A 140GHz power amplifier with 20.5dBm output power and 20.8% PAE in 250-nm InP HBT technology

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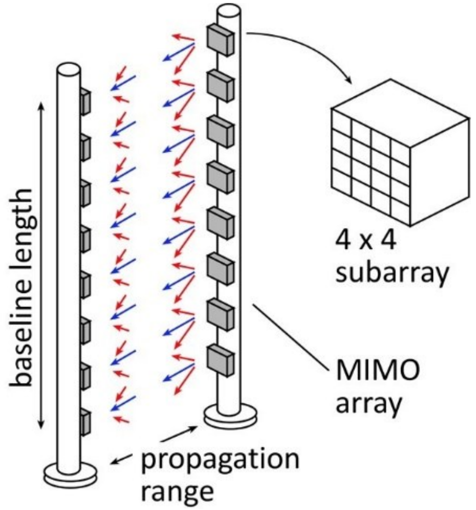
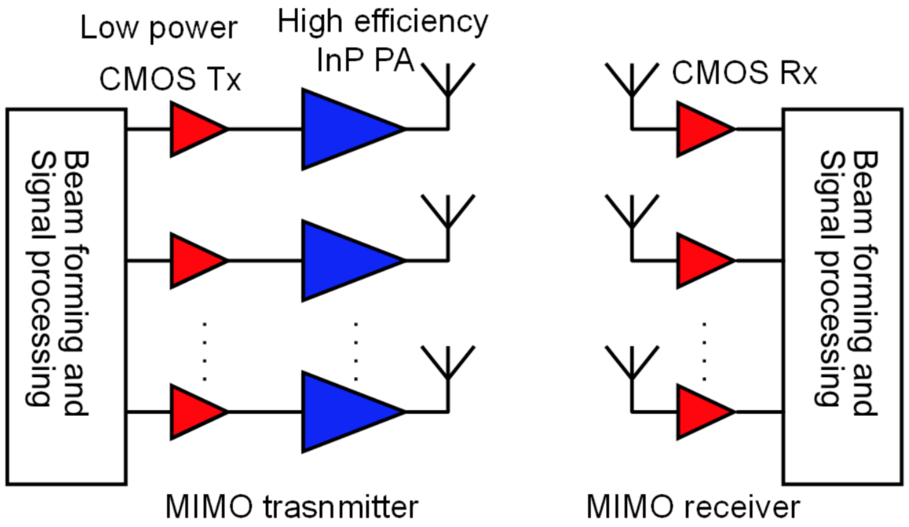
mm-wave Communication (140-1000 GHz)

- Objective
  - –Support high data rate communication.
  - –Spatial multiplexing for high capacity.
  - –Cover long distance.
- Benefits (140- 1000 GHz)
  - –Large available spectrum, high data rate.
  - –Shorter λ: more channels for the same array size.
- Challenge
  - –Atmospheric attenuation is high $P_R \alpha \frac{\lambda^2}{R^2} e^{-\alpha R}$.



PA Requirments and Link Budget

- CMOS chips drives high efficiency InP power amplifiers
- CMOS's output power is ~2dBm
- 20.5dBm output power per element extends the link range to ~50m
- Required gain ~20dB
- Massive MIMO arrays requires high efficiency PAs to avoid thermal destruction or complex heatsink

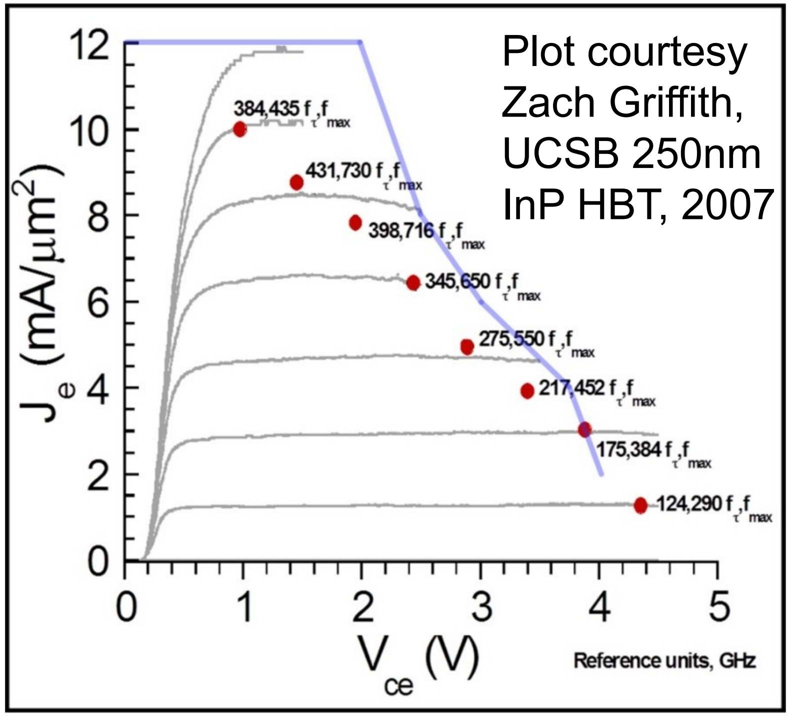


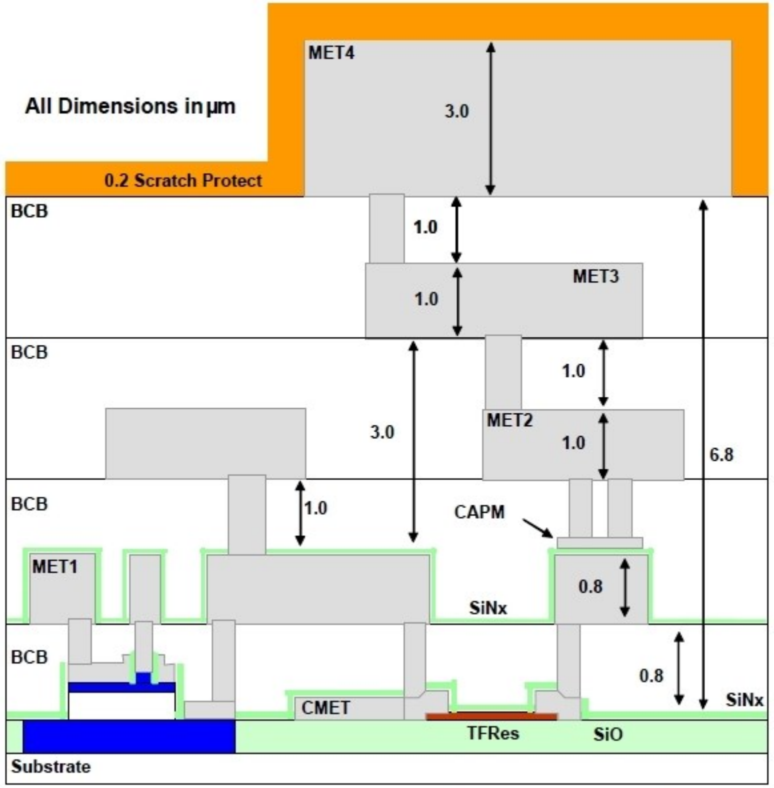
Tx Antenna Gain	22.7 dBi
Rx Antenna Gain	13 dBi
Link range	50 m
Required output power per element	20.5dBm
Friss Path Loss	73 dB
Rx Noise Figure	8.5 dB
Rx BW	5 GHz
Bit rate	10 Gb/s
System Margin	15 dB
No of elements, Tx ($\lambda/2$ spacing)	32
No of elements, Rx ($\lambda/2$ spacing)	4

calculated data are based on https://www.ece.ucsb.edu/Faculty/rodwell/Classes/ece218c/ECE218c.htm

250nm InP HBT Process (Teledyne*)

- f_{max}=650GHz.
- BV_{CEo}=4.5V.
- J_{max}=3mA/µm.
- Four Au interconnect.
- MIM cap (0.3fF/µm2).
- TFR (50Ω/square).



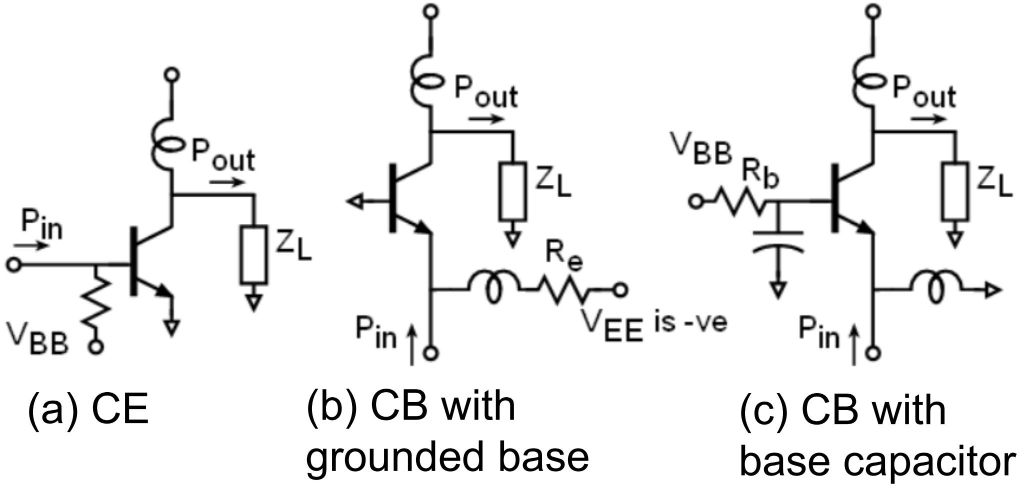


Representative cross-section of TSC250 IC technology. Drawing is not to scale.

*M. Urteaga, et al, Proc. IEEE, June 2017.

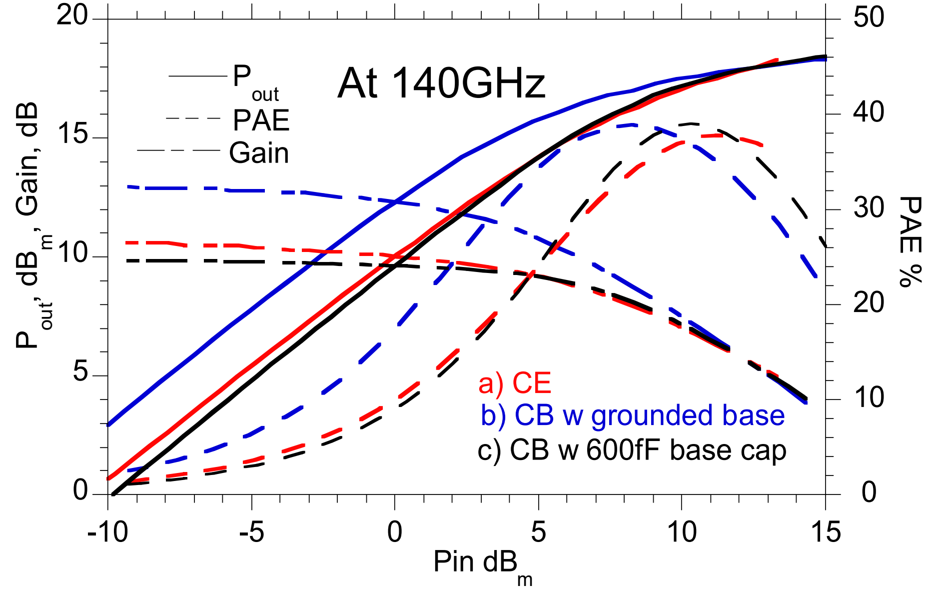
Unit Cell Comparison

- Comparison between CE, grounded CB and CB with base capacitor
- Simulation is done under same bias condition
- Large signal simulation is more relevant in power amplifier
- CB with base capacitor shows the highest OP_{1dB} with associated PAE



	Gain*, dB	PAE**, %	P_{out}**, dB_m
CE	10.7	15.4	12.0
Grounded CB	13.1	22.4	13.5
CB with 600 cap	9.8	29.7	15.2

*under opt load line condition without compression **at 1dB gain compression



P_{out}, gain, and PAE for CE, grounded CB, and CB with base capacitor.

Unit Cell Comparison

- Common emitter
  - Lowest OP_{1dB} and Soft compression
  - Less sensitive to base inductance errors
- Common base with grounded base
  - Higher gain and OP_{1dB}
  - Requires –ve supply-> huge efficiency drop (large DC current in Re)
  - Bias is very sensitive without Re due to exponential relation (I_{CE} vs V_{BE})
  - sensitive to base inductance errors
- Common base with base capacitance
  - Highest PAE and OP_{1dB} due to capacitance feedback linearization
  - Capacitance help stabilization (not shown)
  - Stable bias: negligible efficiency due to R_b ; base current is very small
  - Gain drops with smaller capacitance

	Gain*, dB	PAE**, %	P_{out}**, dBm
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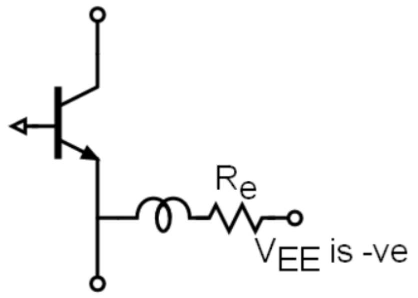
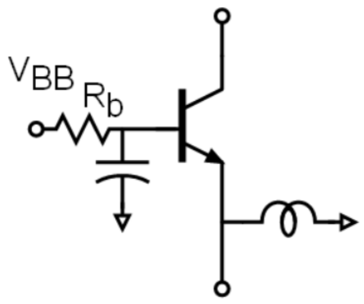


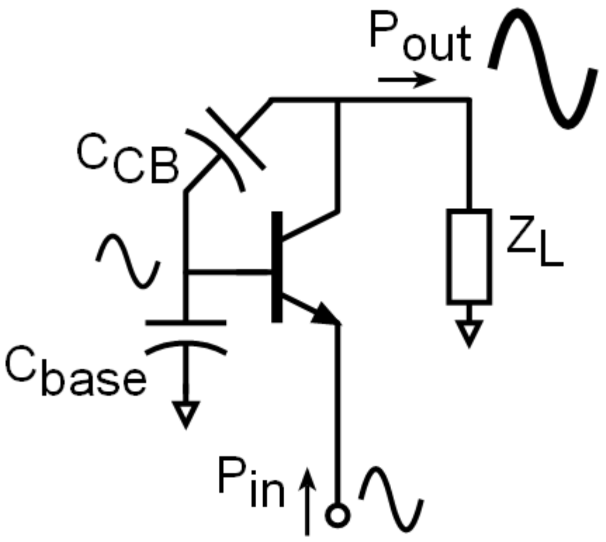
CB with grounded base



CB with base capacitor

CB viewed as stacked PA cell*

- C_{CB} and C_{base} creates negative feedback
- This negative feedback
  - Linearize the amplifier: higher PAE and OP_{1dB}
  - Allows voltage swing on the base: with proper design, the output swing increases yielding in higher output power
  - Drops the output impedance: improves S22



PA unit cell/ stack analogy

*A. Ahmed, et al, EUMIC 2018.

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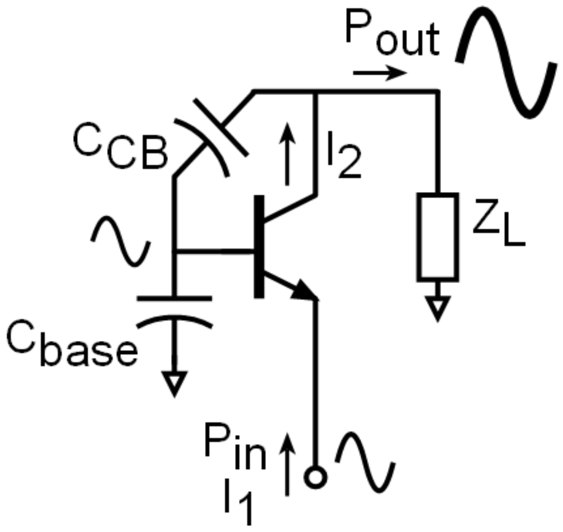
PAE invariance*

- Assuming lossless matching network
- Internal voltages and currents are constant by proper load and base impedances*
- $2(n-1)\omega P_{add} C_{base} = X_1 X_2 \sin(Y_1 - Y_2)$ (derivation not shown)
- The added power per stage is kept constant for the same internal voltages and currents.
- $P_{out} = P_{add} + P_{in}$

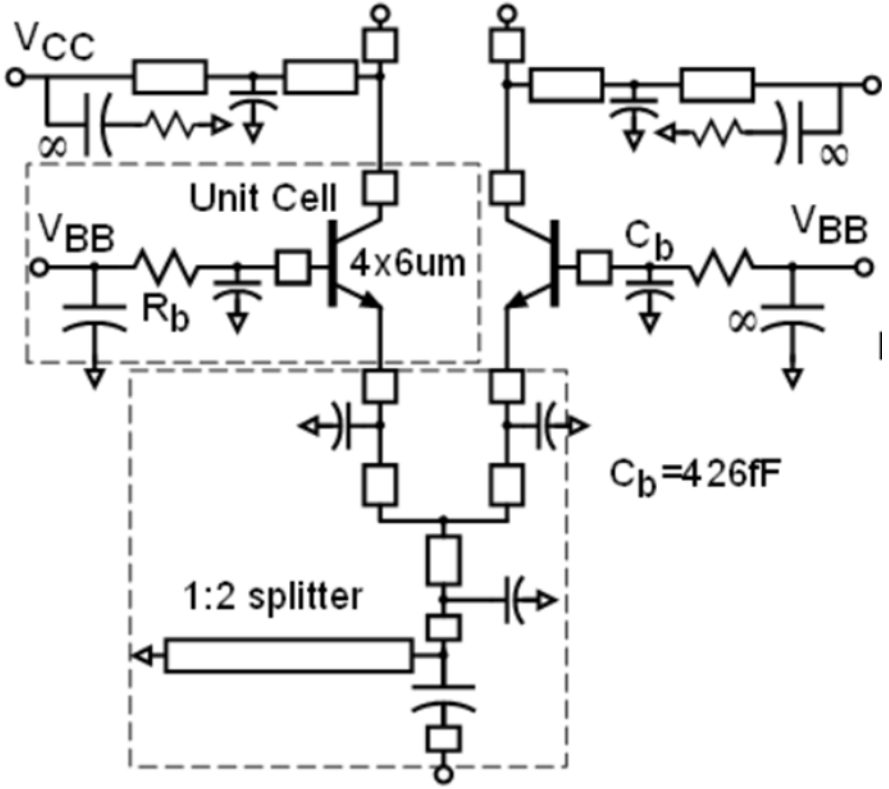


X_1 is the magnitude of I_1
X_2 is the magnitude of I_2
Y_1 is the angle of I_1 in radians
Y_2 is the angle of I_2 in radians

*A. Ahmed, et al, EUMIC 2018.

Power Amplifier Cell

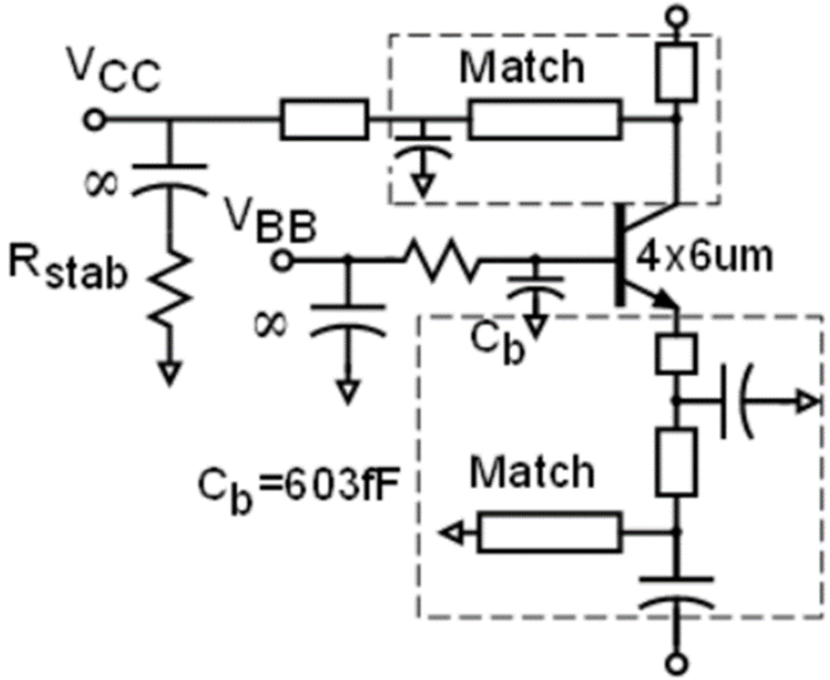
- Common base with base capacitance
- Capacitance dropped slightly
  - More power and hard compression
  - lower output impedance (better S22)
- Shunt stub tunes the transistor parasitics
- Two cells are combined and driven by a single driver-> better PAE
- ADS and HFSS are used for the interconnect and matching circuit simulations



Two combined PA cells

Driver design

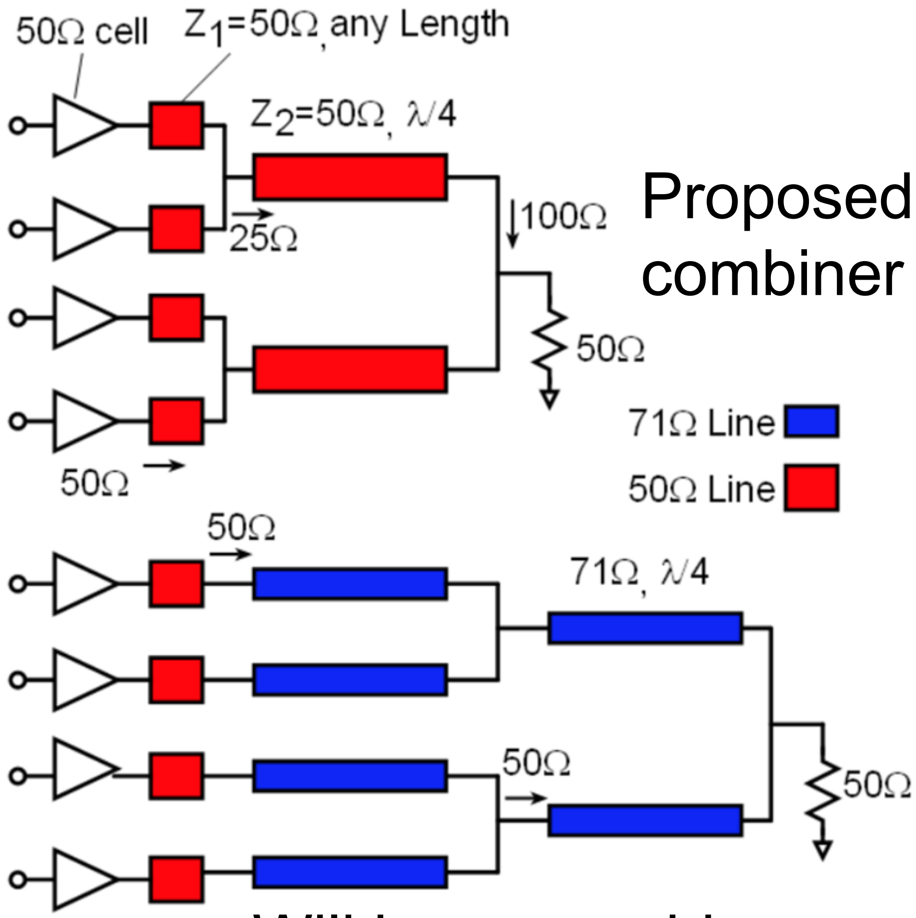
- Higher base capacitance:
  - more gain
- Input ant output are 50Ω matched
- Staggered matching for wider bandwidth



Driver cell

Combiner Design

- Transmission line combiner instead of Wilkinson
- Proposed combiner
  - Low loss and very compact
  - Smaller BW compared to Wilkinson
- Wilkinson
  - Bulky, high loss and skinny line
  - Higher BW



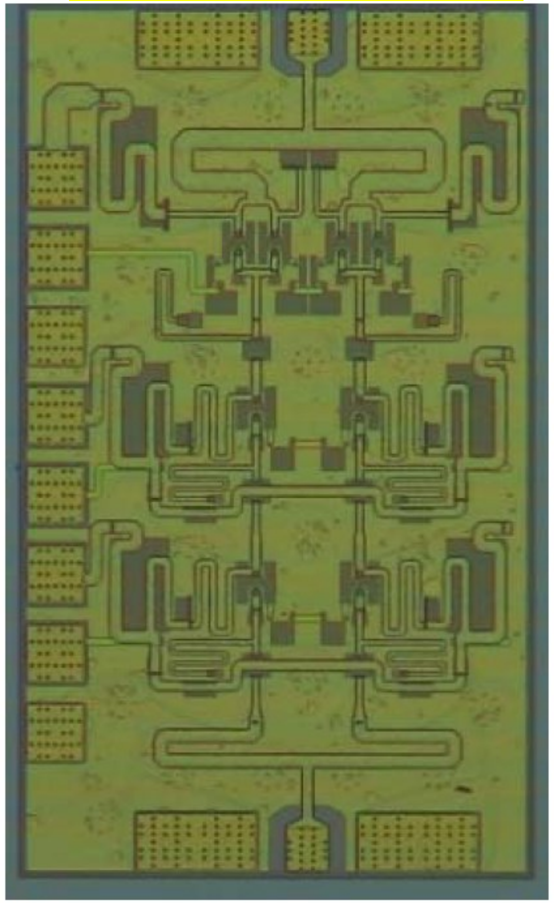
Proposed combiner

Wilkinson combiner

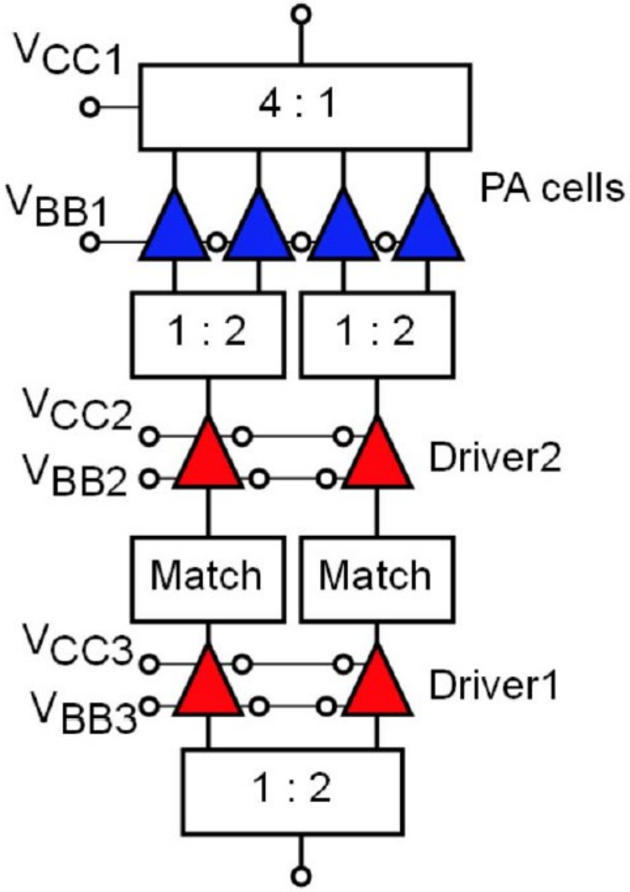
PA block diagram

- Three linearized common base stages
- Low loss and compact transmission line combiner
- First driver scaled to sustain good PAE
- Independent bias for each stage to monitor the current and optimize the PAE

1.08mmx0.63mm



Chip micrograph

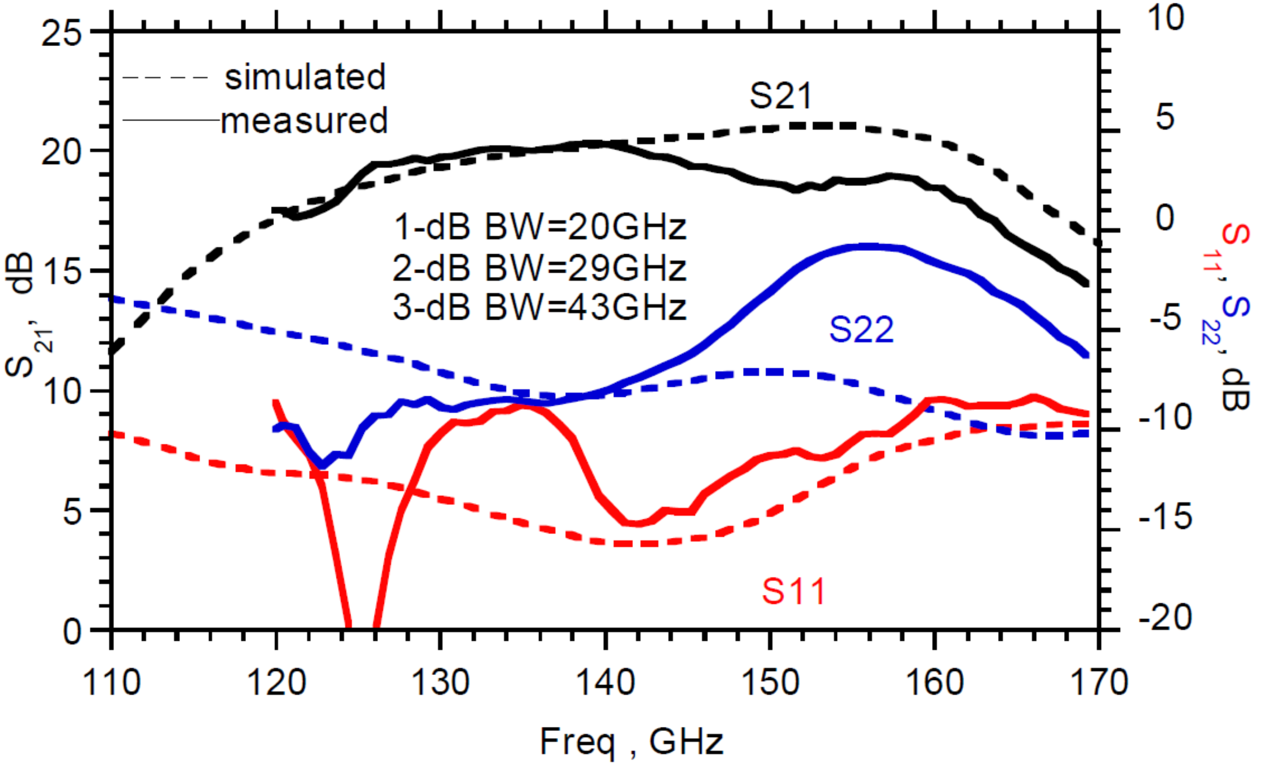


Block diagram

Measurement results

- Wide band operation
- 1dB BW=20GHz
- 3dB BW=43GHz

V_{CC1}	V_{CC2}	V_{CC3}	V_{BB1}	V_{BB2}	V_{BB3}
2.5V	2.5V	1.5V	1.94V	1.36V	1.1V
I_{CC1}	I_{CC2}	I_{CC3}	I_{BB1}	I_{BB2}	I_{BB3}
121mA	52mA	31.8mA	4.1mA	1.7mA	0.95mA

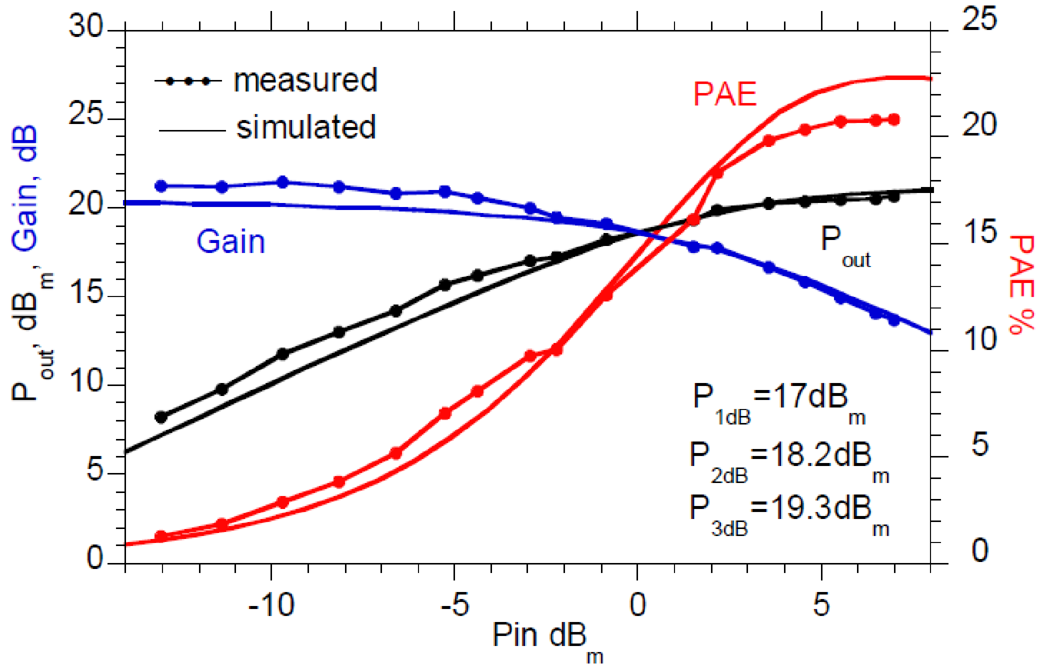


Measured (solid) vs simulated (dotted) S-parameters

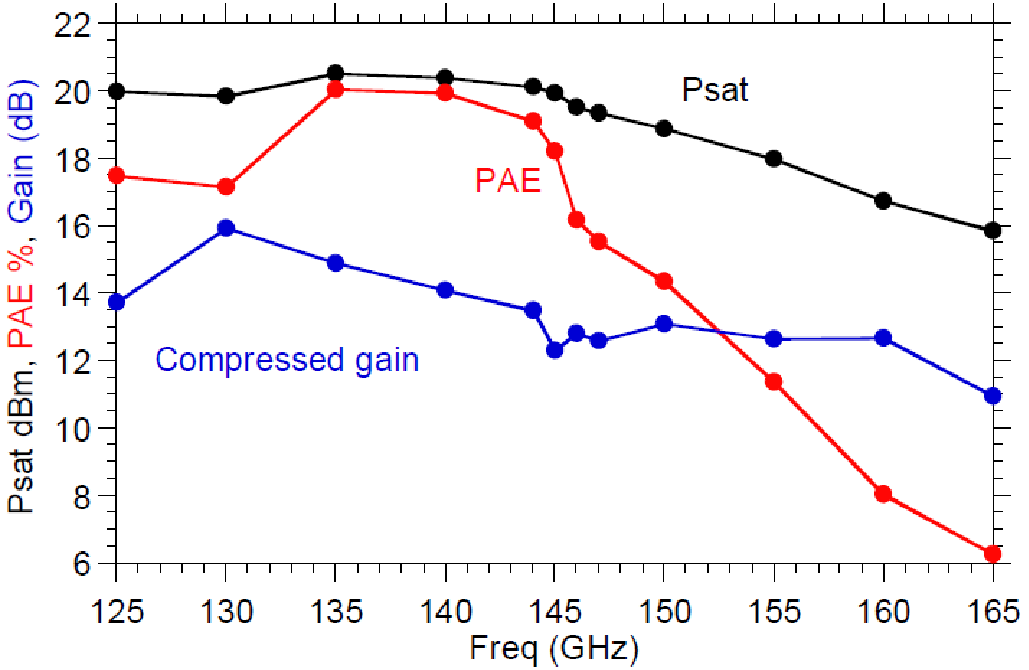
Measurement results

- P_{sat}=20.5dB$_m$, and PAE=20.8%
- P_{sat} =18.9-20.5dB$_m$ over 125-150GHz

V_{CC1}	V_{CC2}	V_{CC3}	V_{BB1}	V_{BB2}	V_{BB3}
2.5V	2.5V	1.5V	1.95V	1.4V	1.1V
I_{CC1}	I_{CC2}	I_{CC3}	I_{BB1}	I_{BB2}	I_{BB3}
130mA	56mA	34mA	5mA	2mA	1mA



Measured and simulated P_{out}, PAE and gain vs input power at 140GHz



Measured and simulated saturated P_{out}, PAE and gain vs frequency

State-of-the-art results

- Highest PAE for comparable P_{sat} and gain

Ref	Technology	Freq (GHz)	P_{sat} (dBm)	BW_{3dB} GHz^{++}	Gain at P_{sat} (dB)	Peak PAE %	Size (mm^2)	P_{DC} (W)	P_{sat}/Area mW/mm^2
[2]	40 nm CMOS	140	14.8	17	13**	8.9	0.34	0.3	88.8
[4]	130-nm SiGe HBT	155-180	18.0	25	23.5**	4.0	0.85	1.57*	74.2
[5]	130-nm SiGe HBT	112-142	17^{+}	16	29**	13^{+}	1.06	0.39*	47.2
[6]	130-nm SiGe HBT	131-180	14	49	22**	5.7	0.48	0.44*	52.3
[7]	250-nm InP HBT	110-150	23.2-24.0	32.7	14-16	5.8-7.0	1.89	3.46	134
[8]	250-nm InP HBT	115-150	21-21.8	34.8	15-17.5	8.2-10.5	0.75	1.54	205
This work	**250-nm InP HBT**	**125-150**	**18.9-20.5**	**43**	**12.3-15.9**	**14.3-20.8**	**0.69**	**0.52**	**162**

Summary

- Demonstration of record PAE at D-band
- Teledyne 250nm InP HBT has high f_{max} and BV_{CEo}
- Capacitively linearized common base
  - Higher OP_{1dB}, and PAE
  - Easier to bias and stabilize
- Compact and low loss transmission line network
- Driver scaling and bias optimization

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