A compact H-band Power Amplifier with High Output Power

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Outline

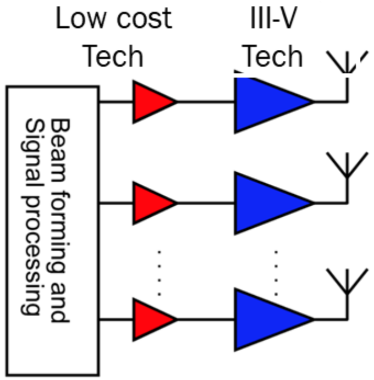
- Motivation for sub-THz frequencies.
- Prior work at H-band.
- Potential applications for the amplifier.
- Amplifier design
  - unit cell and low-loss compact combiner
- Measurement results
- Summary and conclusion

Motivation

- Objective: support high data rates.
- Sub THz (~300GHz)
  - More available spectrum-> high data rates.
  - Shorter λ: more channels for the same array size.
- Main challenge: high losses (path loss $P_R \alpha \frac{\lambda^2}{R^2} e^{-\alpha R}$ +interconnect)
- Solution:
  - Phased arrays increase the directivity, the transmission range.

$$\boxed{P_{received} / P_{trans} = (D_t D_r / 16\pi^2)(\lambda / R)^2}$$

  - Use III-V technologies to produce more output power per element.



MIMO trasnmitter

Prior Work at H-band

- CMOS shows -3.9dBm at 257GHz [1].
- III-V technologies show better performance, though power and efficiency are still low.

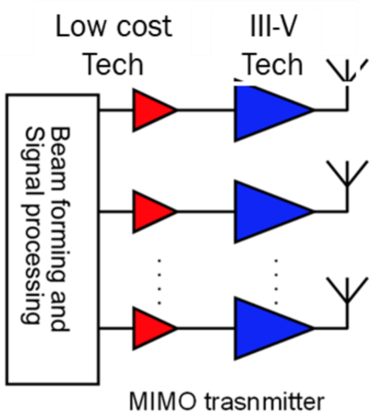
Ref	[1]	[5]	[7]	[8]	[2]	[10]	[9]	[4]	[6]	[11]	[3]
Freq, GHz	257	240	185-255 265	325	275-320	338	300-305	300	290-307.5	301	280-328
P_{sat}, dBm	-3.9	>10.8	20-23.9 17.2	11.3	2.7-4.8	10	9.5-9.8	8	7.8-10	13.5	9.6-13.7
PAE at P_{sat}%	1.35	5	4.1 0.95	1.1	2.3	1.8	1.1	2.97	1.1	1.5	0.8-2.4
Technology	65nm CMOS	35 nm GaAs mHEMT	250-nm InP HBT	130-nm InP HBT	35 nm InAlAs/InGaAs	50 nm InP HEMT	250-nm InP HBT	35 nm InGaAs mHEMT	250-nm InP HBT	250-nm InP HBT	35 nm InGaAs mHEMT

- Compact, low –loss combiner and high-efficiency power cell

  -> increase the efficiency and P_{sat}/area.

This Work and Potential Applications

- Target ~ 17dBm output power with 4%PAE.
- P_{out}~17dBm output power per element extends the link range to ~50m* (8x8 array, vertical and horizontal beam angles=7°)*
- Candidate PA for subTHz transmitters for long-range applications
- Drivers could be designed in InP or low-cost technologies.

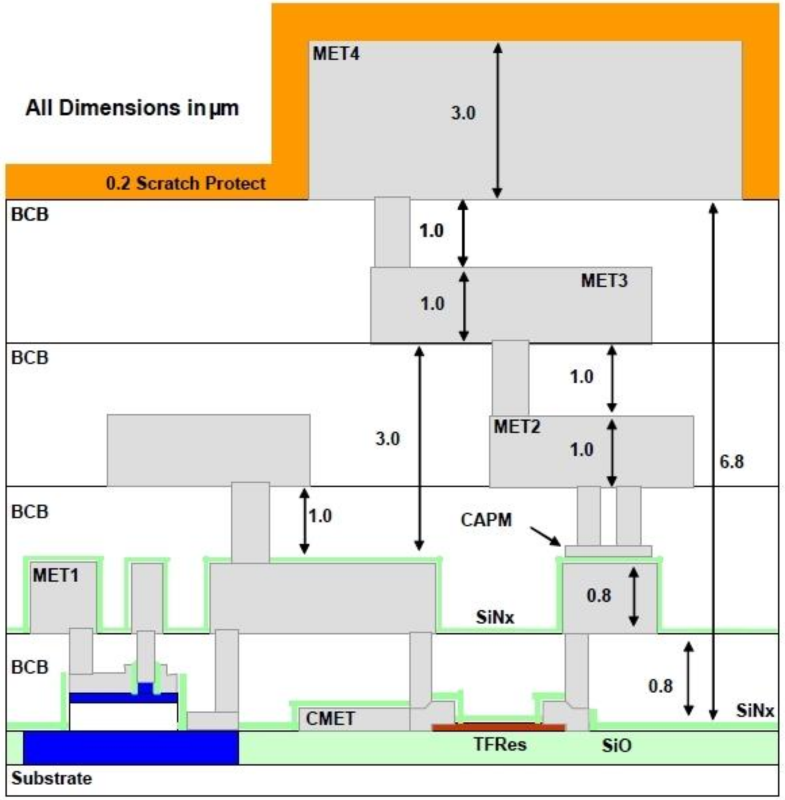


- Measuring equipment->boost the output power of the sources.

*https://web.ece.ucsb.edu/Faculty/rodwell/Classes/ece218c/ECE218c.htm

250nm InP HBT Process, Teledyne [12]

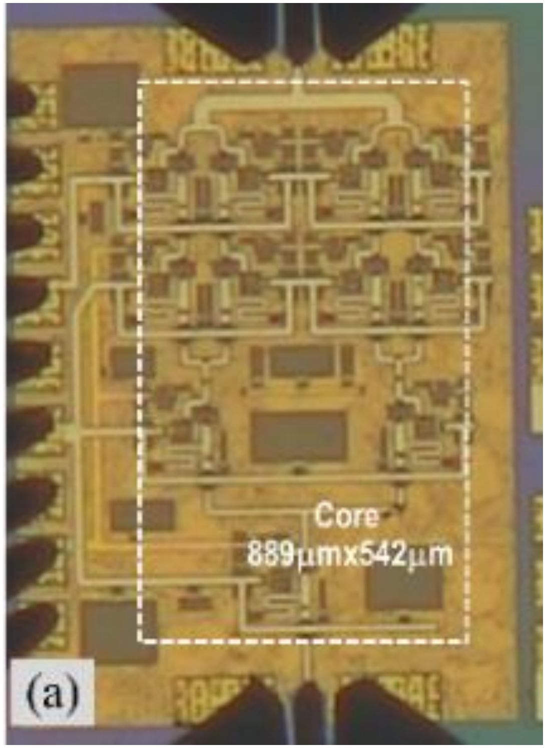
- subTHz amplifier requires fast technologies.
- f_{max}=650GHz.
- BV_{CEo}=4.5V.
- J_{max}=3mA/µm.
- Four Au interconnect.
- MIM cap (0.3fF/µm2).
- TFR (50Ω/square).



Cross section of TSC250 IC

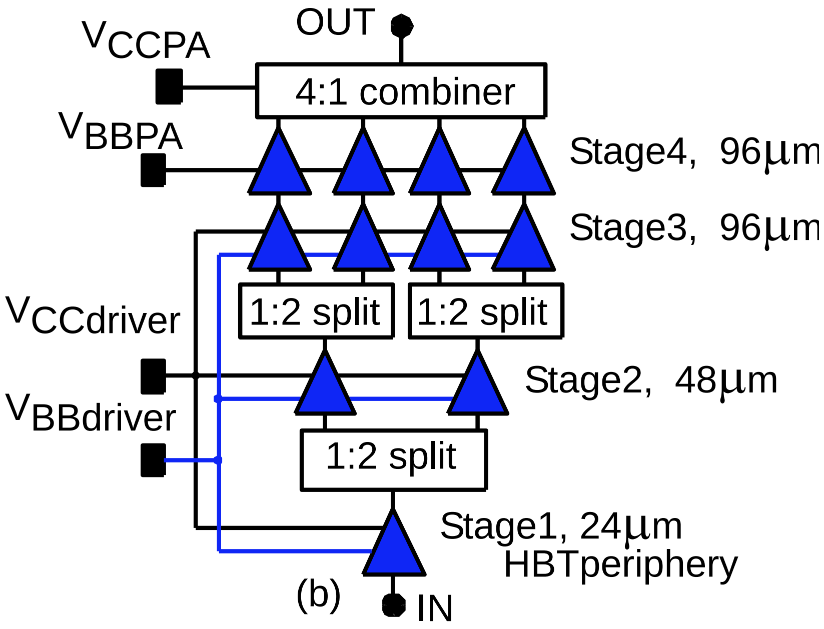
Power Amplifier Design

- Four-stage amplifier.
- Combine four power cells.
- Driver scaling sustains good PAE.



Chip micrograph of the amplifier

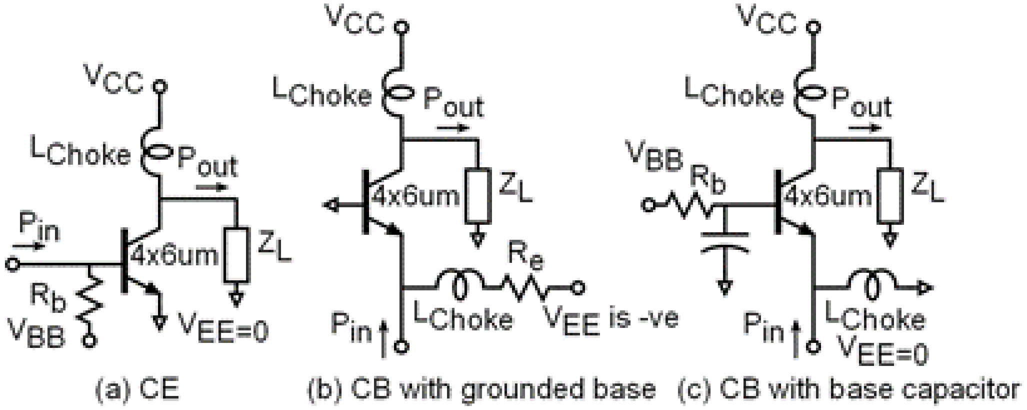
- Power combining techniques
  - Parallel combining: 4:1 transmission line combiner.
  - Series combiner: stacked unit cell.



Block diagram of the amplifier

Unit Cell Comparison

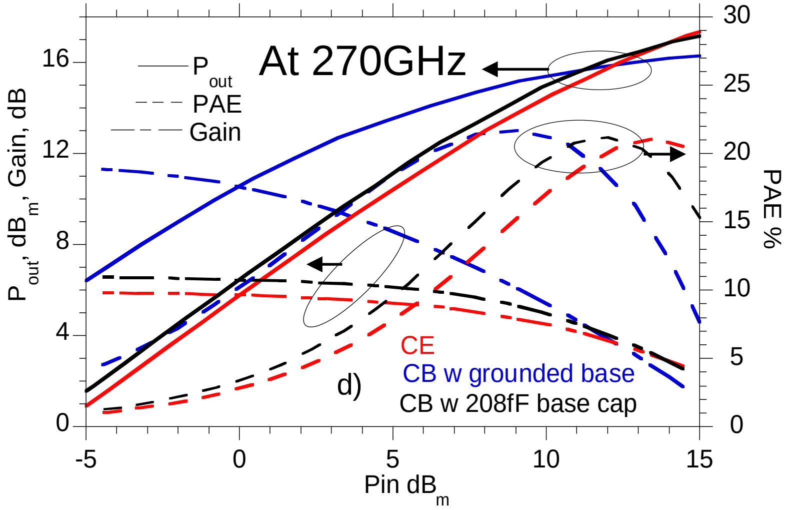
- Comparison between CE, grounded CB and CB with base capacitor
- Simulation under same bias condition
- Large signal simulation is more relevant in power amplifier
- CB with base capacitor shows the highest OP$_{1dB}$ with associated PAE
- Design is still challenging.



(a) CE (b) CB with grounded base (c) CB with base capacitor

	Gain*, dB	PAE @ OP$_{1dB}$**, %	OP$_{1dB}$, dB$_m$
CE	4.9	13.6	13.1
Grounded CB	10.8	8.4	9.6
CB with 208f cap	5.6	16	13.7

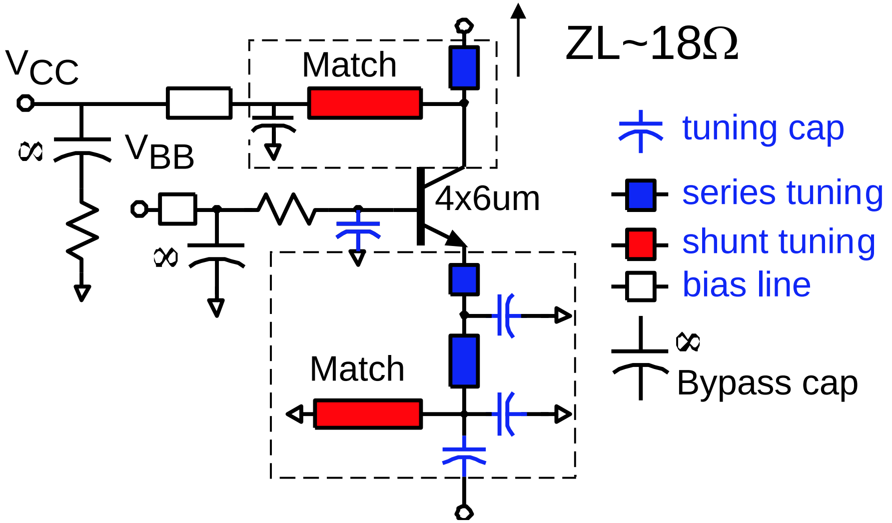
*under opt load line condition without compression



P$_{out}$, gain, and PAE for CE, grounded CB, and CB with base capacitor.

Unit Cell Design

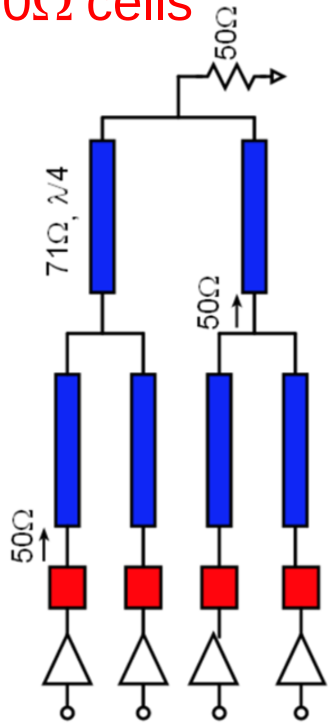
- Shunt inductor: tunes the transistor parasitics.
- The cell requires resistive load impedance (~18Ω).
- Base capacitance is significantly reduced (~208fF).
  - Lower parasitic inductance → higher self resonance frequency.
  - Avoid gain uncertainty and stability problems.



Schematic of the unit cell

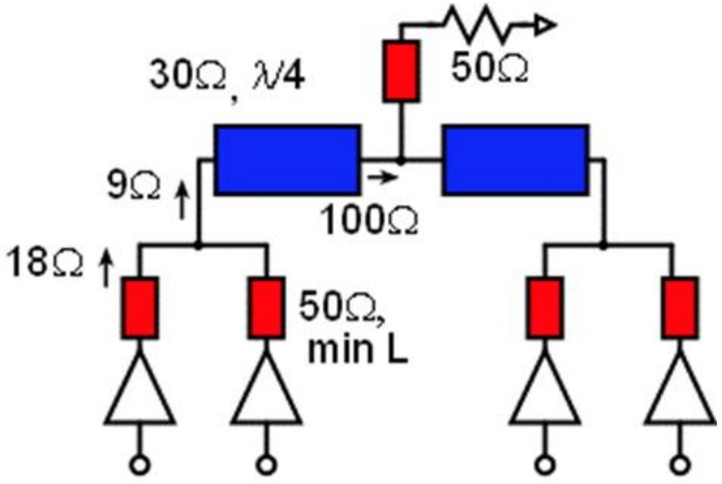
Combiner Design

- Wilkinson
  - Two $\lambda/4$ sections-> Bulky
  - High loss and skinny line
  - Works only with 50Ω cells
  - Higher BW



Wilkinson combiner

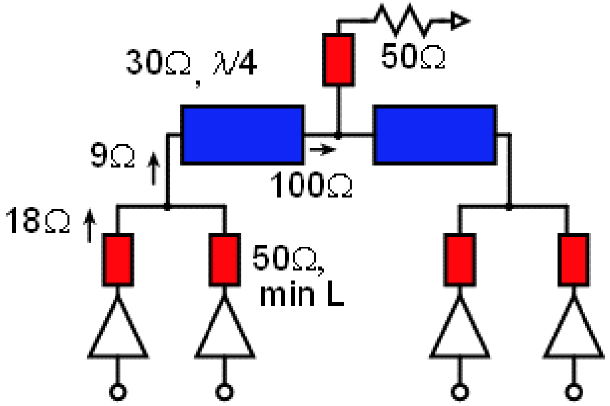
- Proposed combiner
  - Single $\lambda/4$ section->very compact
  - Low loss
  - Works with non 50Ω cells
  - Smaller BW compared to Wilkinson



Proposed combiner

Combiner Design

- Low loss 4:1 transmission line combiner.
- Transforms 50Ω to the required loadline impedance for each cell using a single $\lambda/4$ transmission line.
- Each two cells are combined by a TL with negligible electrical length.
- The required impedance for the two combined cells is 18/2Ω.
- The quarter line's impedance is chosen to transform 100Ω to 18/2Ω.



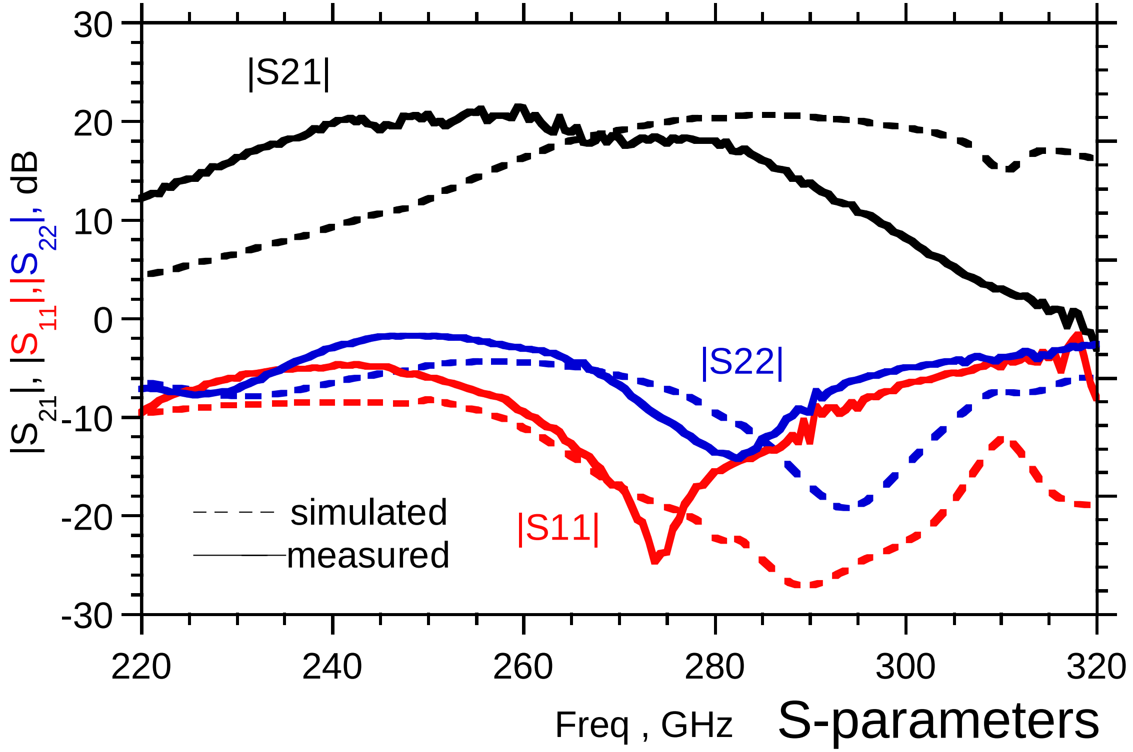
Chip micrograph of the proposed combiner

Chip micrograph of the proposed combiner

Measurement Results: s-parameters

- Setup: PNA with 220-325GHz Oleson extender modules.
- Measured 3-dB bandwidth=48GHz.

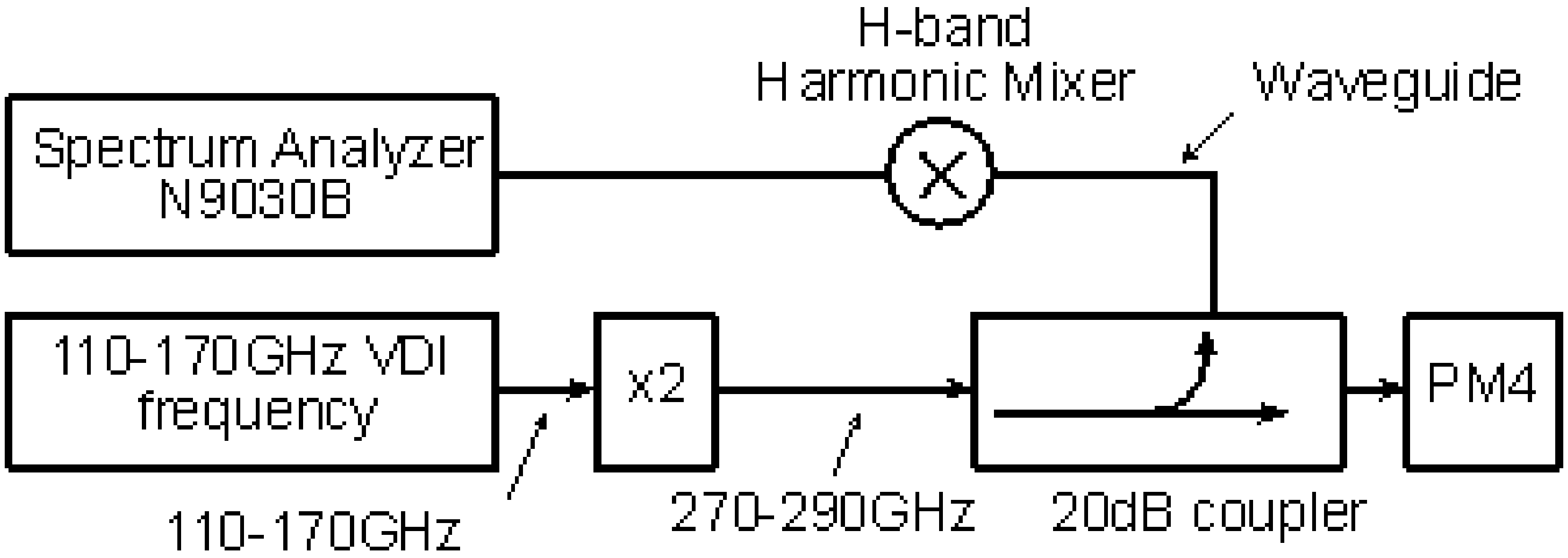
V_{CCPA}	V_{BBPA}	$V_{CCdriver}$	$V_{BBdriver}$
2.2V	2.3V	2.5V	2.1V
I_{CCPA}	I_{BBPA}	$I_{CCdriver}$	$I_{BBdriver}$
172mA	9.4mA	275.5mA	14.8mA



S-parameters

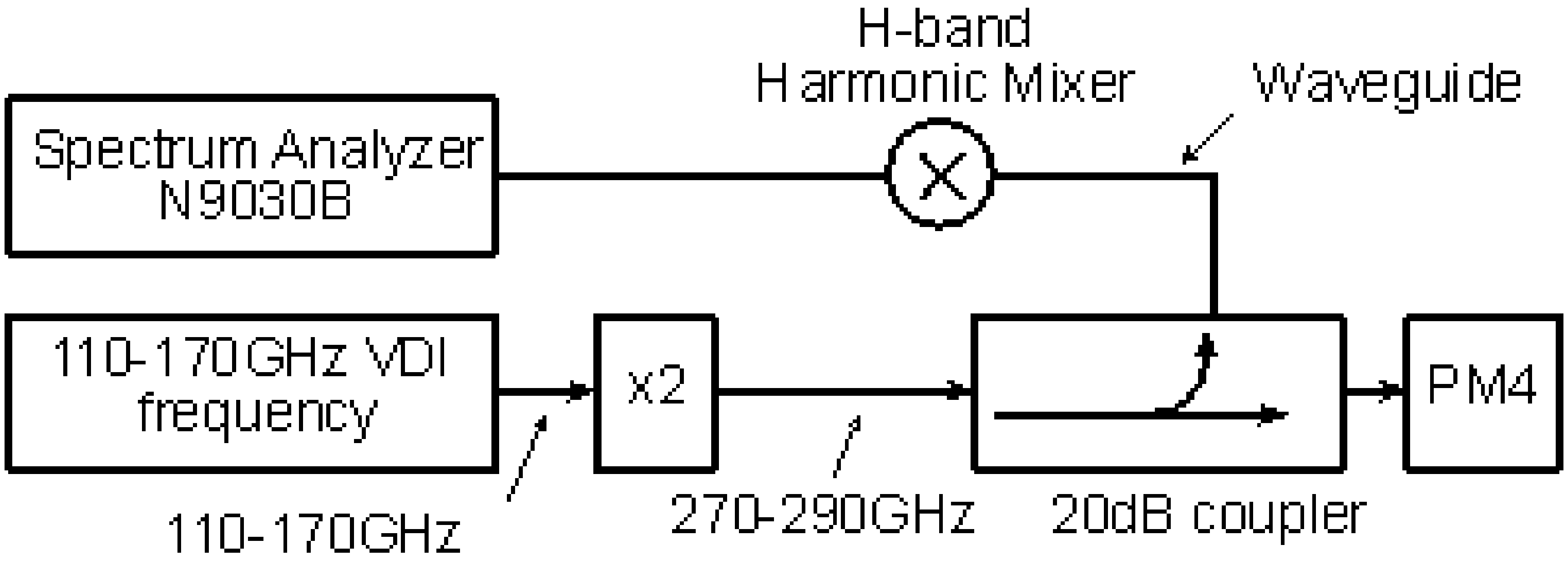
Power Measurement: setup

- 110-170GHz VDI+ doupler->270-290GHz-> coupler
- Input power is sensed by the coupler and monitored by the spectrum analyzer
- Power is varied by changing the signal generator power.



Calibration phase

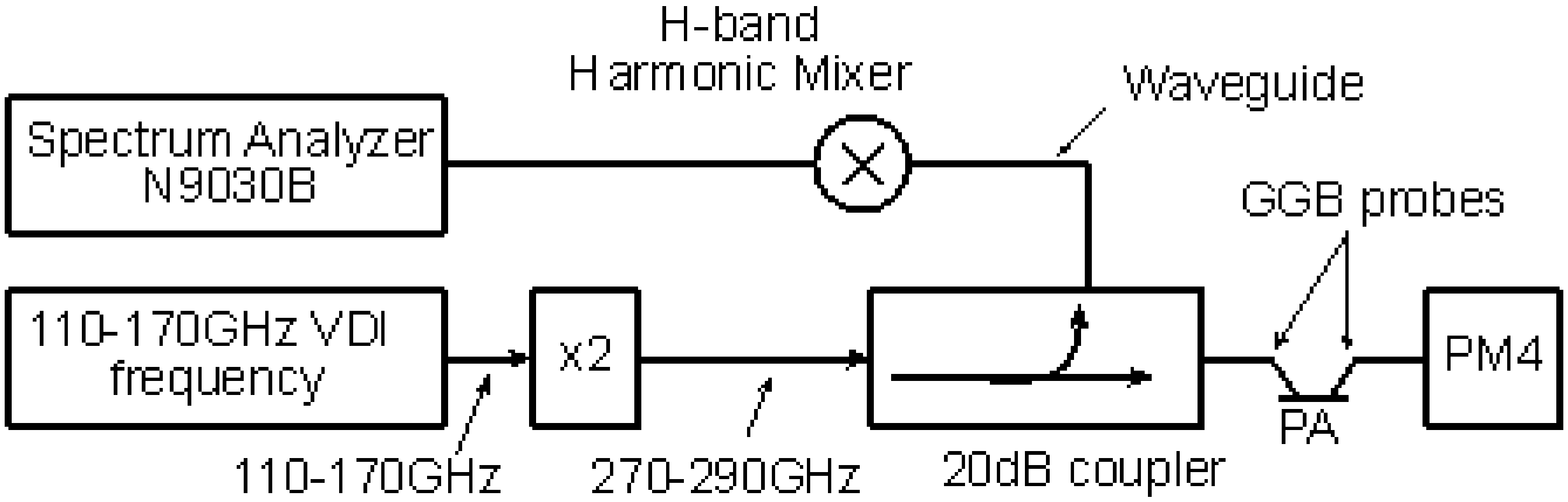
- Correction factor=power difference between the power meter and spectrum analyzer readings.



(a) Calibration

Measurement Phase

- Sweep the signal generator power.
- Report the spectrum analyzer readings + correction factors=input power.
- Report the power meter reading.
- The power meter readings +probe losses= amplifier output power



(b) Measurement

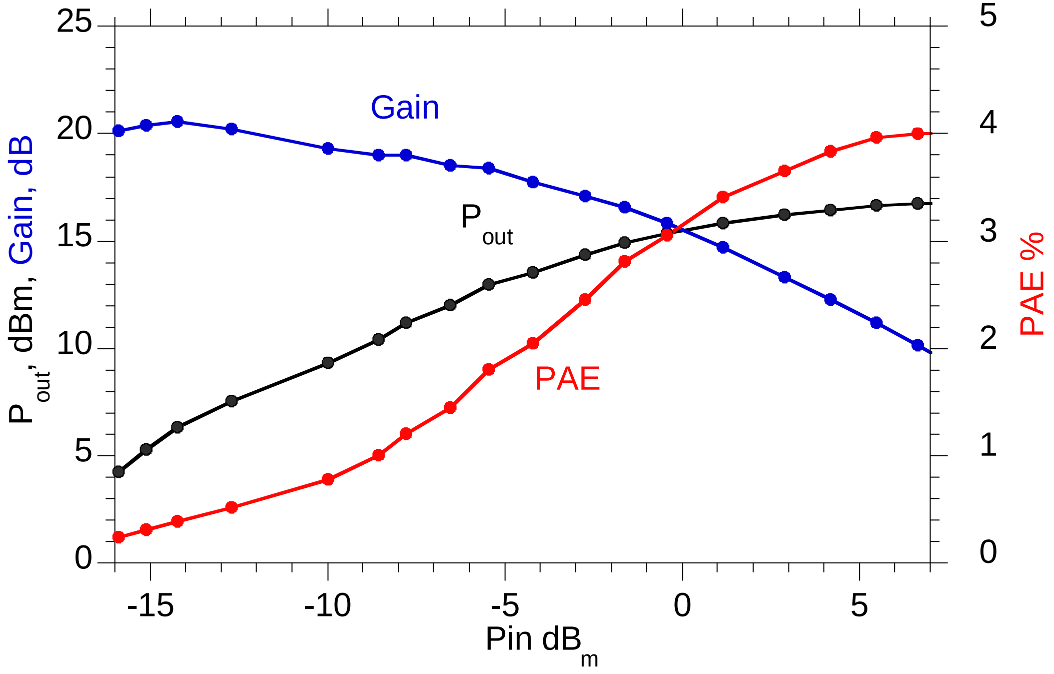
Power Measurement Results

- Many points are recorded at different frequencies.
- At 270GHz: P_{out}=16.8dBm, 4%PAE

V_{CCPA}	V_{BBPA}	$V_{CCdriver}$	$V_{BBdriver}$
2.2V	2.5V	2.4V	2.2V
I_{CCPA}	I_{BBPA}	$I_{CCdriver}$	$I_{BBdriver}$
173.3mA	10.8mA	274.8mA	16.2mA

- No heatsink was used.

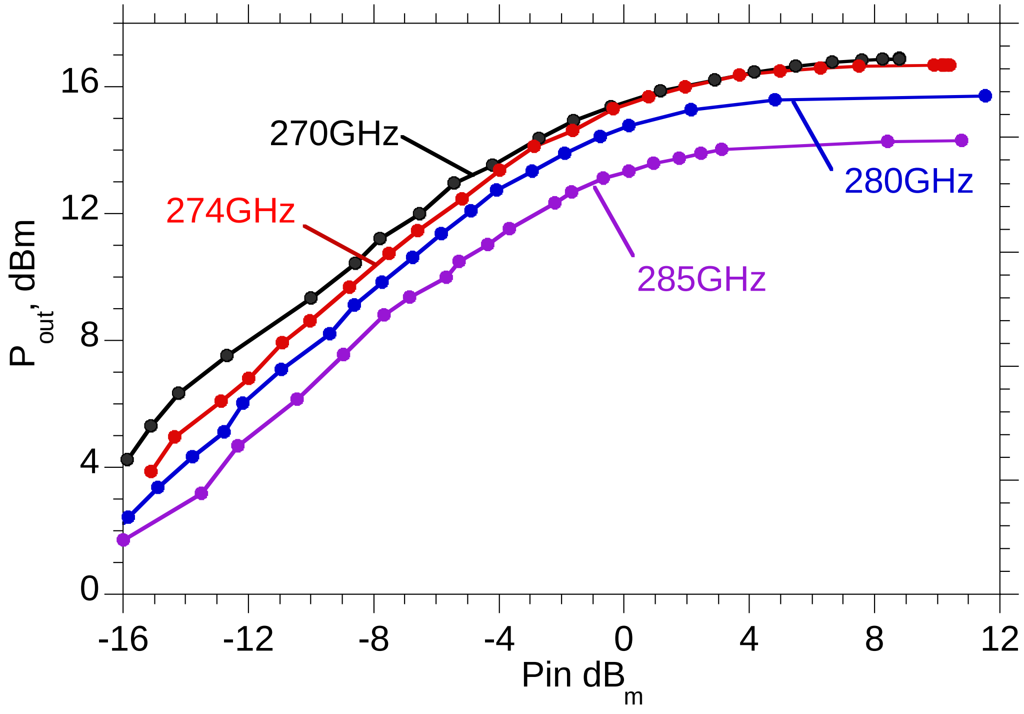
- Better performance is expected with proper heatsinking.



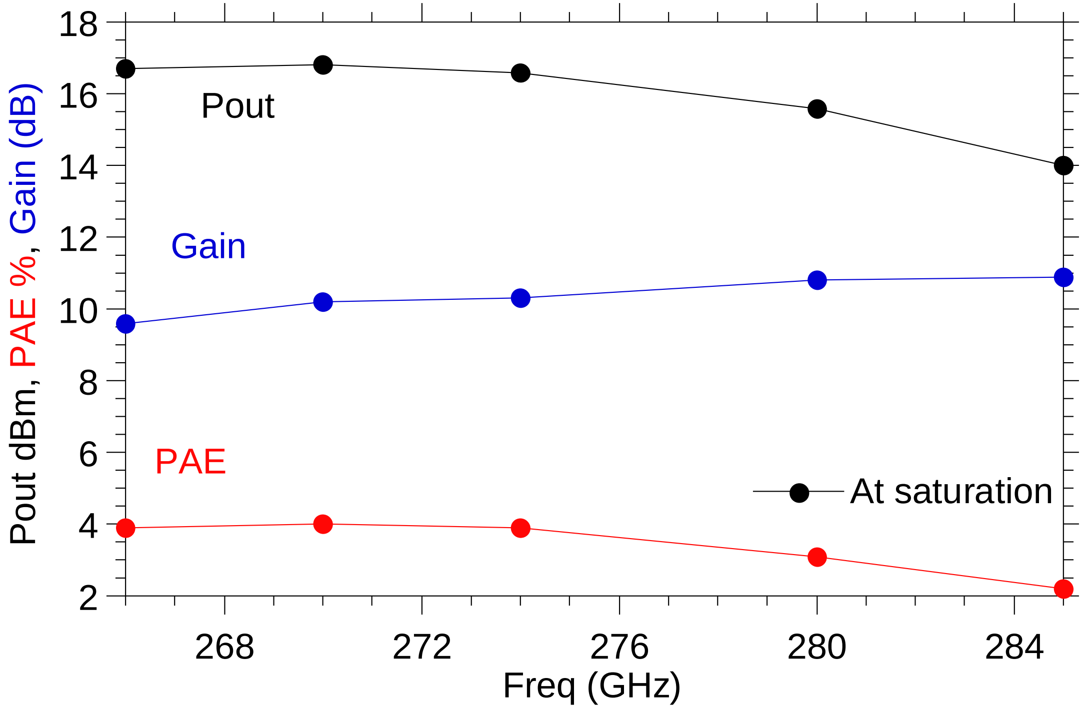
Pout, Gain, and PAE vs Pin at 270GHz

Power Measurement Results

- More points are taken at different frequencies.
- P_{sat}=14-16.8dB$_m$, with PAE=2.2-4% over 266-285GHz



Measured Pout vs Pin at various frequencies.



Measured P_{out} with the associated PAE and gain vs. frequency reported at the peak PAE.

State-of-the-art results

[a]module results

Ref	[5]	[7]	[8]	[2][a]	[10][a]	[9]	[4]	[6]	[11]	[3]	This work
Freq, GHz	240	185-255 265	325	275-320	338	300-305	300	290-307.5	301	280-328	266-285
P_{sat}, dBm	>10.8	20-23.9 17.2	11.3	2.7-4.8	10	9.5-9.8	8	7.8-10	13.5	9.6-13.7	14-16.8
Gain at P_{sat} (dB)	15	12.2-17 11.7	9.4	13.5-15	3.3	7.5-7.8	11	10-12	11.8	11.5-13.8	9.6-10.9
PAE at P_{sat}%	5	4.1 0.95	1.1	2.3[d]	1.8	1.1	2.97	1.1	1.5	0.8-2.4	2.2-4
BW_{3dB}, GHz	55	53[c]	9	~100[c]	10	40	57	21	15[c]	48[c]	48
Chip Size (mmxmm)	1.5x0.75	2.14x1.58	0.98x1	0.5x1.35	2x0.75	0.55x0.55[b]	2x0.75	1.45x0.44	0.67x0.68	0.6x1.3[b]	1.08x0.77
P_{DC} (W)	-	5.24	1.12	0.129[d]	0.29	0.72	0.2	0.85	1.49	-	1.09
P_{sat}/Area mW/mm^2	10.6	72.5 15.7	13.9	4.5	6.66	31.6	4.2	15.7	22.3	30	57.6
Technology	35 nm GaAs mHEMT	250-nm InP HBT	130-nm InP HBT	35 nm InAlAs/InGaAs	50 nm InP HEMT	250-nm InP HBT	35 nm InGaAs mHEMT	250-nm InP HBT	250-nm InP HBT	35 nm InGaAs mHEMT	250-nm InP HBT

- This work shows a record P_{sat}/mm^2 over 266-285GHz frequency range.

Summary

- Record P_{sat}/area at H-band
- Common base cell with finite base impedance shows a good performance at subTHz frequency.
- Transmission line combiner are compact and have low losses
- Careful EM simulation is necessary to get accurate results
- Millimeter wave communication becomes more feasible.

Acknowledgement

- This work was supported in part by the Semiconductor Research Corporation and DARPA under the JUMP program.

- The authors thank Teledyne Scientific & Imaging for the IC fabrication.

Thank You

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Fig. 9. Measured output power with the associated PAE and compressed gain vs. frequency reported at the peak PAE.

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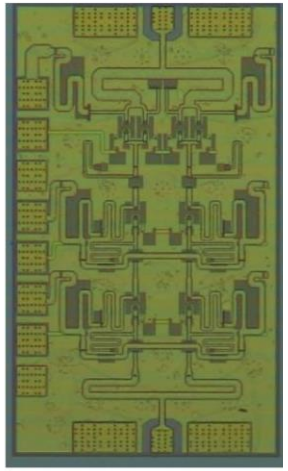
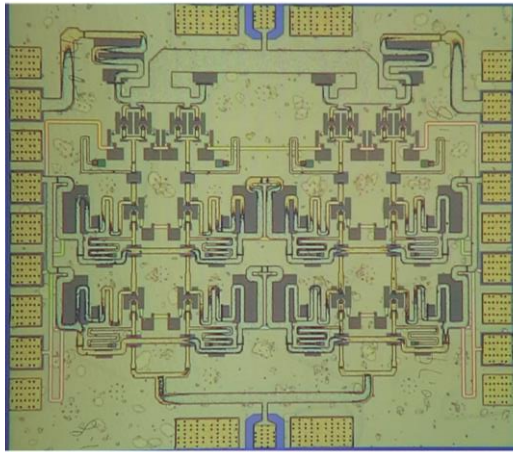
More Details: power amplifier family

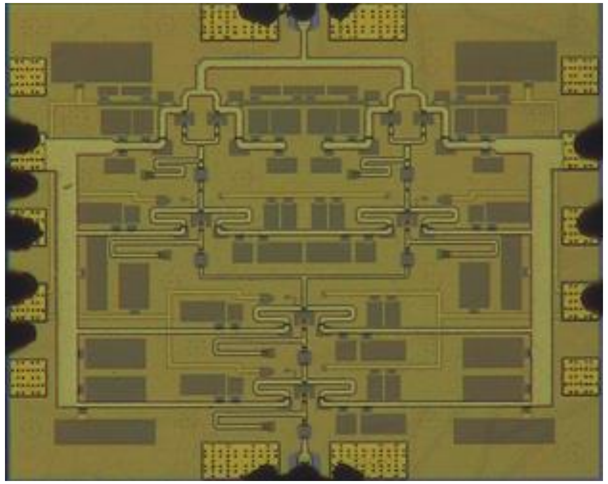
- Record output power and efficiency (125-285GHz)



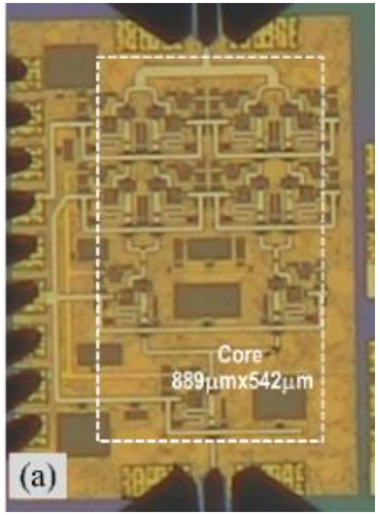
[13] 140GHz, 20.5dBm, 20.8% PAE



[14] 130GHz, 200mW, 17.8%PAE



[15] 194GHz, 17.4dBm, 8.5%PAE



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