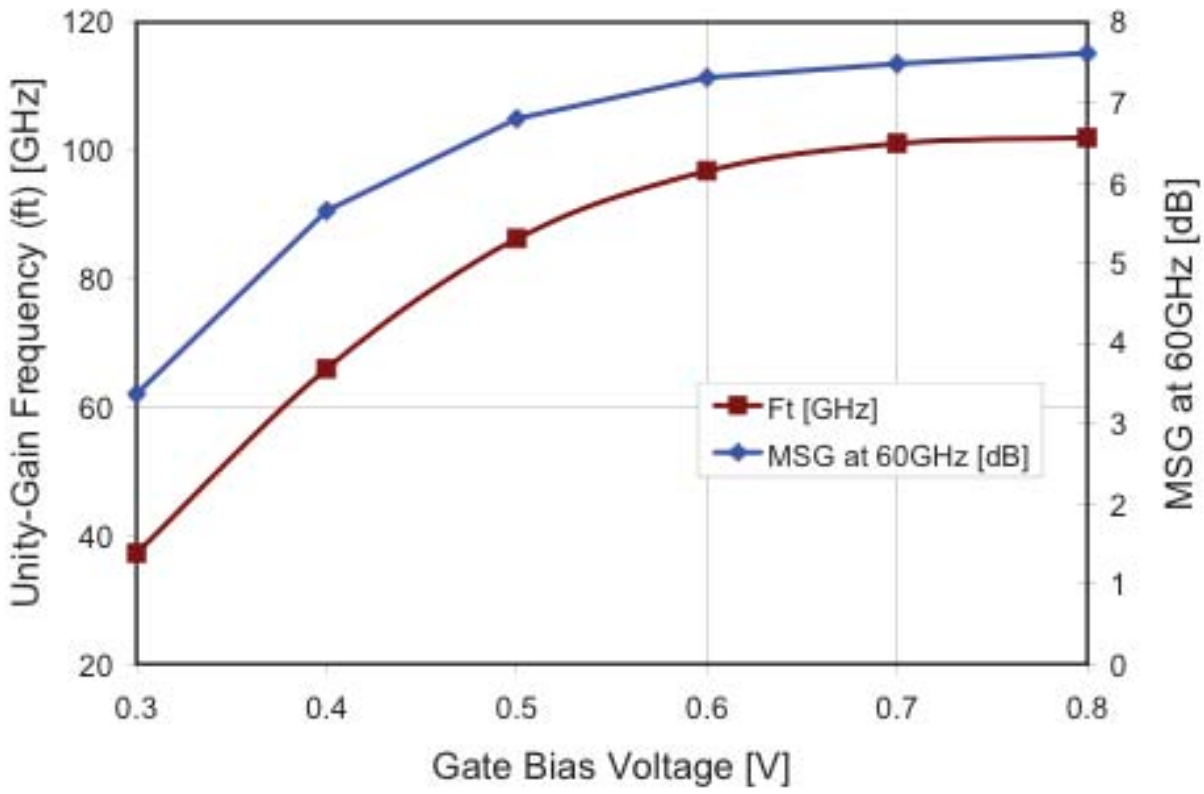


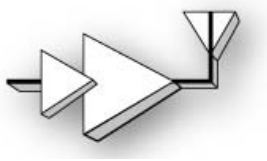
400u x 1u device



PA Bias / Class of Operation

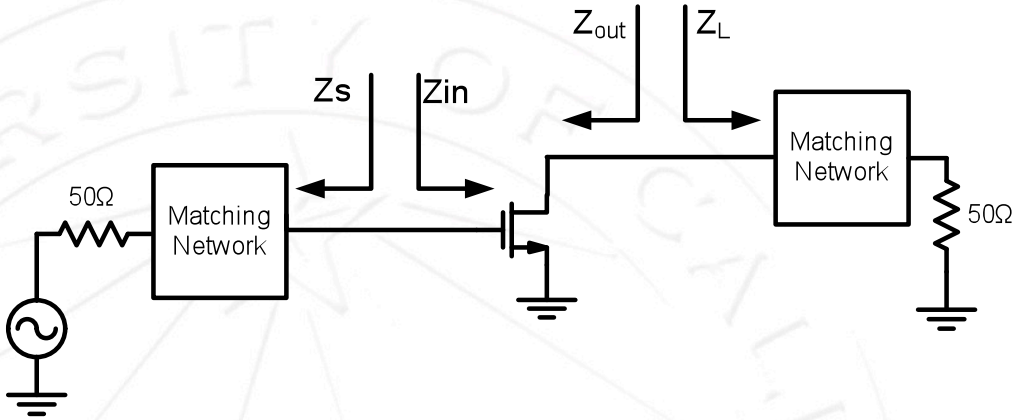
- Gain of device drops quickly requiring operating in the strong inversion regime
- Class AB biasing does not provide sufficient gain (PAE too low)



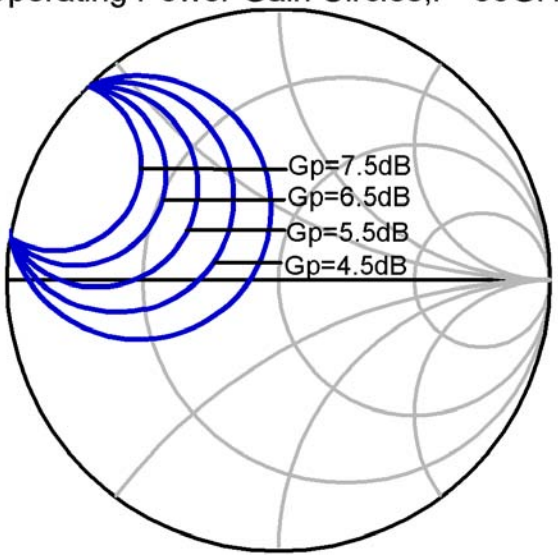


Berkeley Wireless Research Center

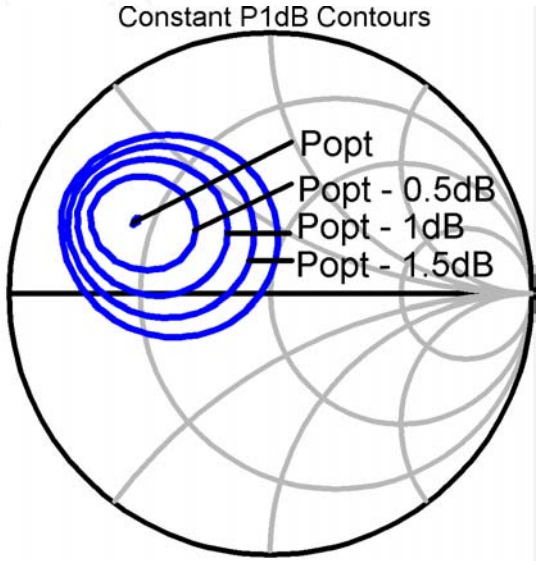
Gain vs. Output Power Tradeoff

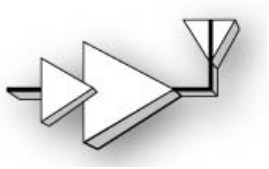


Operating Power Gain Circles,F=60GHz



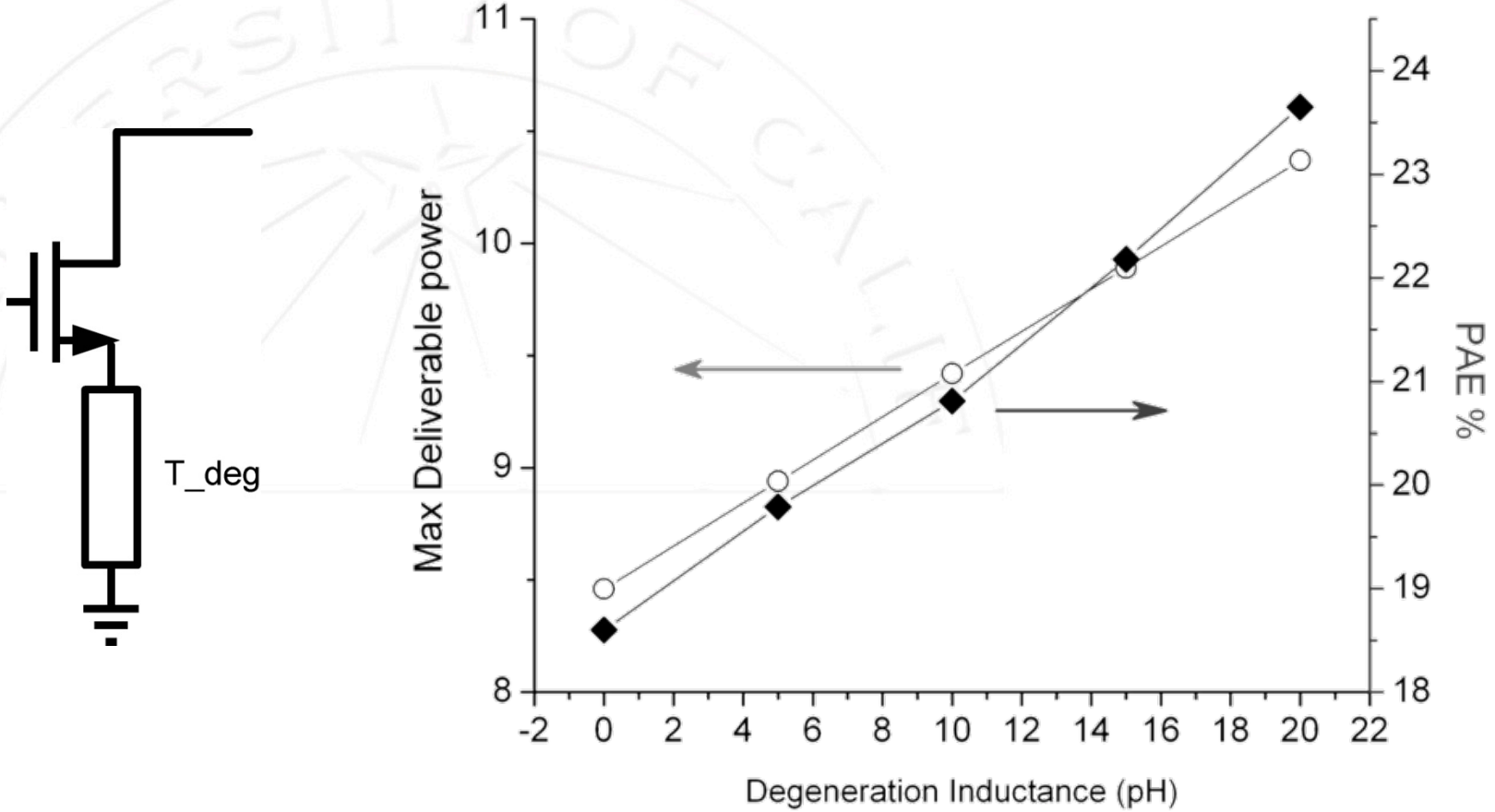
Constant P1dB Contours



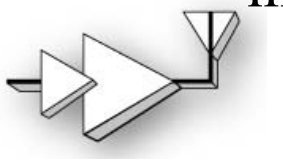


Berkeley Wireless Research Center

Output Stage Degeneration (I)

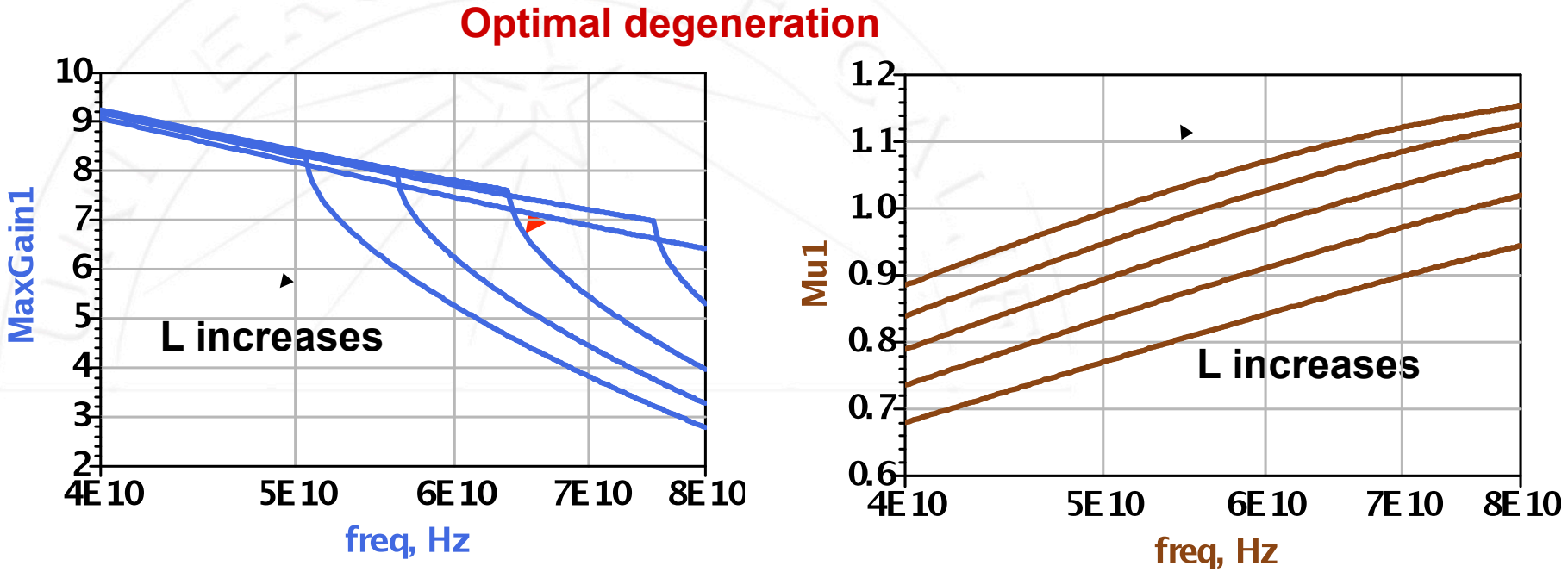


- Output power and PAE increase with small source inductive degeneration

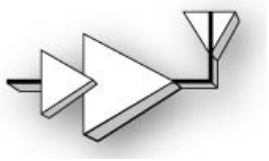


Berkeley Wireless Research Center

Output Stage Degeneration (II)

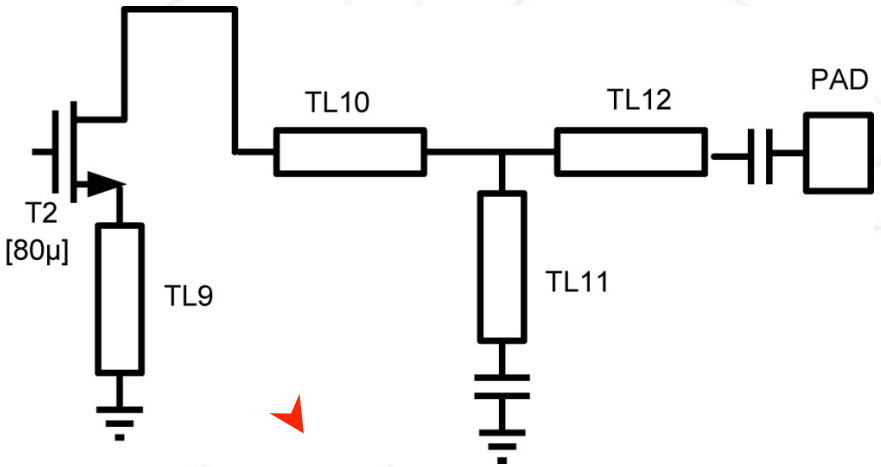


- Degeneration also increases stability, but could reduce the gain significantly!

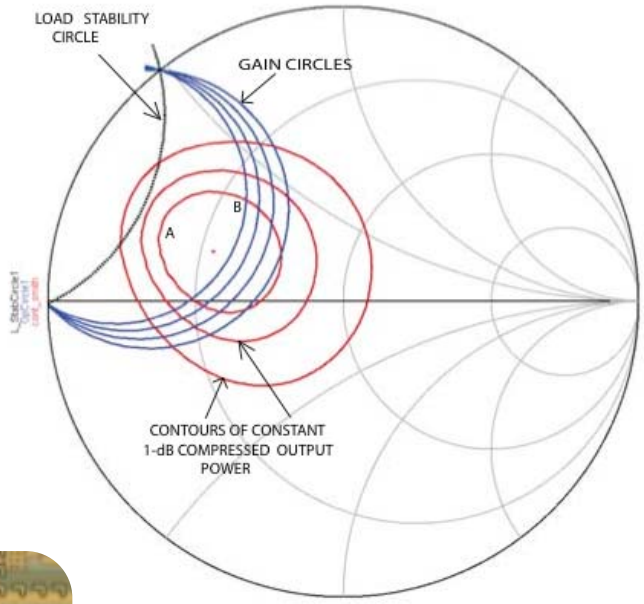


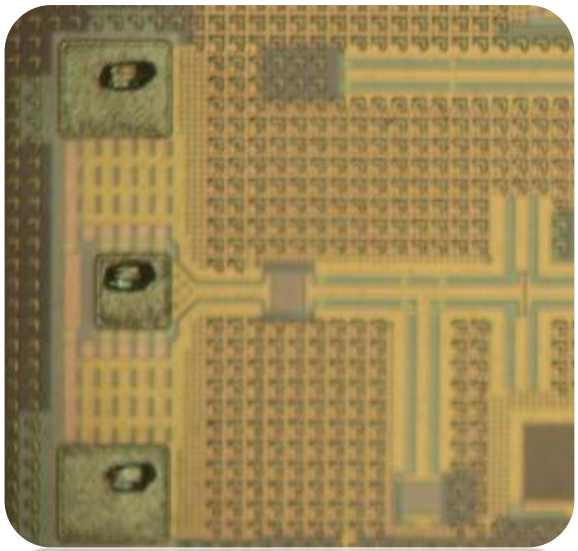
Berkeley Wireless Research Center

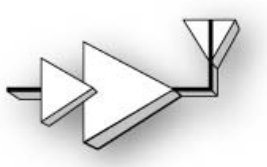
Output Stage Network



Power Device

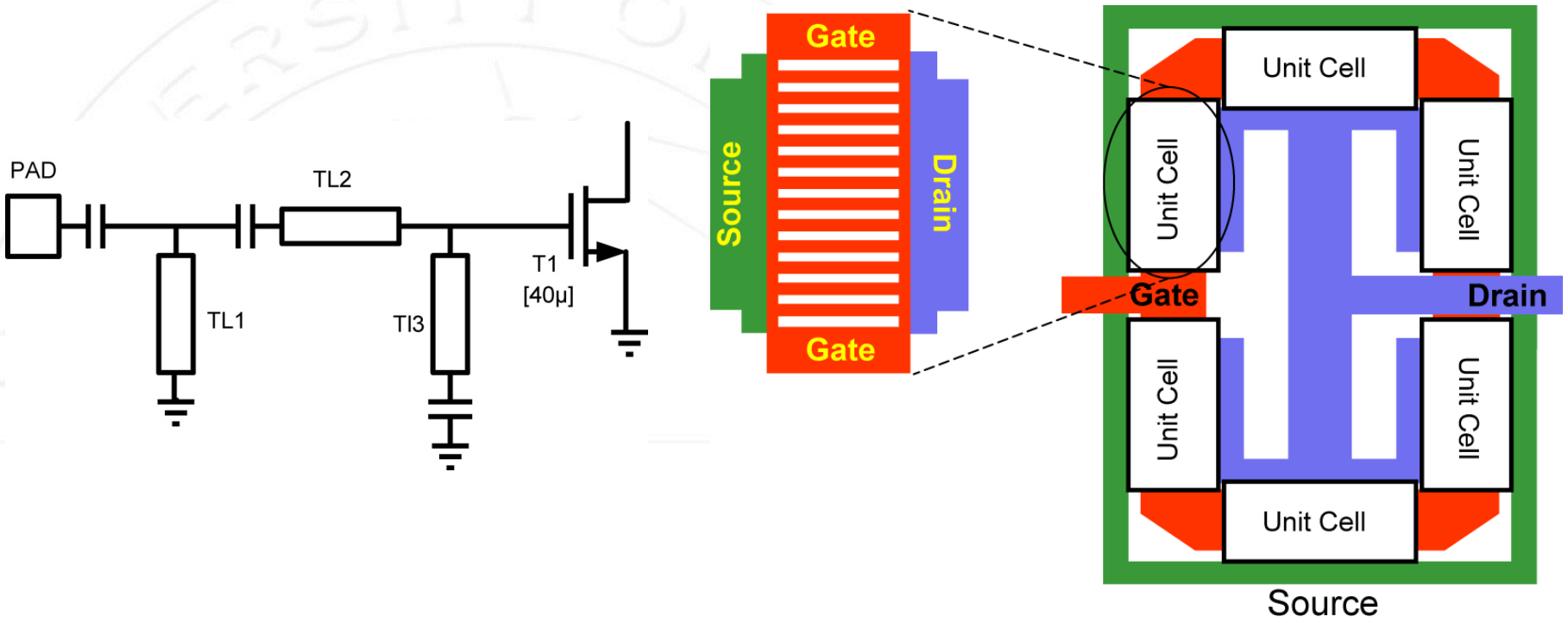




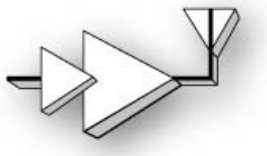


Berkeley Wireless Research Center

Gain Stage

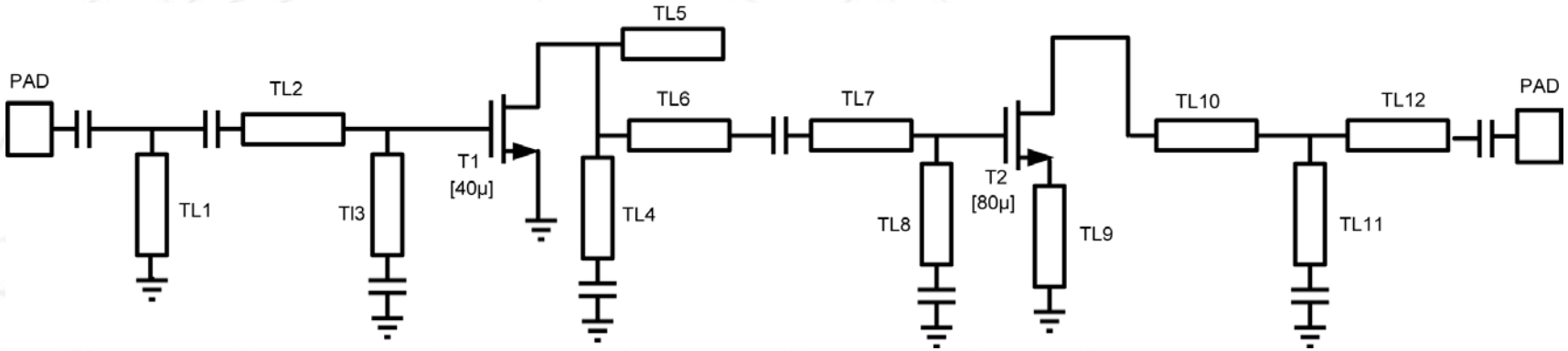


- The first Stage is optimized to give the maximum Gain
- Round-table device was used to achieve the maximum available gain (MSG=8.5dB)

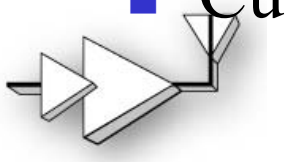


Berkeley Wireless Research Center

PA Schematic

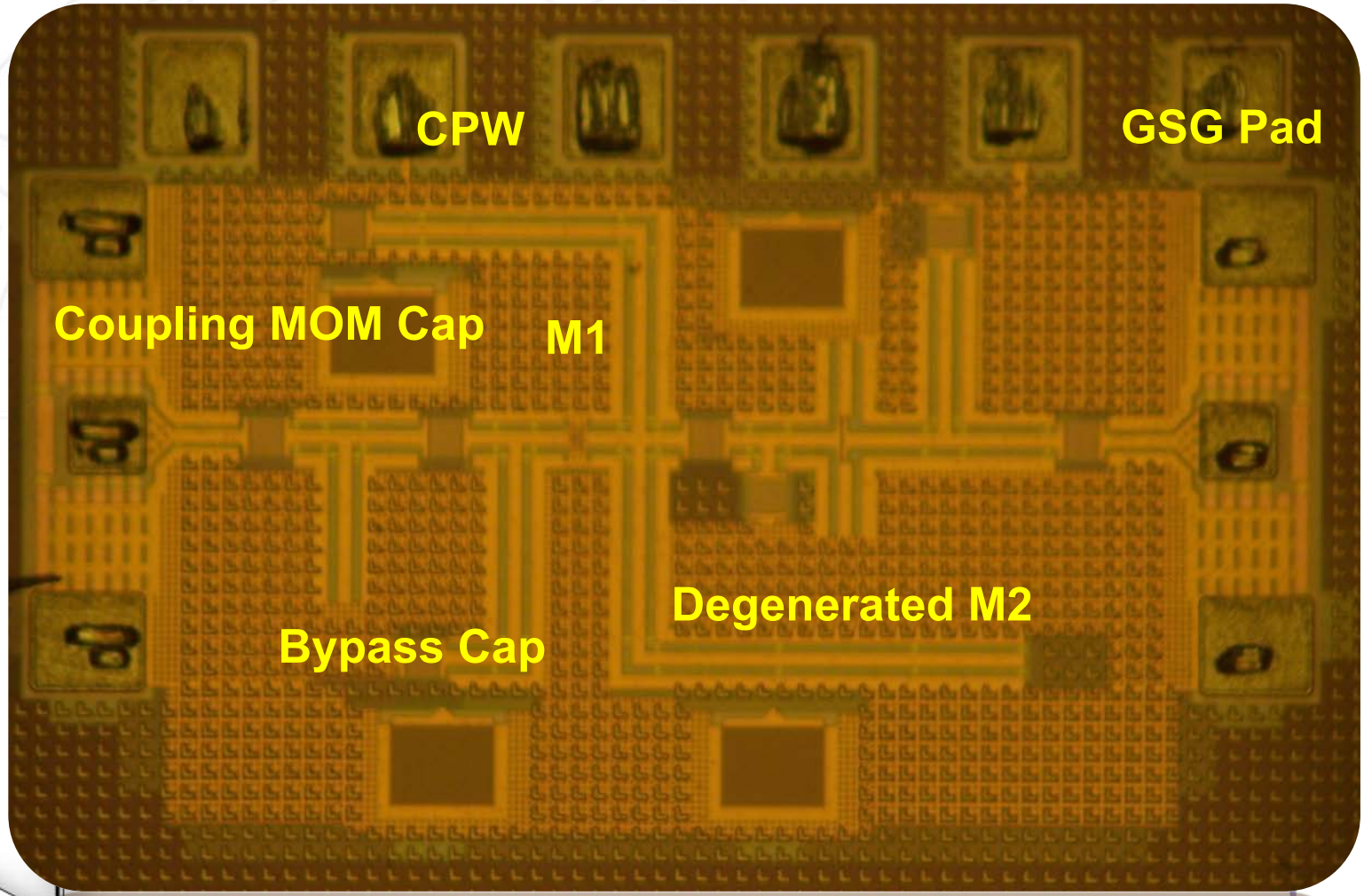


- Two-stage design single-ended design
- CPW matching, coupling caps (embedded)
- 40µm driver, 80µm output stage
- Custom bypass for low inductance

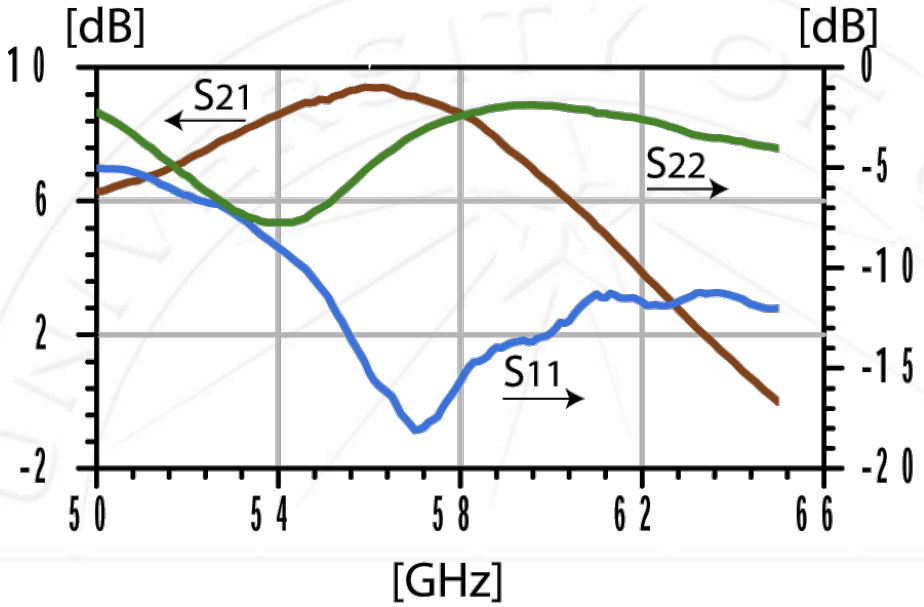


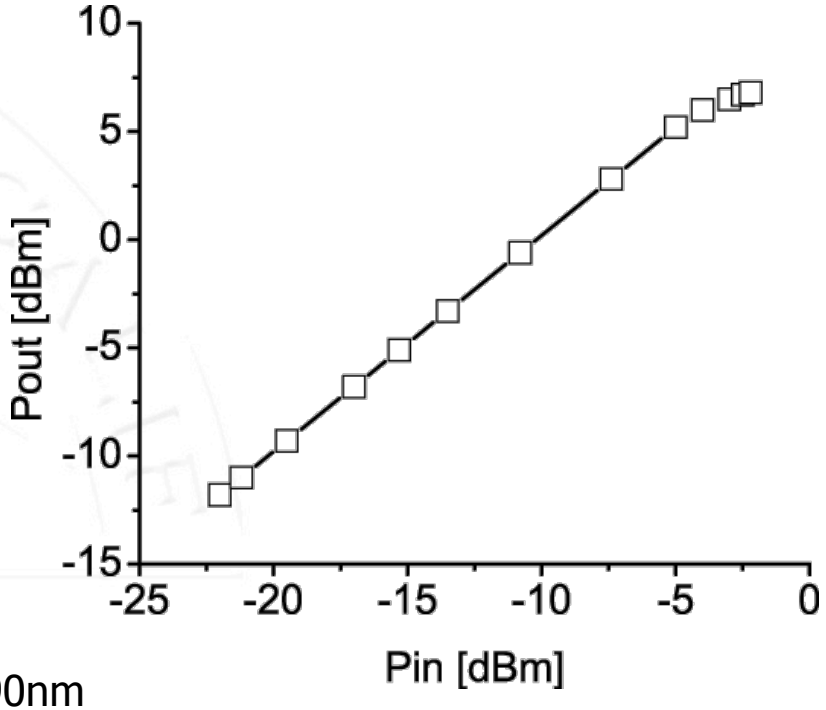
Berkeley Wireless Research Center

Chip Micrograph

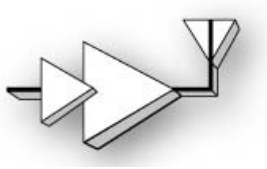


60 GHz PA Measurements



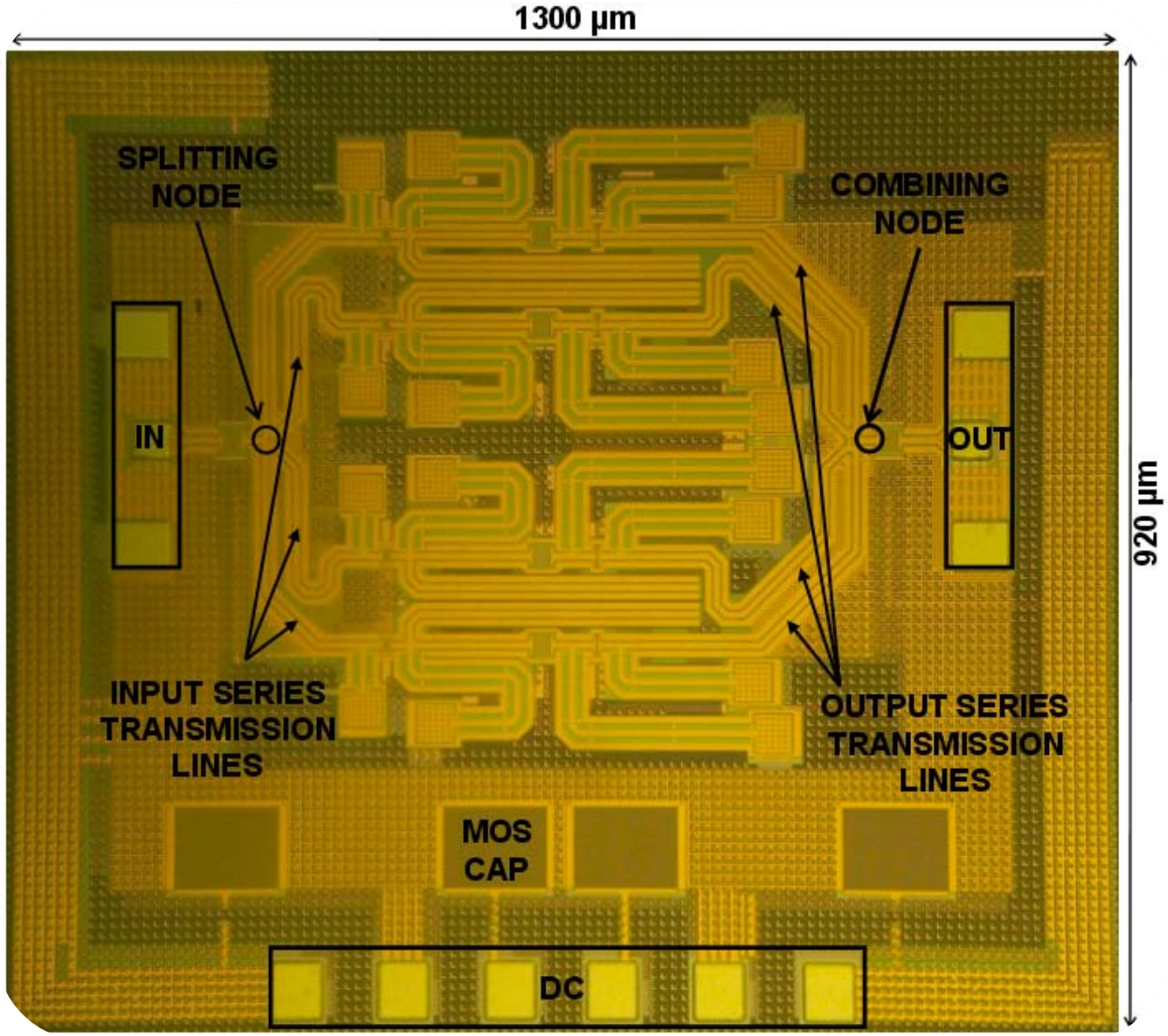


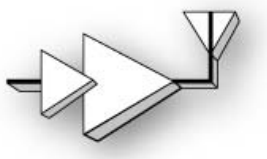
Technology	90nm CMOS (1V)
DC Power	23 mW
Gp	9.8 dB
P_{-1dB}	6.7 dBm
Efficiency	20%
S11 (57 GHz)	-18 dB



Berkeley Wireless Research Center

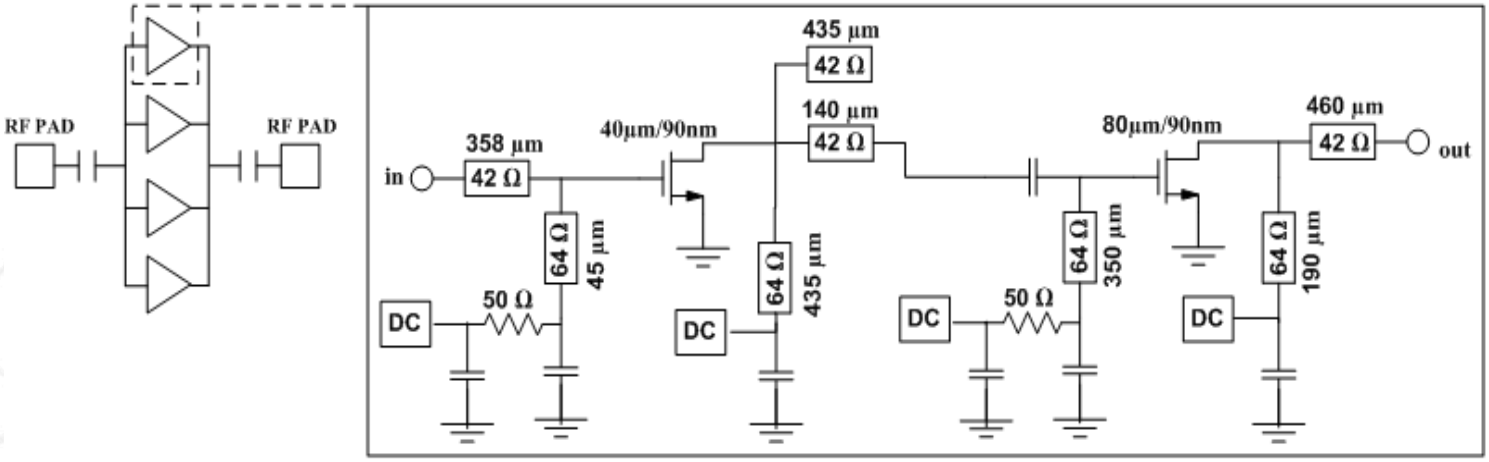
Current Combing Power Amplifier





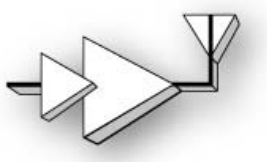
Berkeley Wireless Research Center

Current Combining Power Amplifier



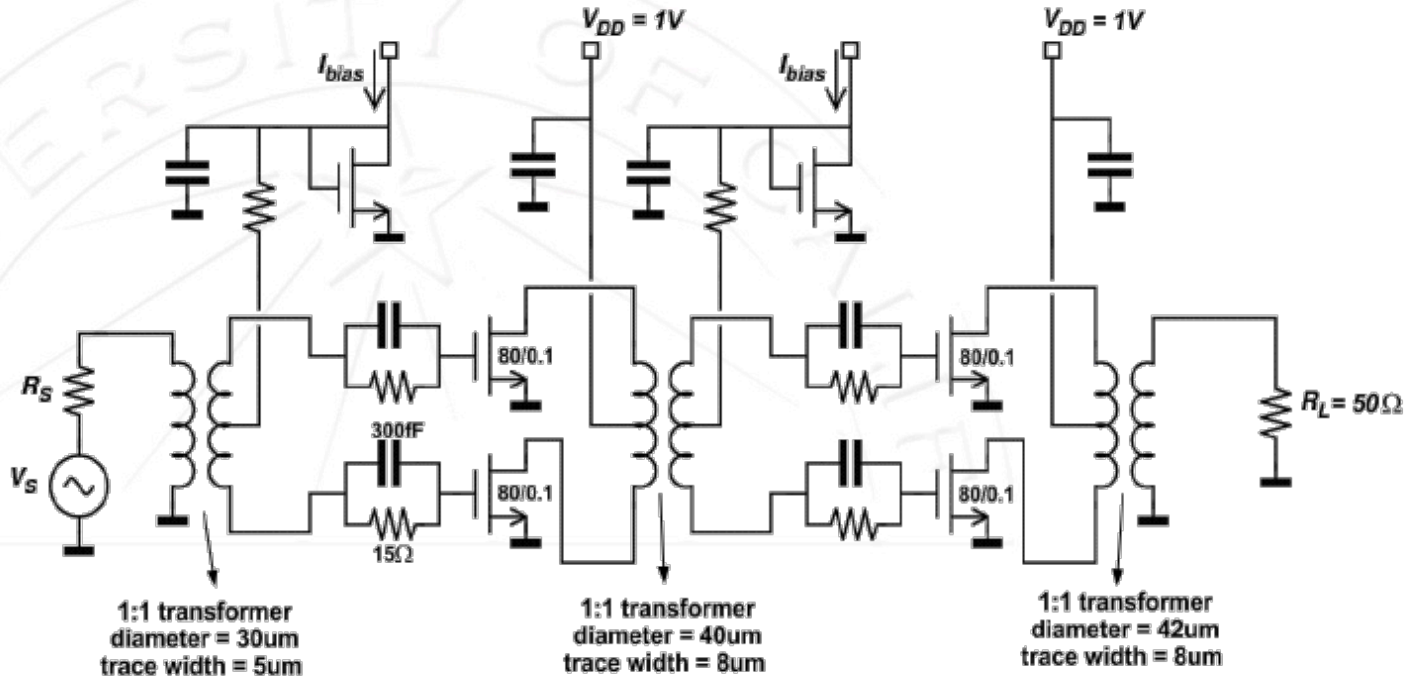
	2-Way	4-Way
Output P_{1dB}	10.1 dBm (10.5)	12.1 dBm (12.8)
Output $P_{saturation}$	11.6 dBm (12.2)	14.2 dBm (15.0)
Power Gain	8.2 dB (9.0)	4.2 dB (6.2)
1dB compression drain efficiency	12.6% (13.8%)	11.2 % (13.2)
Saturation efficiency	17.7% (20.5%)	18.1 % (20.7)
Maximum PAE	11.5% (12.5%)	5.8 % (9.8)

Meas (Sim)

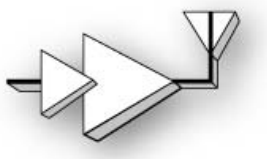


Berkeley Wireless Research Center

Broadband PA



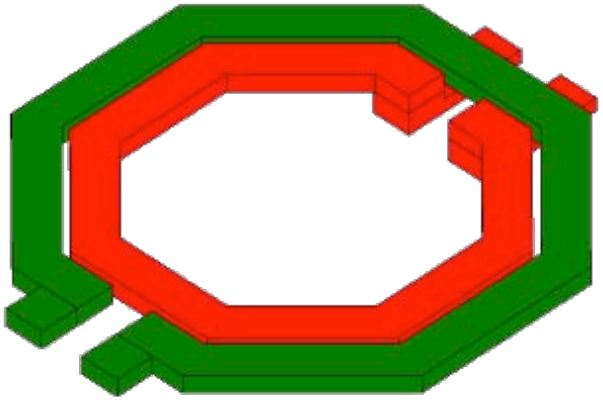
- Two-stage transformer coupled PA
- Pseudo-differential design
- Transformer used for tuning, AC coupling, and biasing

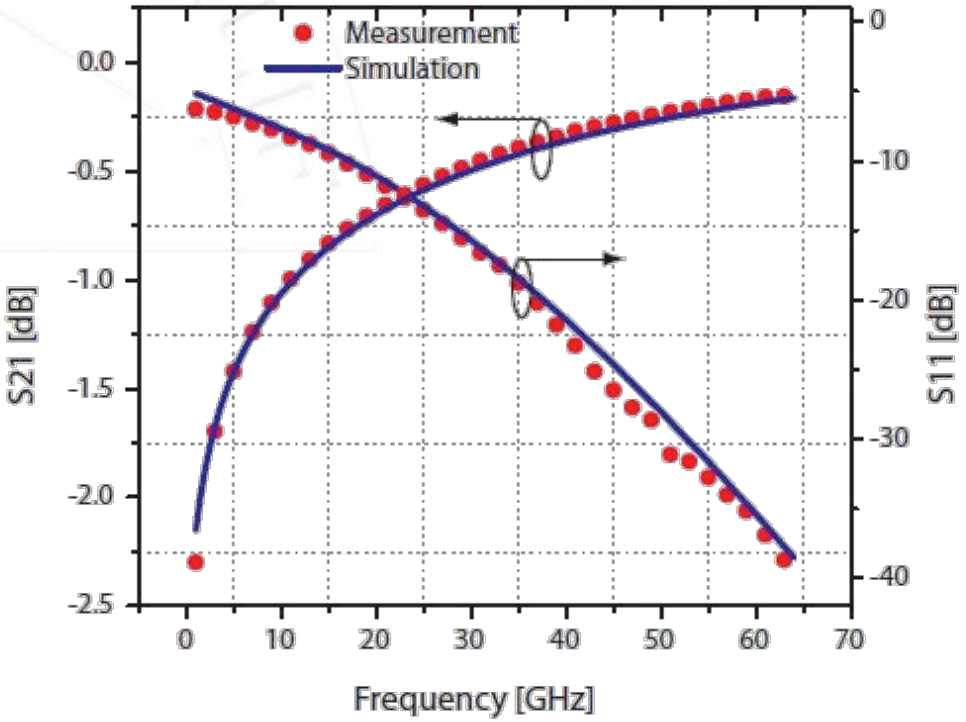


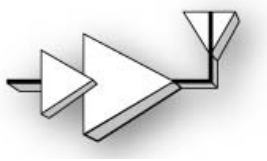
Berkeley Wireless
Research Center

Transformers Scale to mm-Waves

- Isolation, impedance matching, biasing …
- Good insertion loss
- Compact layout compared to T-lines

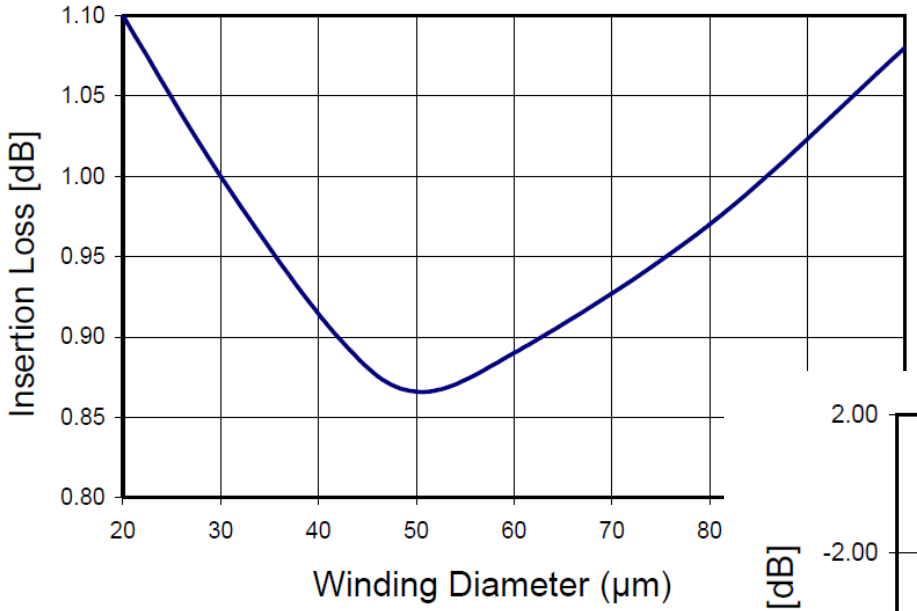


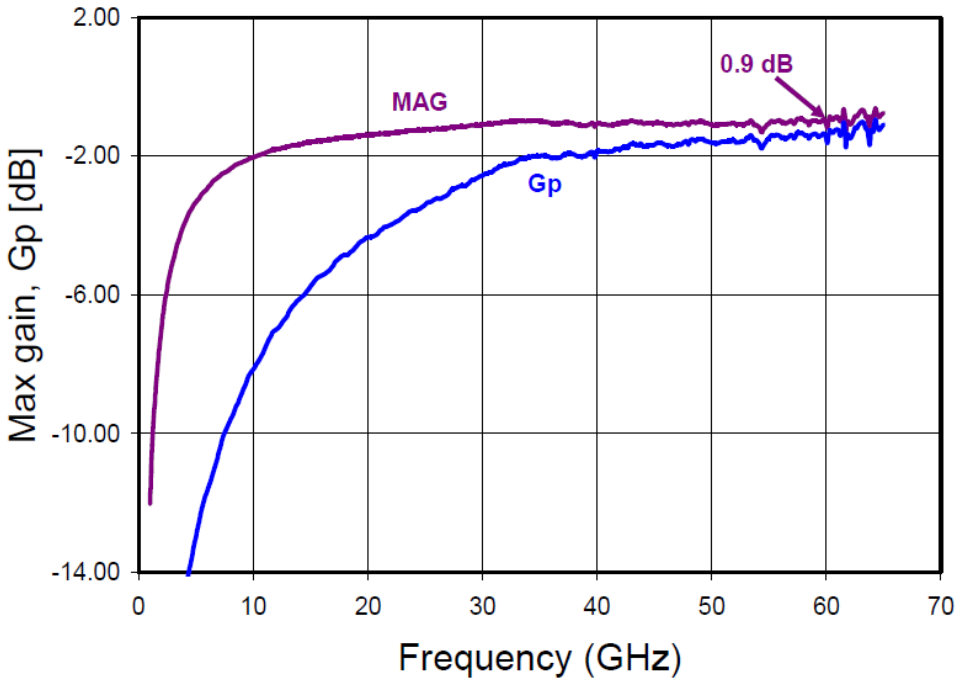


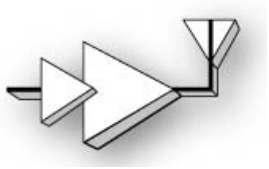


Berkeley Wireless Research Center

Transformer Design

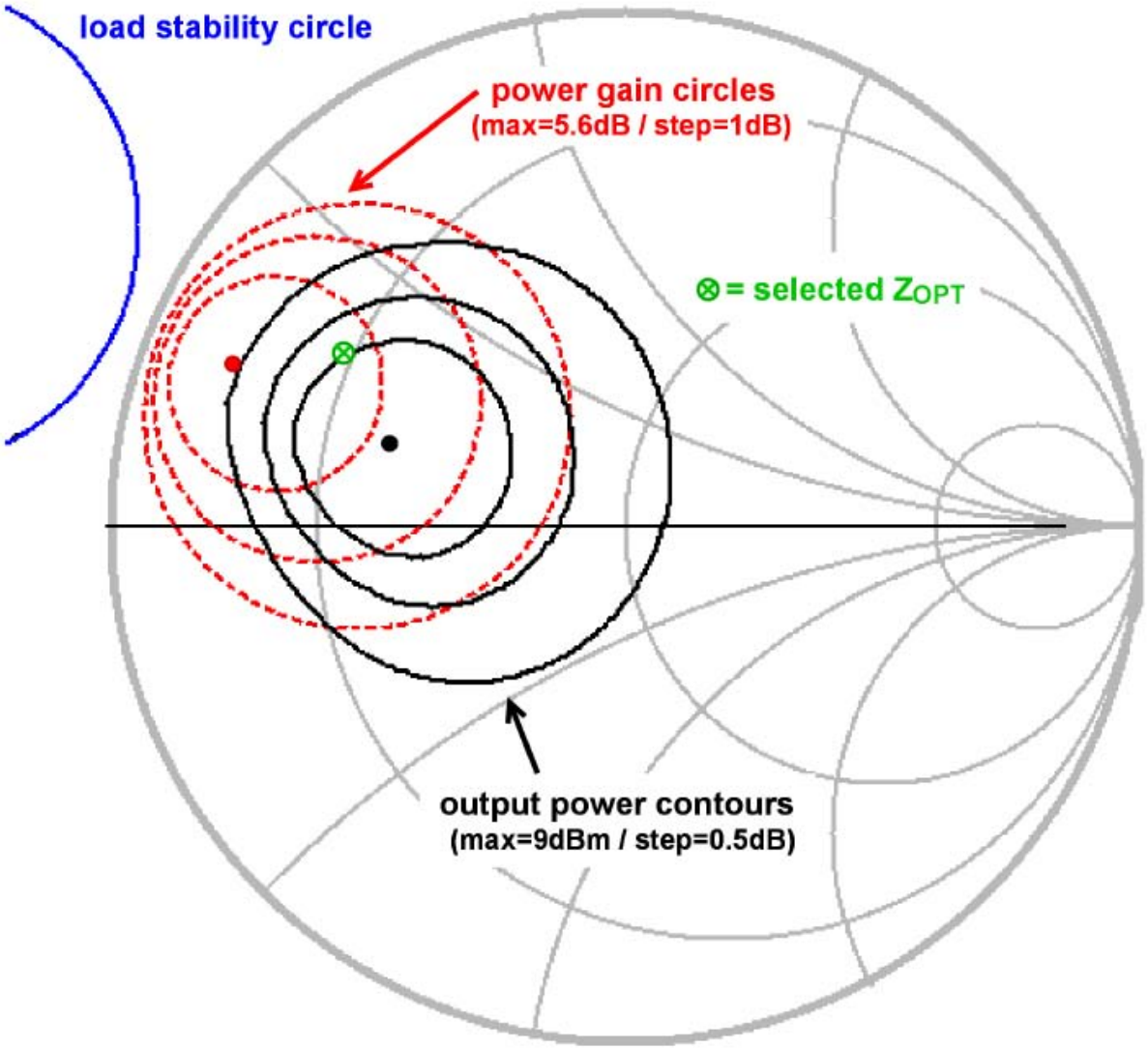


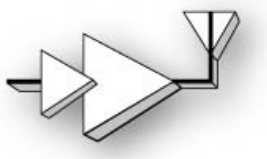




Berkeley Wireless Research Center

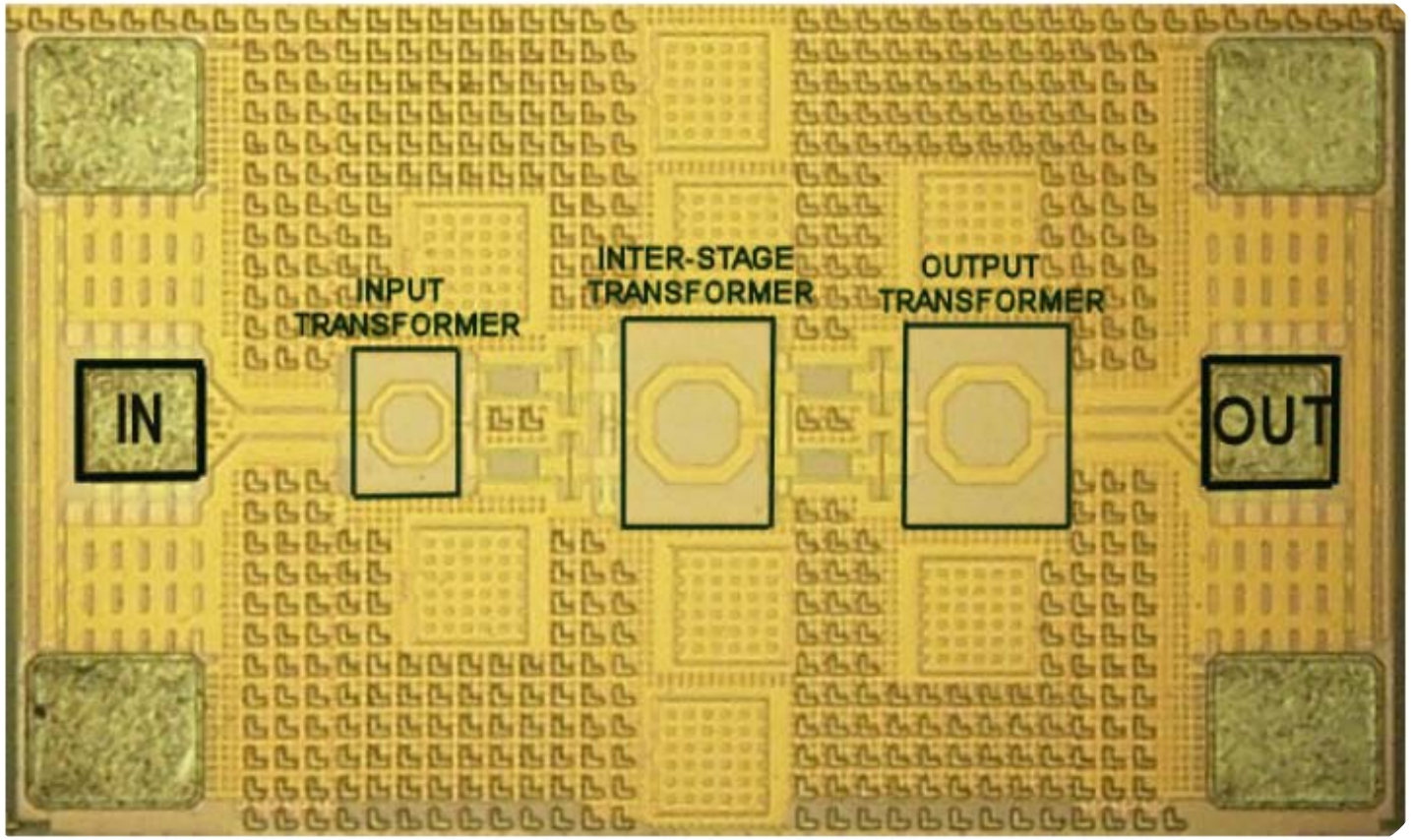
Impedance Matching



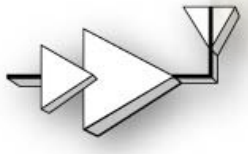


Berkeley Wireless
Research Center

PA Die Photo

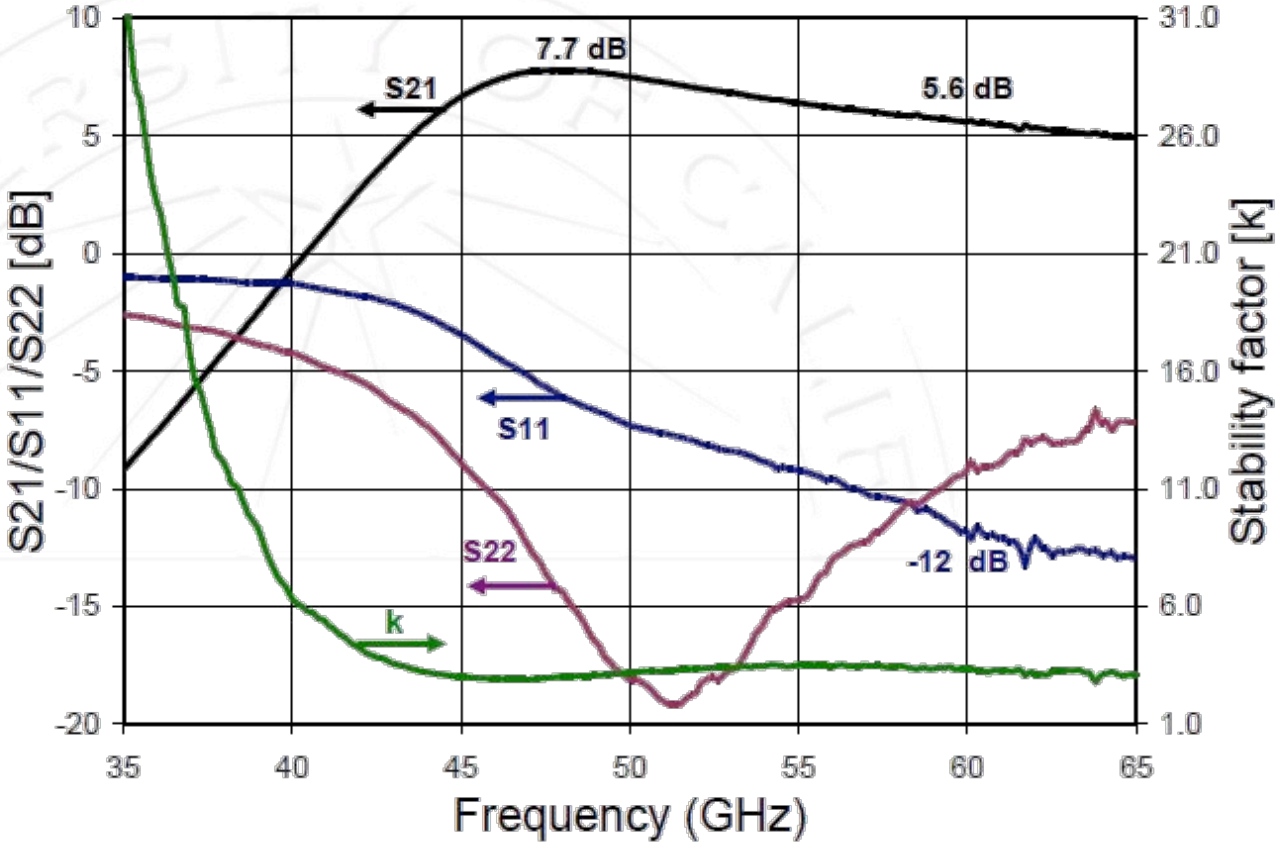


- Area: 0.25 mm^2
- Small area due to transformers

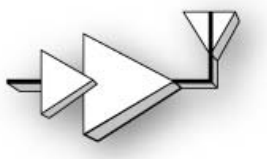


Berkeley Wireless
Research Center

Measured S-Parameters

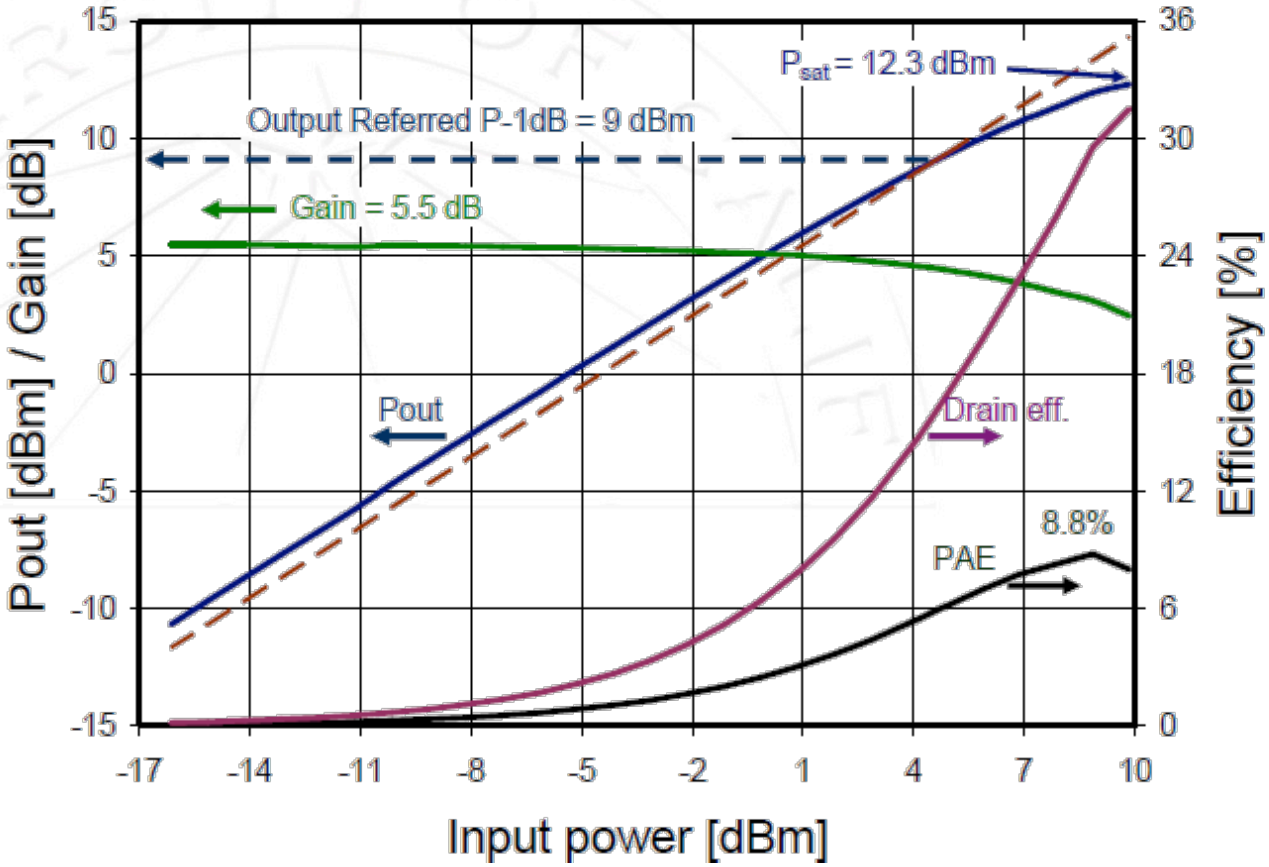


- Broadband gain (45 - 65 GHz)
- Good matching (55 -65 GHz)
- Stable (K > 1)

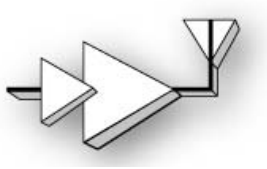


Berkeley Wireless Research Center

Power Measurements

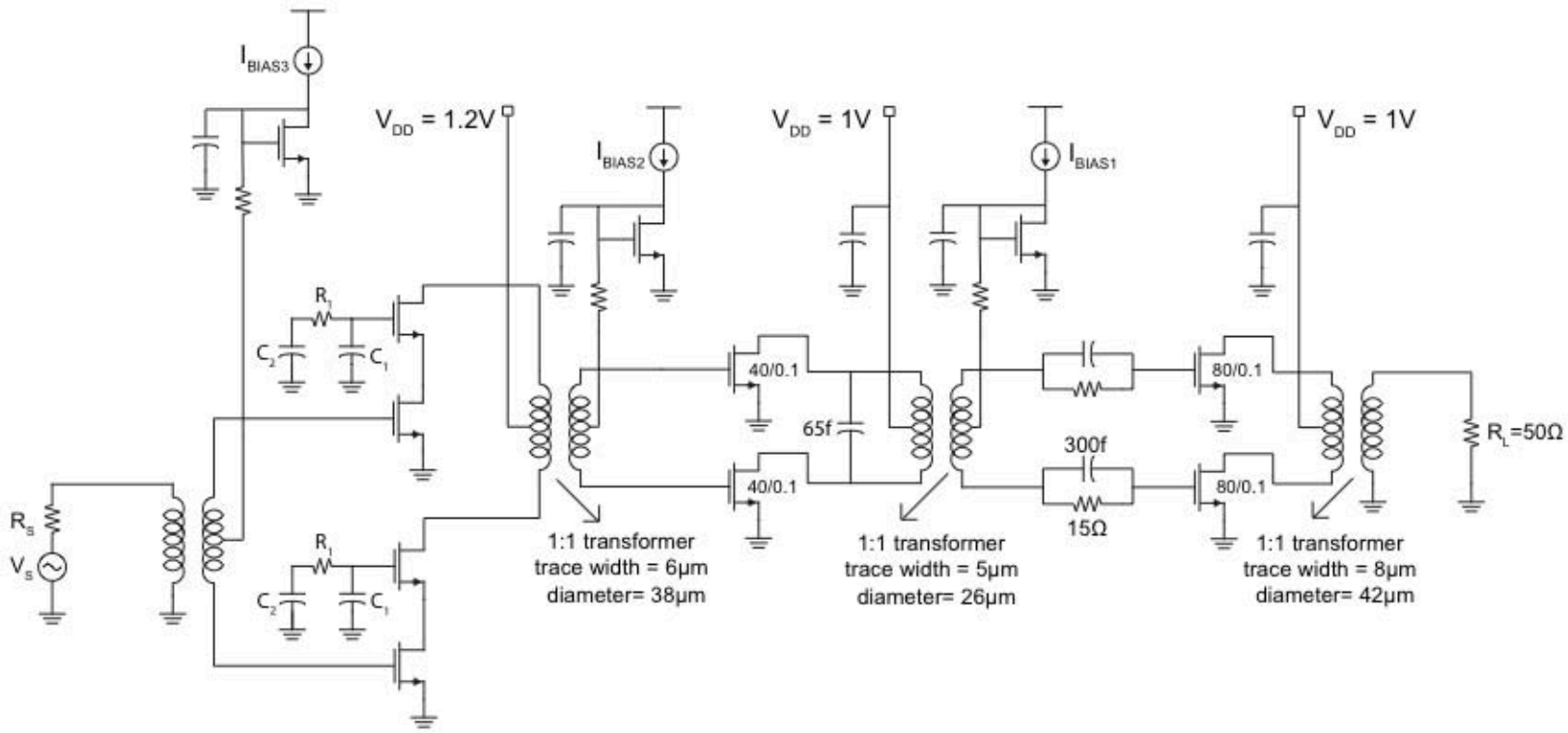


- P_{-1dB} > 9dBm (up to 10dBm measured)
- P_{sat} = 12.3 dBm

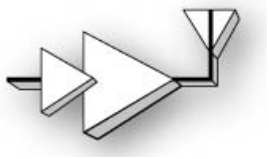


Berkeley Wireless Research Center

Improved Three-Stage PA

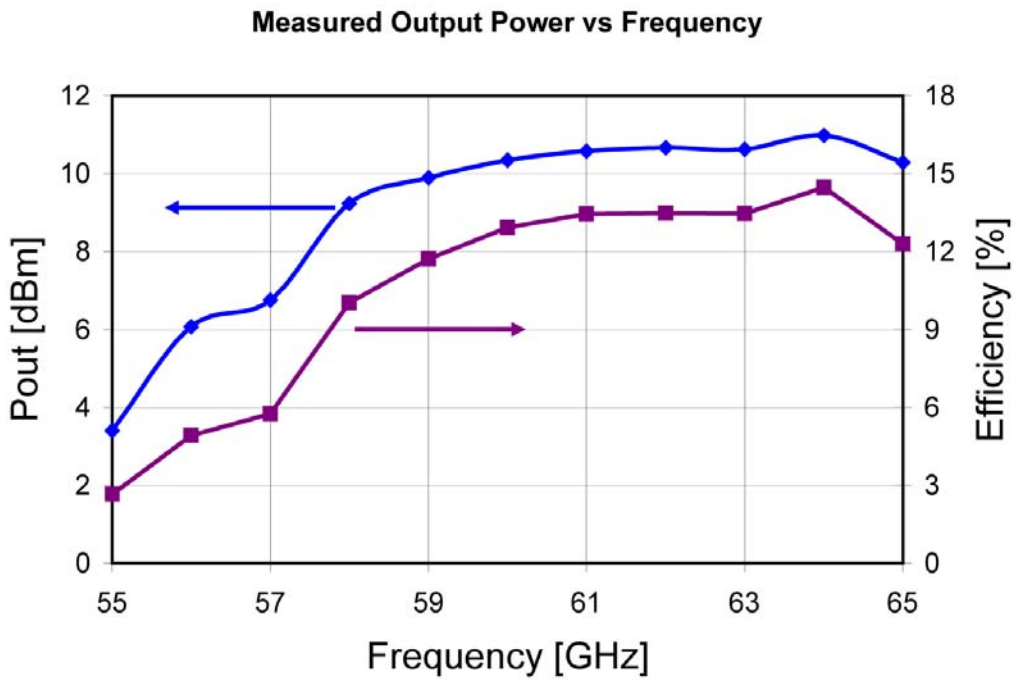


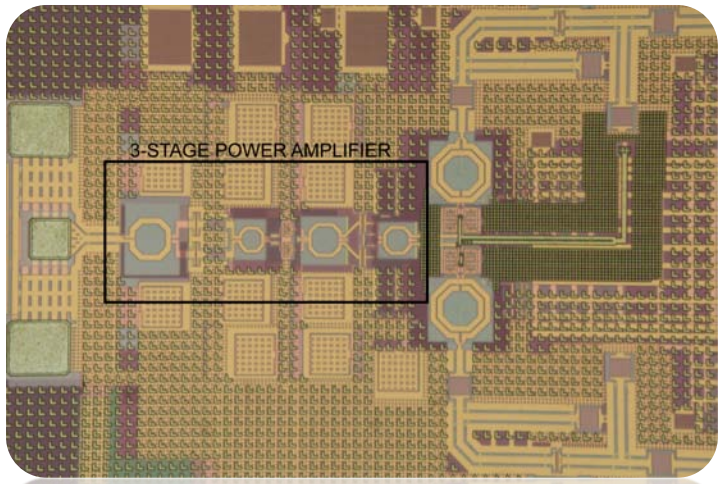
- Optimized driver stage (smaller transistors) for higher gain
- First driver stage cascode configuration for slightly higher gain and unconditional stability at 60GHz



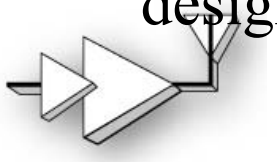
Berkeley Wireless Research Center

Three-Stage PA Measurements



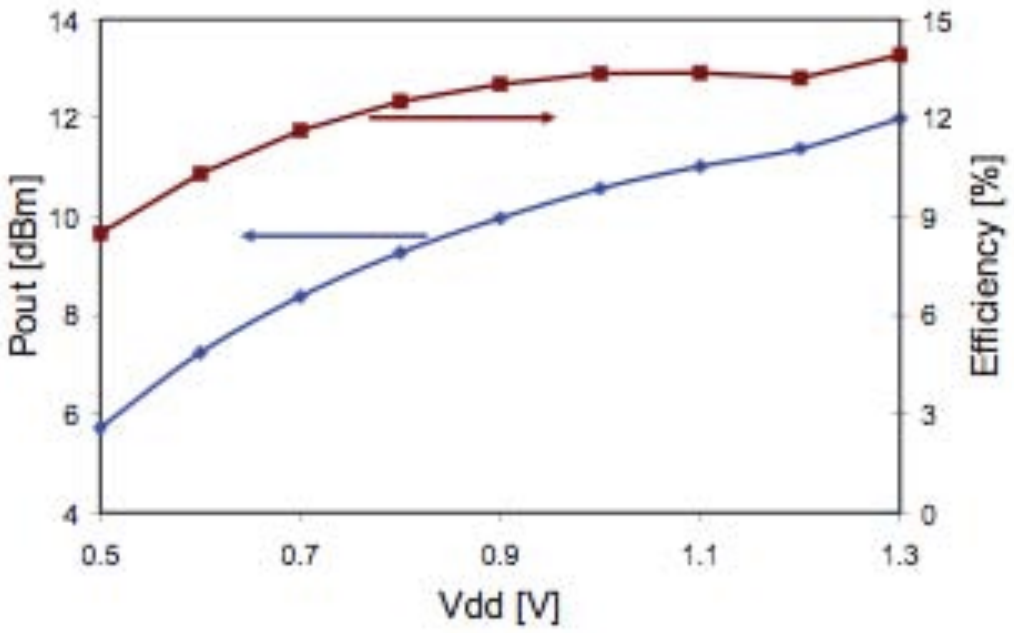


- Driver design critical since MSG at mm-wave frequency low → simultaneous gain-output power based optimization necessary
- Measured PAE close to 15% (nearly double the two-stage design) with 14dB of power gain at 60GHz

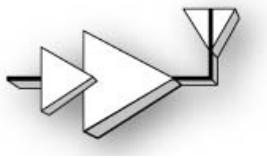


Berkeley Wireless Research Center

PA Output / PAE versus Supply

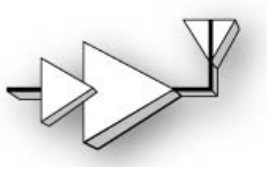


- As expected, output power increases with supply.
- Reliability is a major concern for CMOS devices. In our design we operate the CMOS PA at a lower supply voltage.



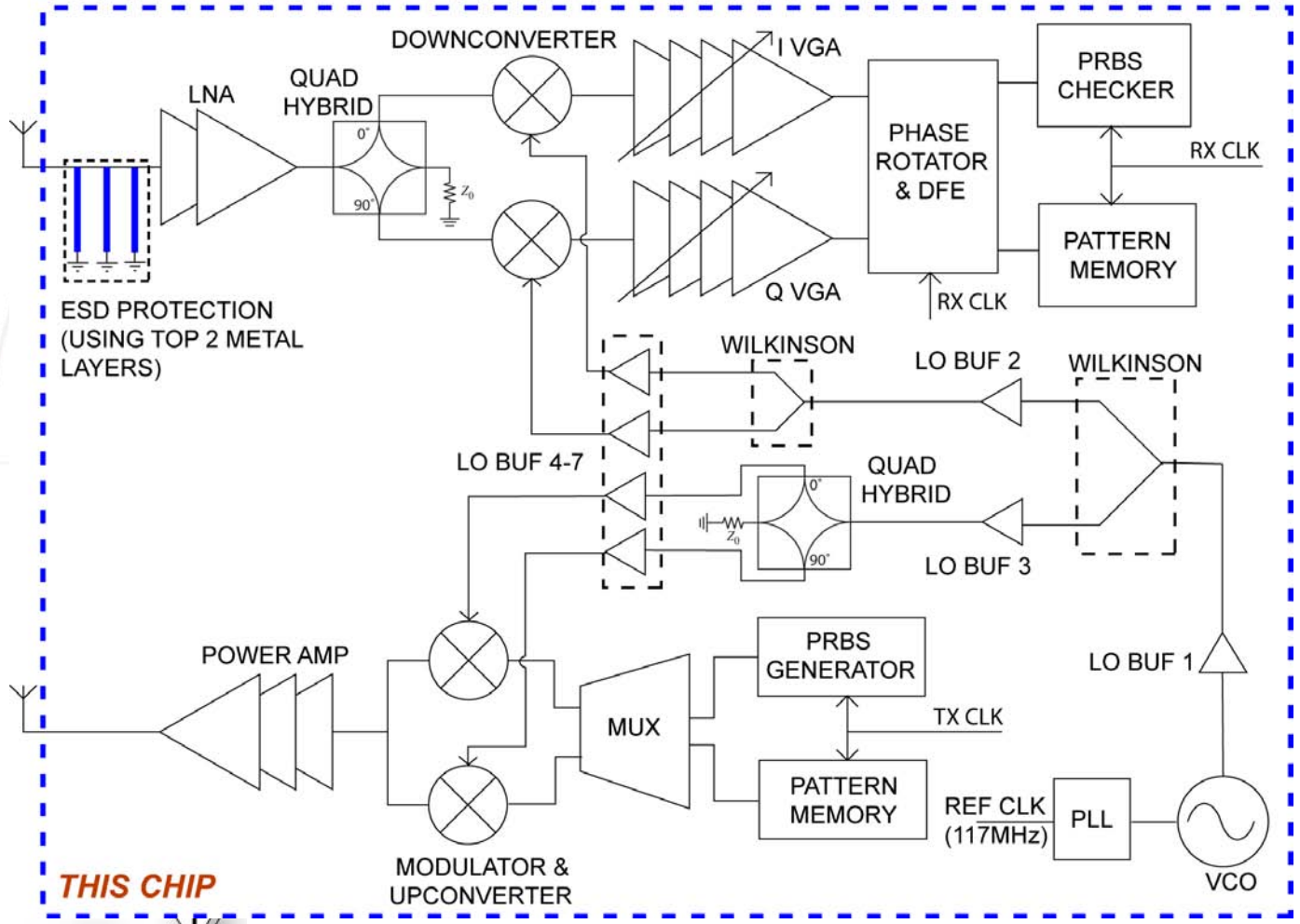
Berkeley Wireless Research Center

60 GHZ TRANSMITTER



Berkeley Wireless
Research Center

Transceiver Block Diagram



Vdd = 1.2V

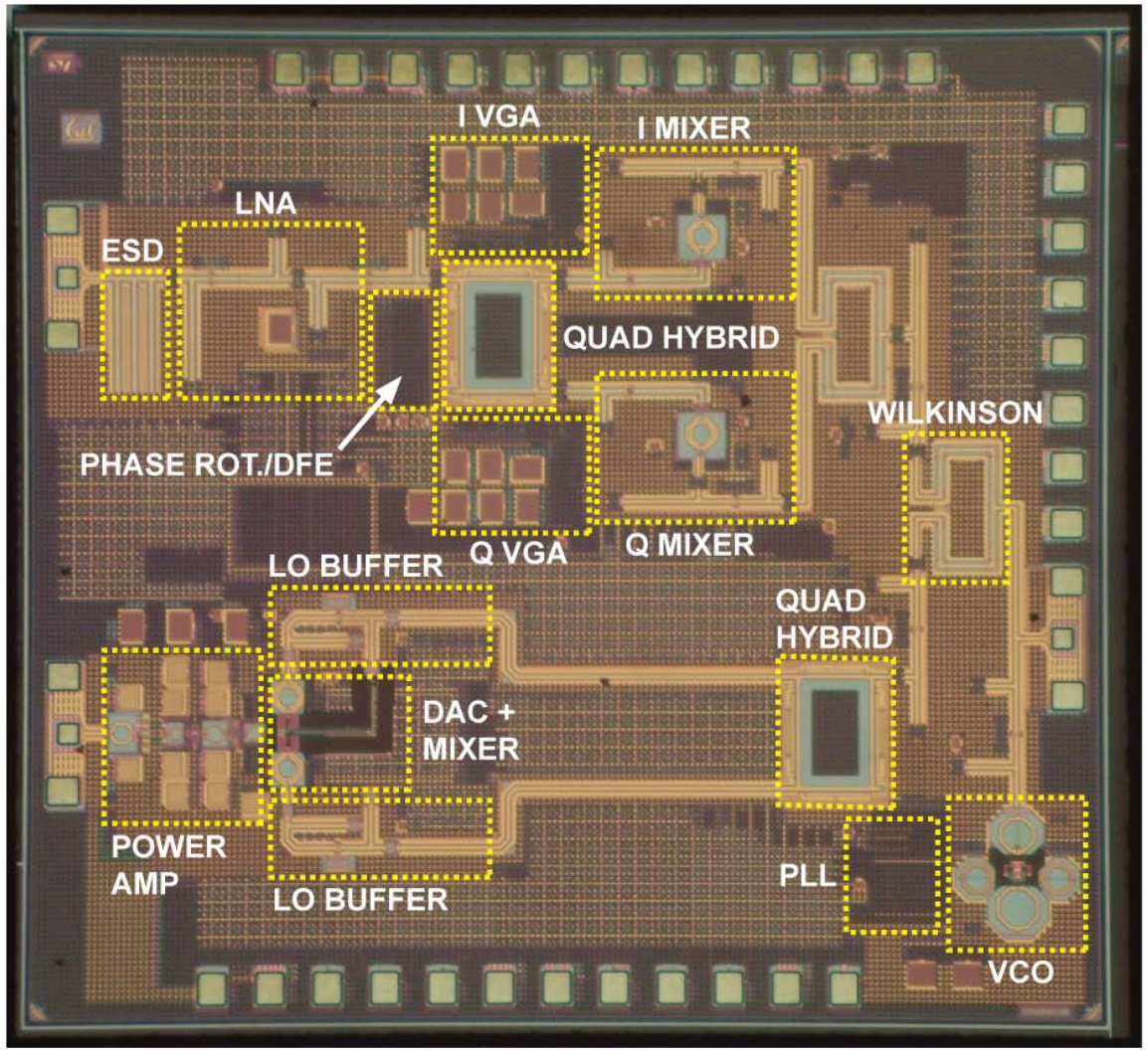
~5GHz RF BW

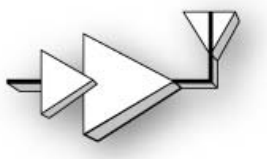
TX: 170mW

RX: 138mW

Berkeley Wireless Research Center

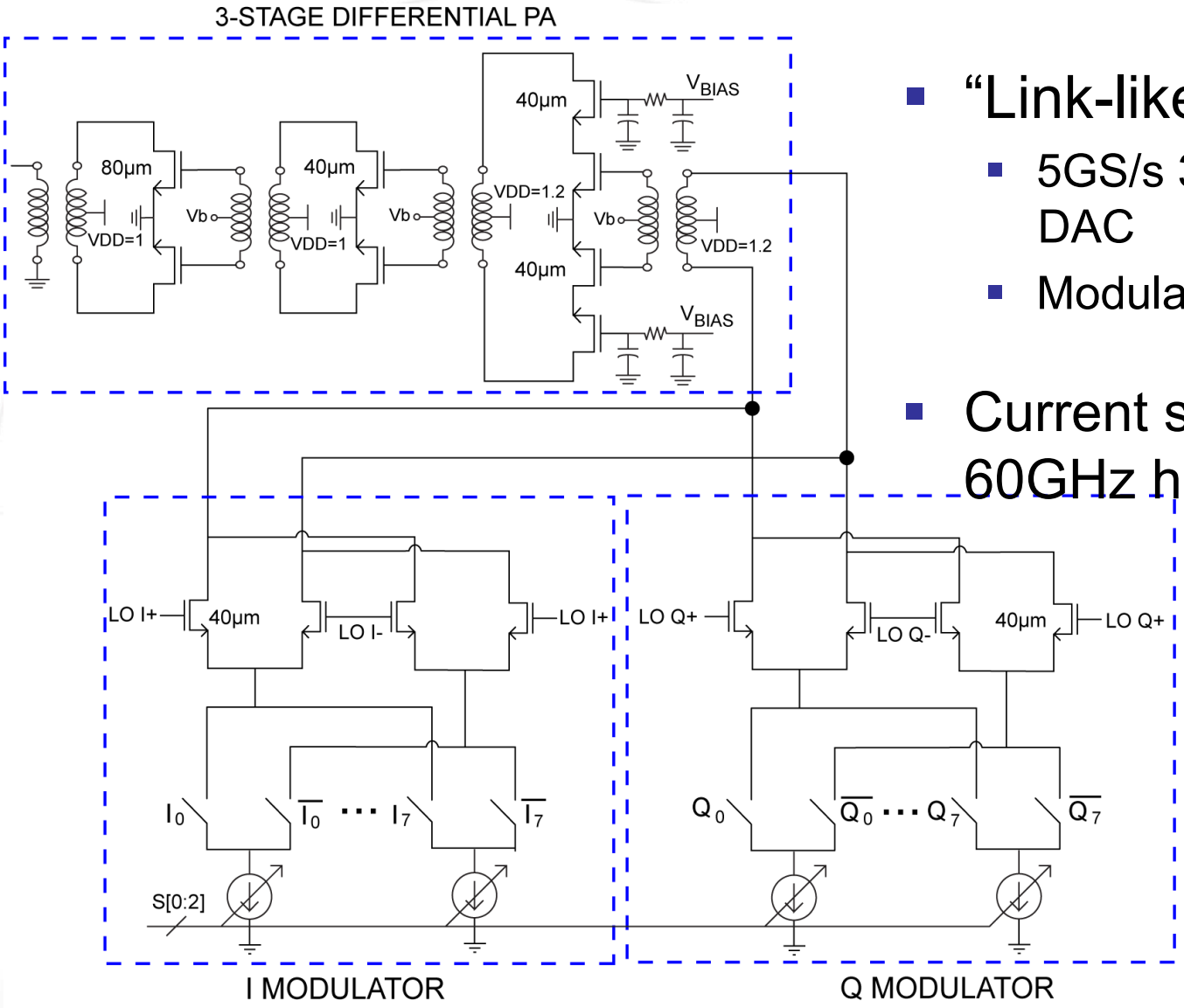
Chip Layout





Berkeley Wireless
Research Center

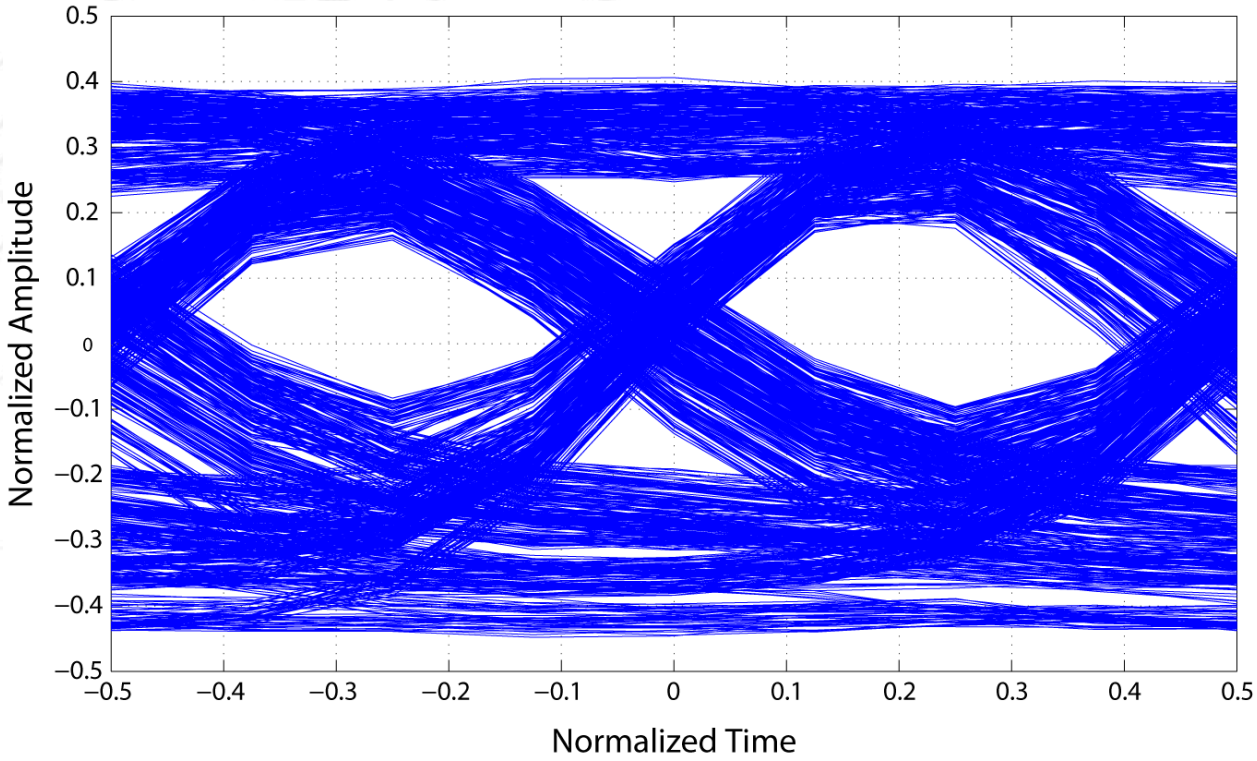
Modulator and PA



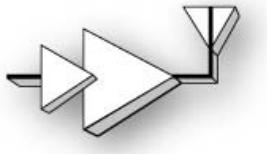
- "Link-like" TX:
  - 5GS/s 3-bit current mode DAC
  - Modulator power ~22mW
- Current summation at 60GHz hard
  - PA input needs low impedance

Berkeley Wireless Research Center

Measured Eye Diagram

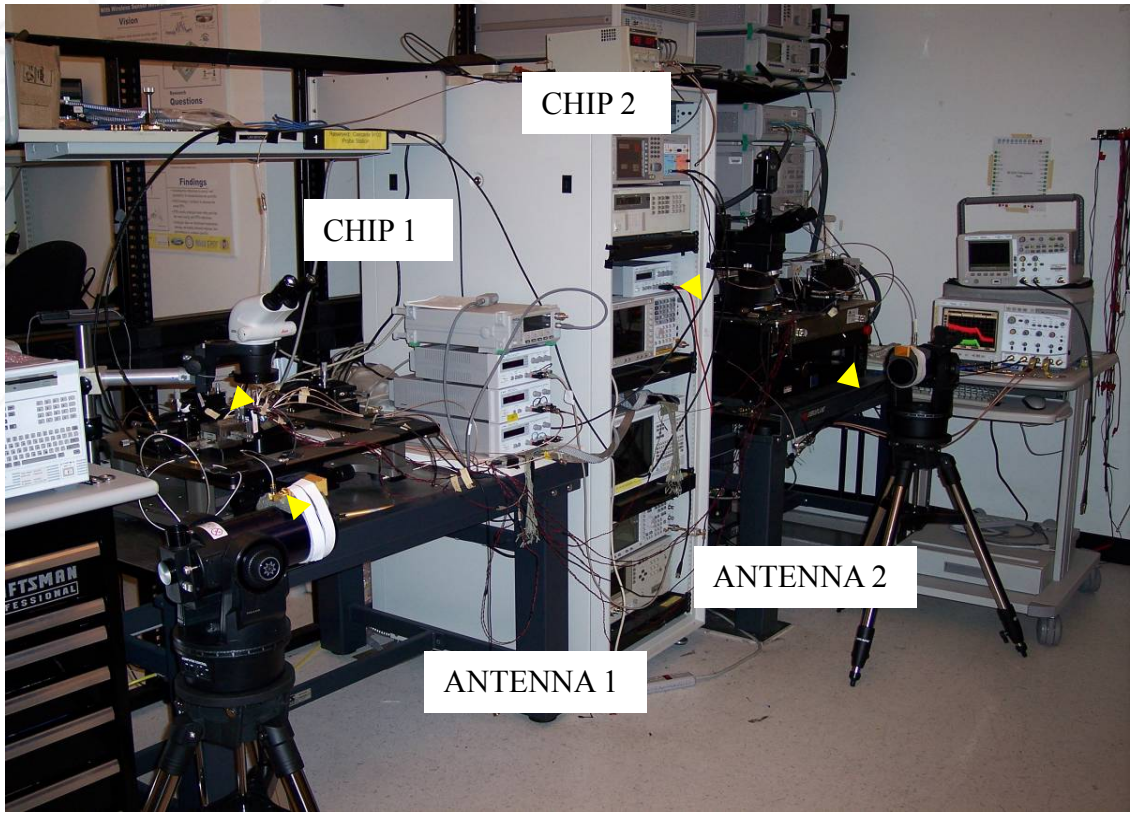


- Simulated modulator output power: -2.3dBm
  - Power from just I or Q is -1dBm → loading
- Measured PA output power: ~10dBm

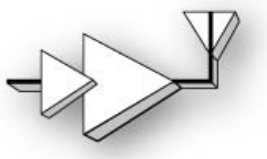


Berkeley Wireless Research Center

Wireless Test



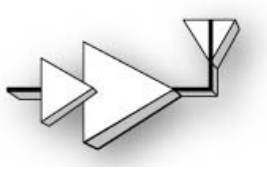
- 1m distance (+ ~2m cables), 25dBi horn antennas
- Received up to 4Gb/s at 10^{-11}



Berkeley Wireless Research Center

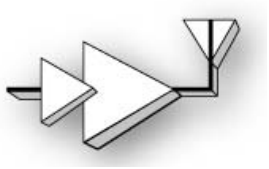
Conclusion

- CMOS device have F_t ~ mm-wave range. Low voltage devices make mm-wave operation challenging.
- Optimized layout results in F_{max} ~ 2-3 F_t
- CMOS power amplifiers with Psat ~ 12 dBm can be realized in 90nm technology (1V supply). Higher power levels is challenging.
- A complete transceiver is demonstrated in 60 GHz with record energy consumption
- CMOS of tomorrow will enable dream of millions of RF/ mm-wave transistors allowing EM to bits



Acknowledgements

- 60 GHz Research Team:
  - Mounir Bohsali, Babak Heydari, Ehsan Adabi, Bagher Afshar, Debopriyo Chowdhury, Amin Arbabian, Maryam Tabesh, Jung-Dong Park
- DARPA TEAM Project / C2S2 Marco Center
- ST Microelectronics
- BWRC Member Companies



Berkeley Wireless Research Center