D-Band Power Amplifier with 27 dBm Peak Output Power and 14.9% PAE in 250-nm InP HBT Technology

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100-300 GHz Wireless

High capacity:

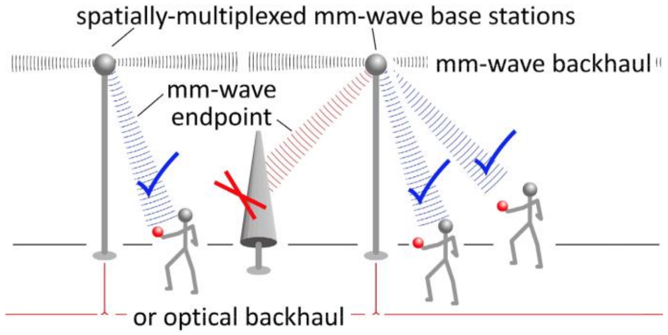
- potentially wide available bandwidth
- massive spatial multiplexing even with compact arrays

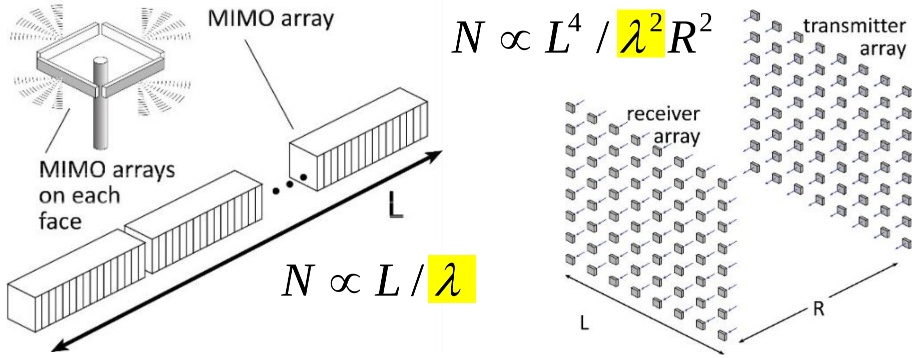
Limited range:

- high λ^2/R^2 path losses
- high worst-case atmospheric attenuation

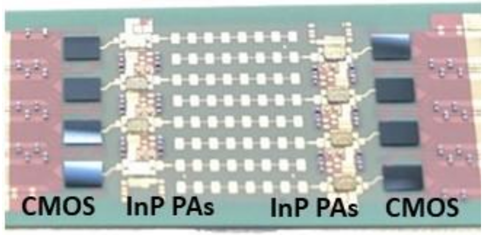
Need:

- arrays with many elements
- low receiver noise figure
- **compact, efficient, 100-300 GHz power amplifiers**



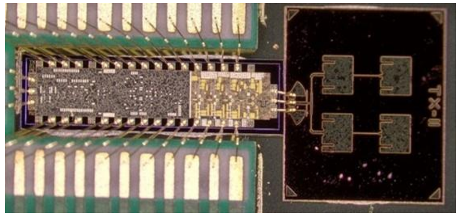


140 GHz MIMO Hub



Abu-Surra, Samsung/UCSB
2022 IEEE ICC

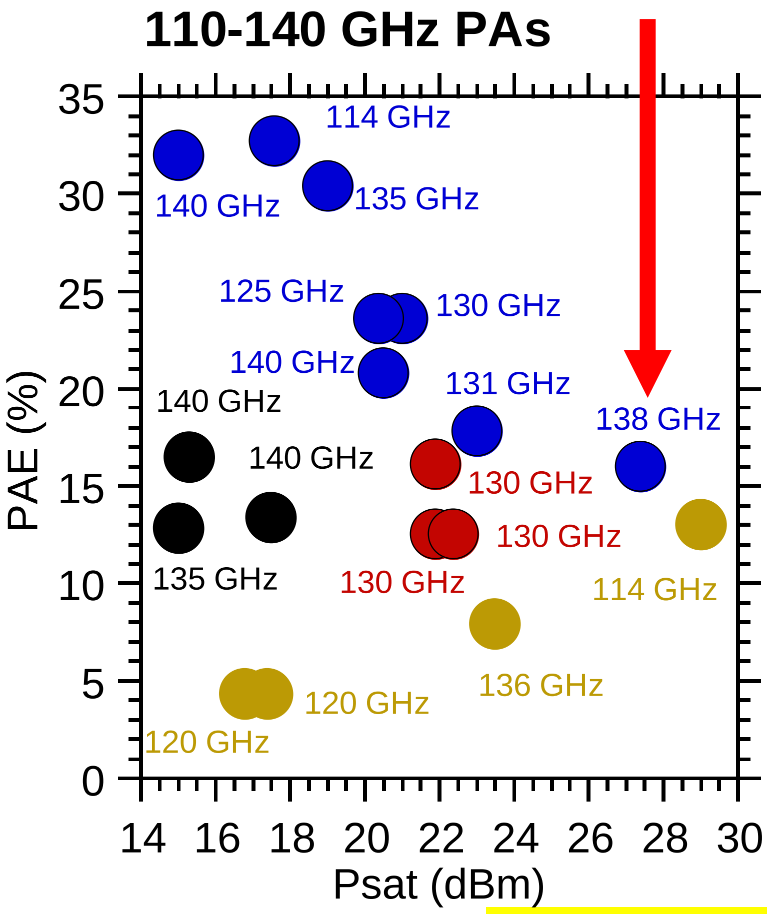
200 GHz backhaul

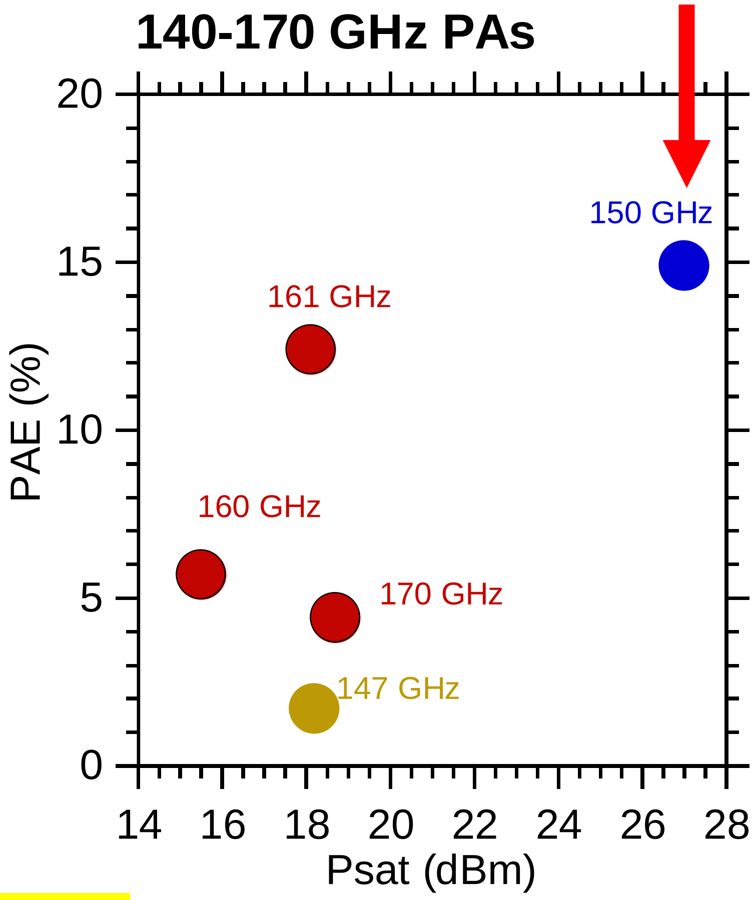


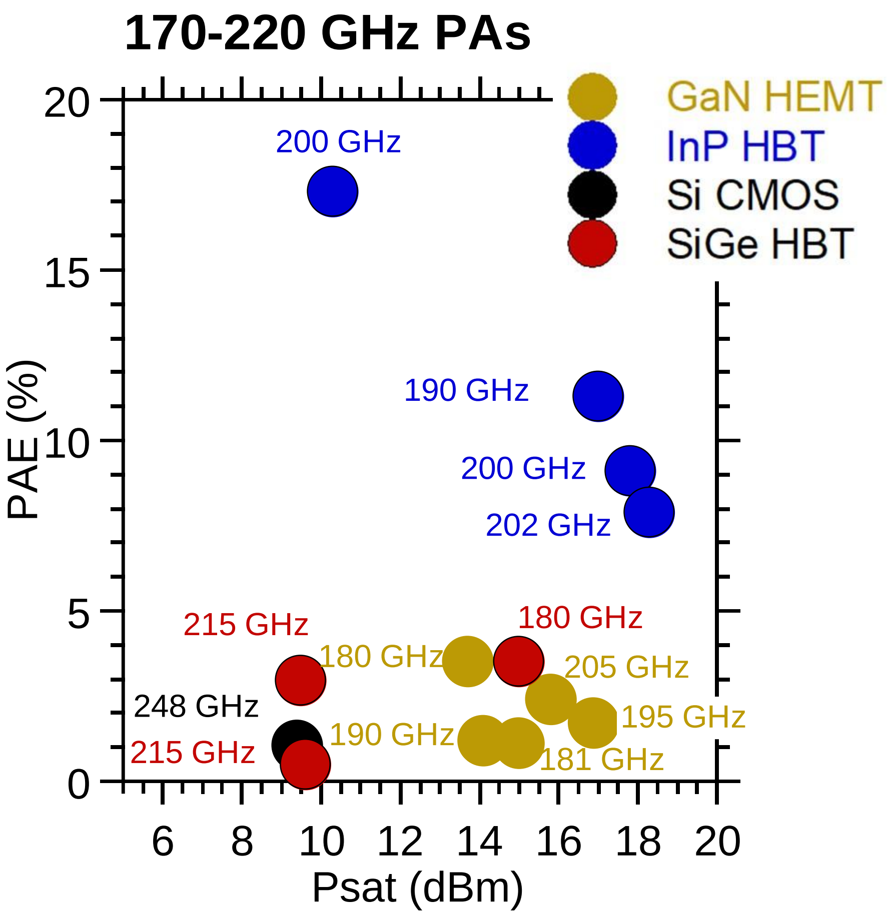
Soylu, UCSB
2023 IEEE BCICTS

Technology Comparison: 100-220 GHz PAs

110-200 GHz: InP HBT provides leading output power vs. efficiency
200-300 GHz: InP HBT and InP HEMT are both excellent





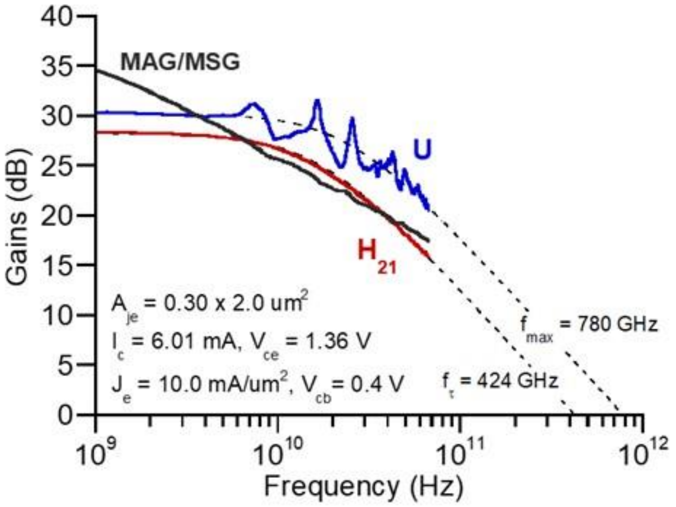


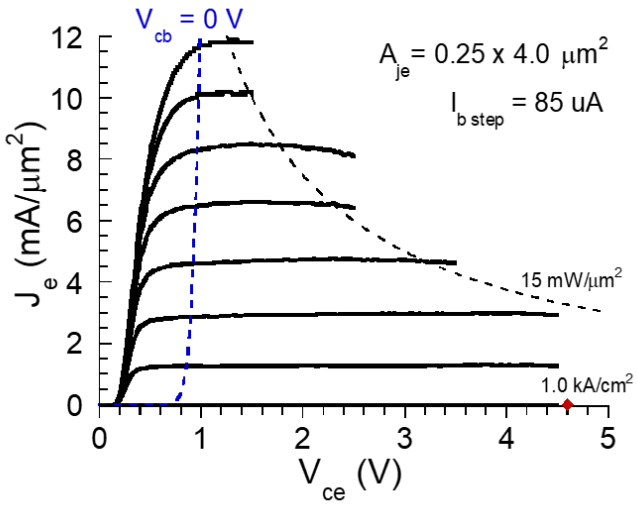
Results compiled 8/16/2023

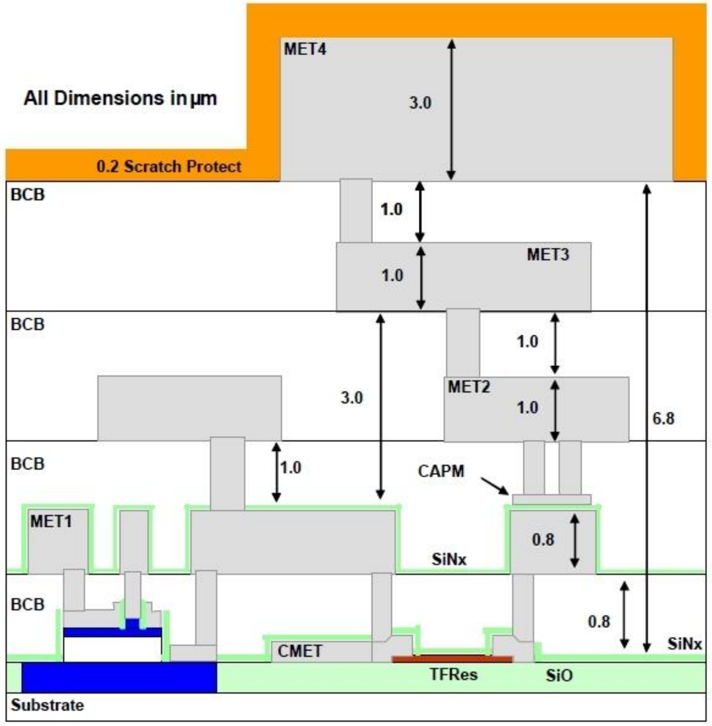
Teledyne 250 nm InP HBT Technology

HBTs:
~200-400 GHz f_τ; varies with V_{ce}, I_c
~650 GHz f_{max}
~3 mA/μm maximum current
~4.5 V breakdown
~0.6 V minimum at 2mA/μm (Kirk effect)

Back end:
4 Au wiring layers, BCB dielectric (ε_r=2.65)
5 μm M1-M4 separation→ ~0.9 dB/mm loss @ 140 GHz
MIM capacitors: 0.3 fF/μm^2
Thin-film resistors: 50 Ω/square







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

Griffith, 2007 IEEE IPRM
Urteaga, 2017 IEEE Proceedings

500 mW, 150 GHz PA Design Challenges

Overheating (~3 W dissipation):
minimum output transistor power cell spacing, IC bonded to metal heat sink

~1 Amp DC supply currents:
electromigration, I^2R losses→ wide conductors

Efficiency:
minimize tuning & power-combining losses

Electrothermal self-destruction:
power cell ballasting

Efficient class-AB operation:
electrothermally stable adaptive bias circuits

Capacitively Degenerated Common-Base

Common-base with AC grounded base :

more small-signal gain than common-emitter

Capacitively degenerated common base

finite base capacitance

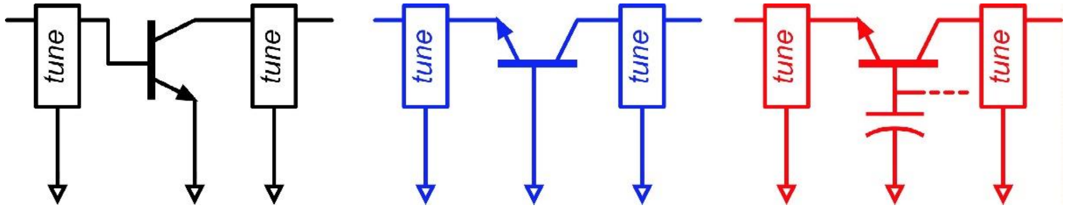
smaller gain, same peak PAE at same (P_{out}-P_{in})

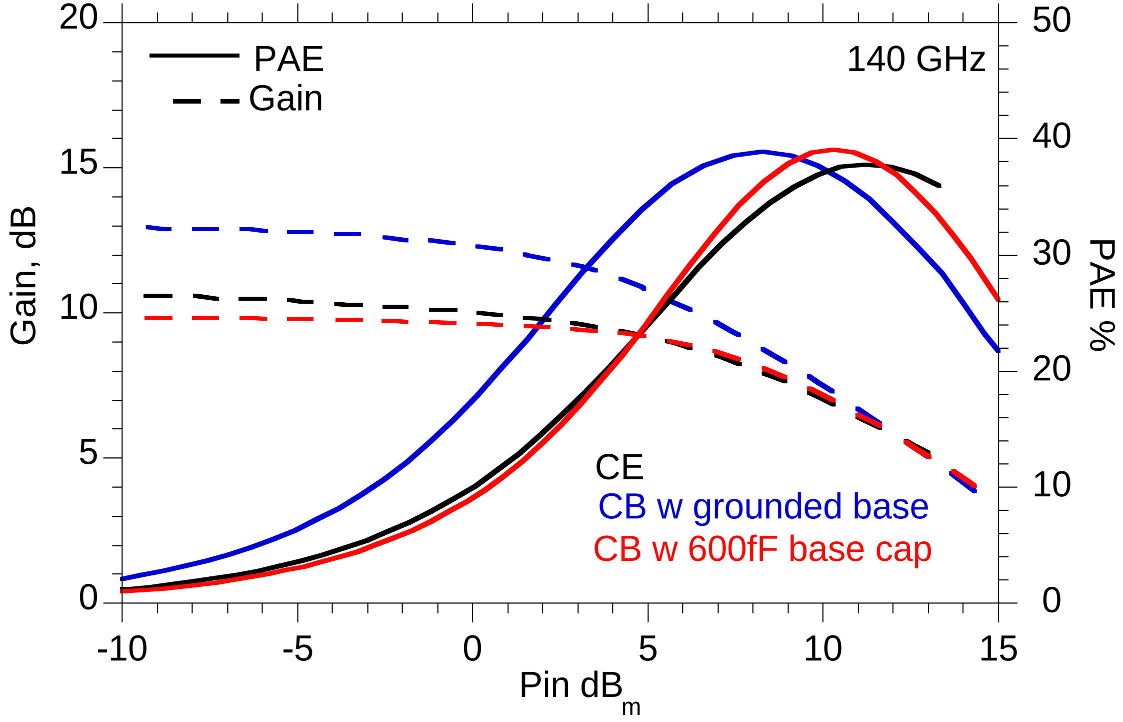
less gain compression @ peak PAE.

broadband stability with no loss in PAE

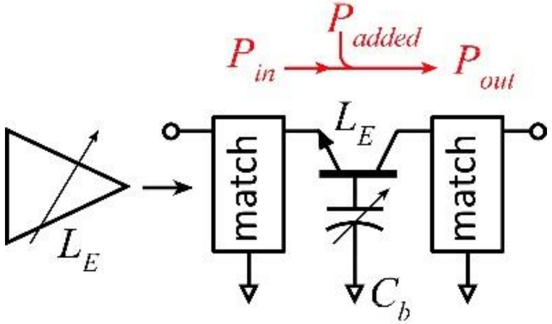
Power from previous stages contributes to P_{out}.

...similar to stacking





4x 6 μm HBT cell; no cell parasitics

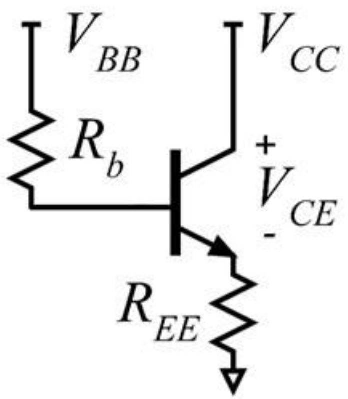


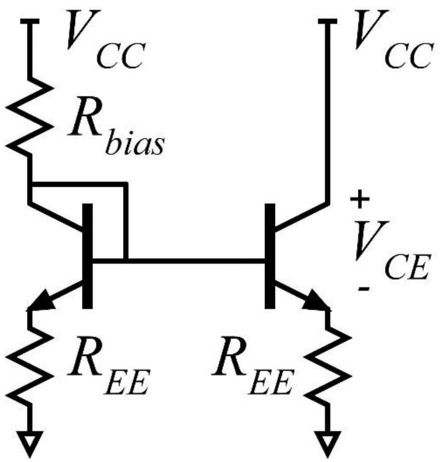
Bipolar Transistor Electrothermal Runaway

Thermally unstable unless

$$K_{\text{thermal stability}} = \left(\frac{-dV_{be}}{dT}\right)\frac{V_{CE}\theta_{JA}}{R_{ex}+R_{EE}+R_b/\beta+nkT/qI_E} < 1$$

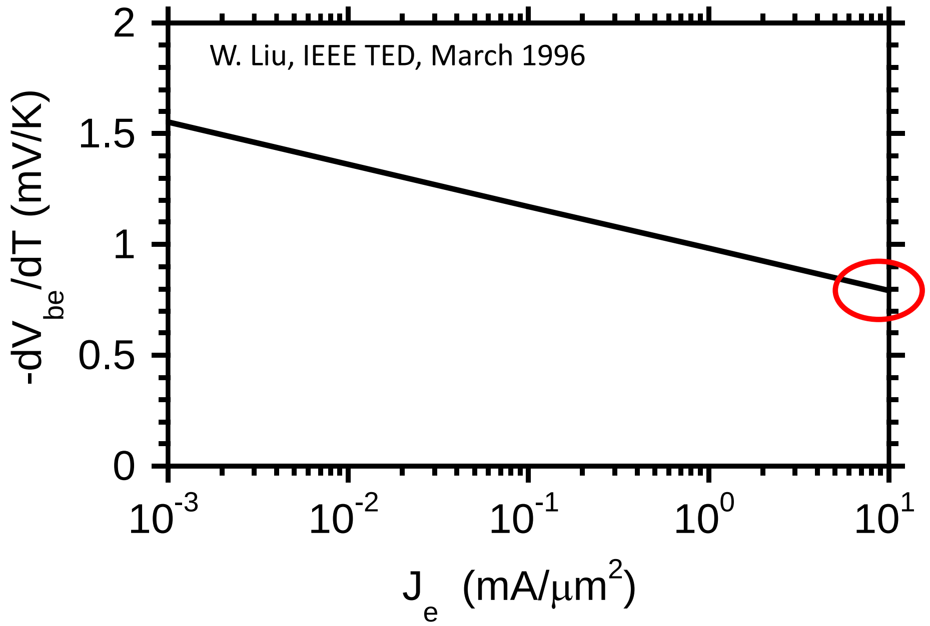
Thermal runaway $\rightarrow$ increasing current $\rightarrow$ destruction





Teledyne 250 nm InP HBT technology $\theta_{JA} \approx 55\,\frac{\text{Kelvin}}{\text{mW}} \cdot \frac{1\ \mu\text{m}}{L_E}$

InP HBT @ $J_E \sim 8\ \text{mA}/\mu\text{m}^2 : \frac{dV_{be}}{dT} \approx -0.8\ \text{mV/Kelvin}$



Thermal compensation does not help much:
only weak thermal coupling, even if HBTs are very close.

Class-B biasing of HBT power amplifiers

Class-B bias: $I_{C,DC} = \dfrac{I_{RF,peak}}{\pi} \propto \sqrt{P_{out}}$

Constant I_C or I_B bias:

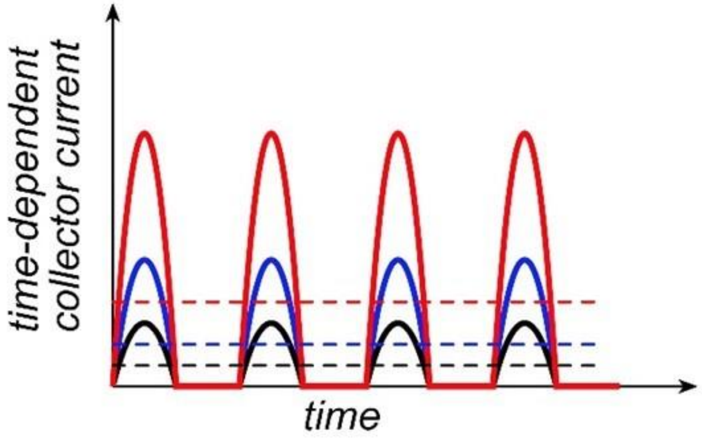
class B only at one RF power level

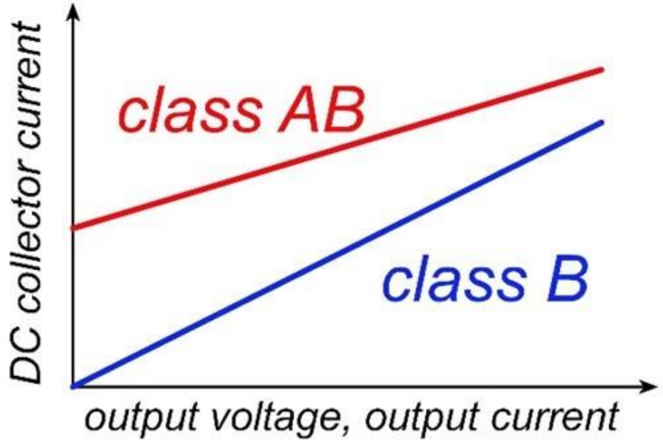
Constant-V_{be} bias:

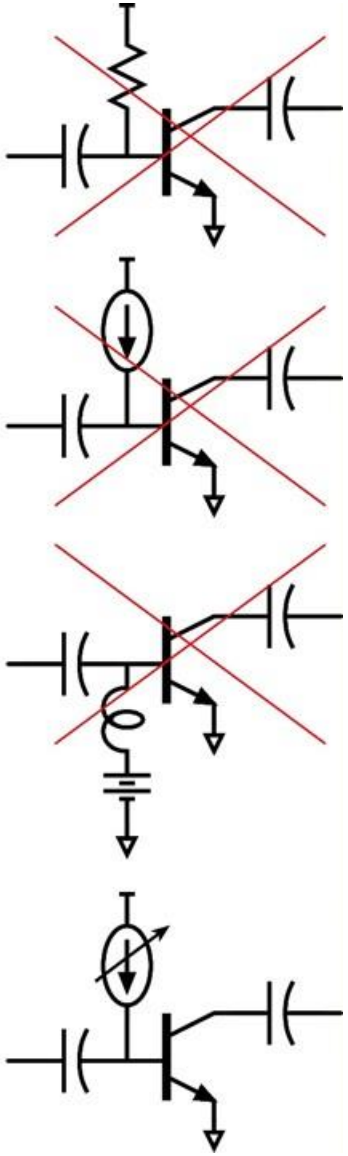
electrothermally unstable $\rightarrow$ destruction

Need adaptive bias circuit

I_C bias increasing with $\sqrt{P_{out}}$



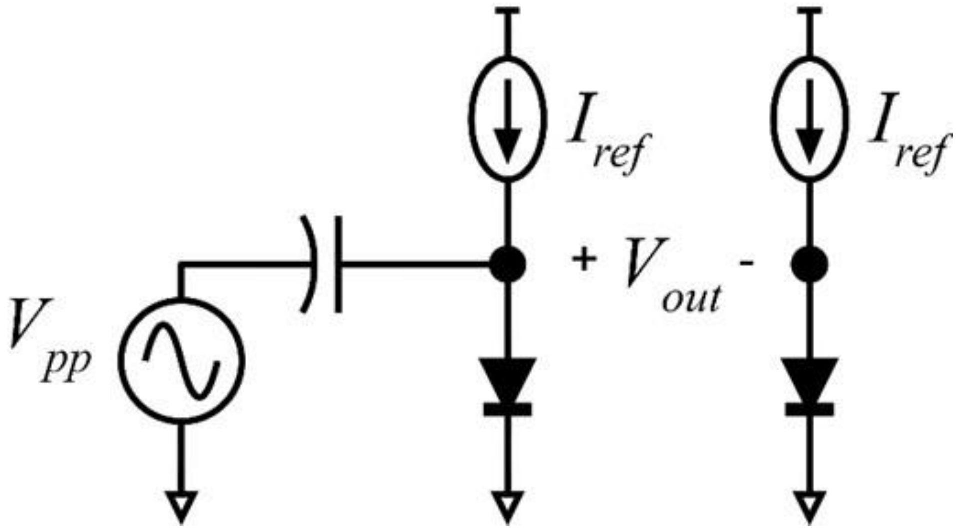


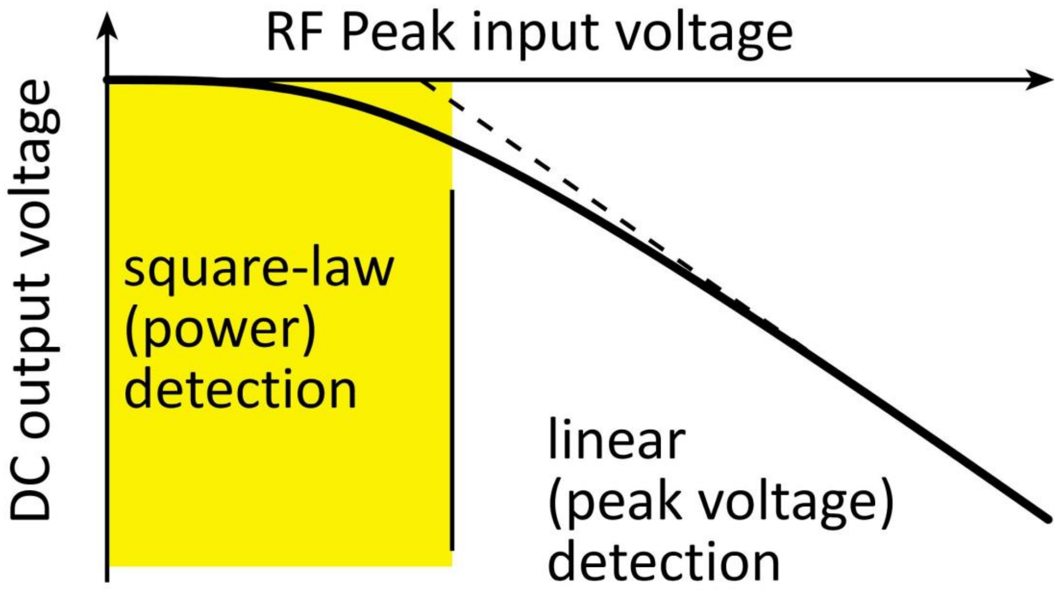


Power detectors & peak detectors

$$V_{out} \approx \begin{cases} -\dfrac{V_{pp}^2}{4nkT/q}\text{(power detection)} & \text{if } V_{pp} << \dfrac{nkT}{q} \\ -\left(\dfrac{V_{pp}}{2} - V_{offset}\right)\text{(peak detection)} & \text{if } V_{pp} >> \dfrac{nkT}{q} \end{cases}$$

(V_{offset} is hard to derive given sinusoidal drive; easy with squarewave drive)





Common-base class-AB adaptive bias circuit

Q1: RF gain; Q2: DC bias.

Low-power operation:

current I_{ref} produces voltage across R_2.

→ produces equal voltage across R_1

→ forces base current I_{b1}, produces collector current I_{c1}

I_{c1} is independent of ambient temperature

High power operation

$V_{be1,DC}$ and $V_{b2,DC}$ both decrease by $(V_{in,RF,peak})^2/4V_t$.

→ increases the voltage drop across R_1.

→ increases $I_{b1,DC}$, $I_{c1,DC}$

$I_{c1,DC}$ varies as $k_1+k_2P_{RF}$; increases with RF power

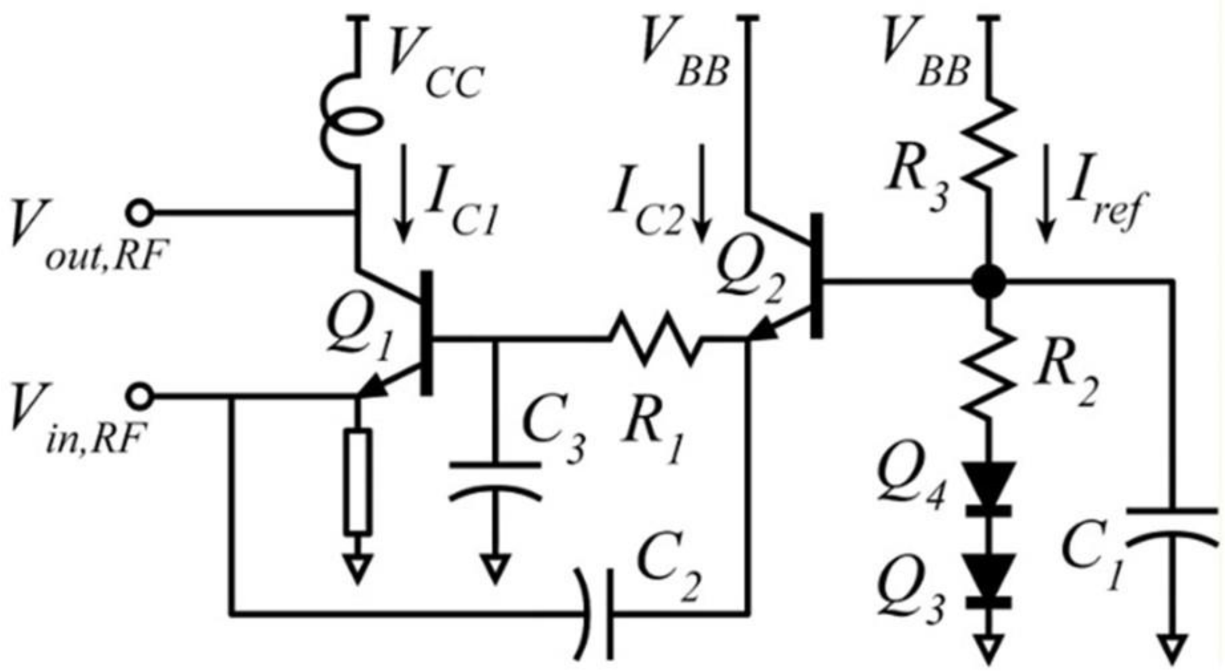
Why two rectifying elements ?

doubles the rectified DC voltage.

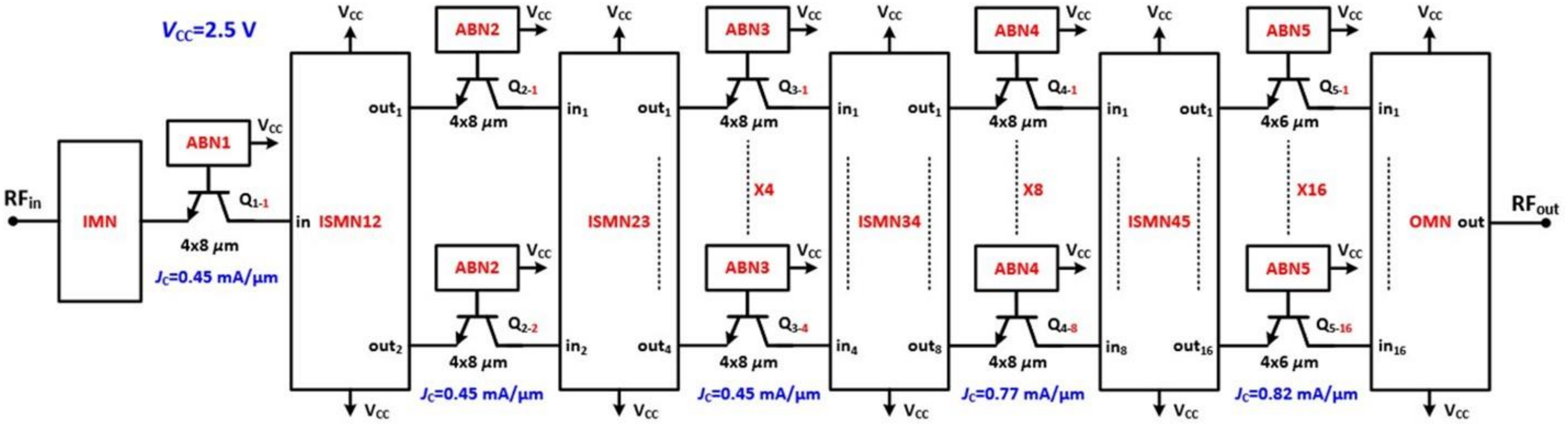
R_1 can be 2:1 larger for a given variation of $I_{c1,DC}$ with P_{RF} .

→ increases electrothermal stability factor.

Adaptive bias also reduces gain variation vs. output power.



High-power D-band class-AB amplifier



ABN = Active Bias Network

IMN = Input Matching Network

ISMN = Inter-stage Matching Network

ONM= Output Matching Network

Simulated bias currents shown at peak RF power.

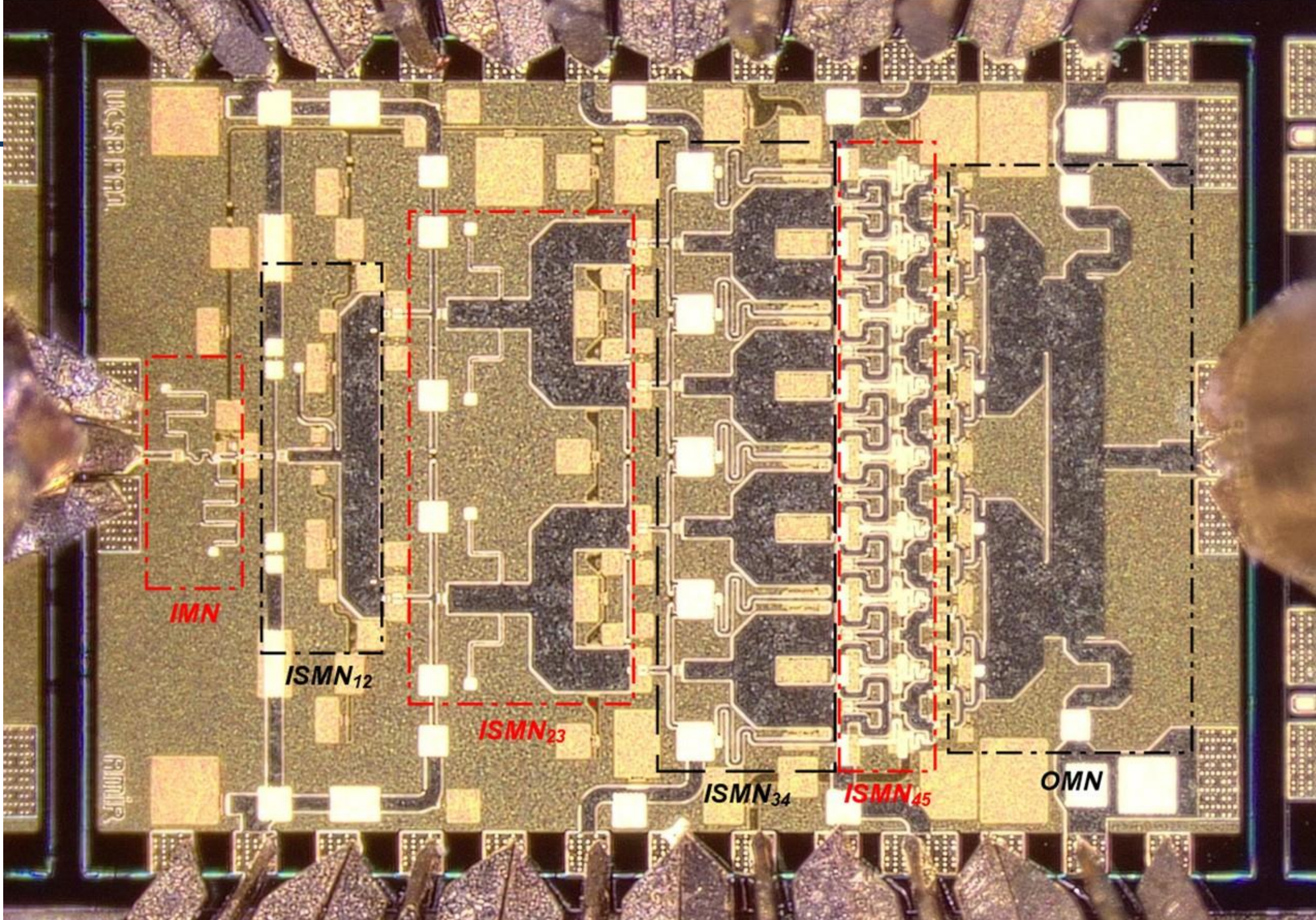
die photo

2 mm x 1.5 mm:

designed to fit in
140 GHz linear array

1 active bias network
for each 4-finger HBT

Each bias network
is very close to
the HBT being biased.

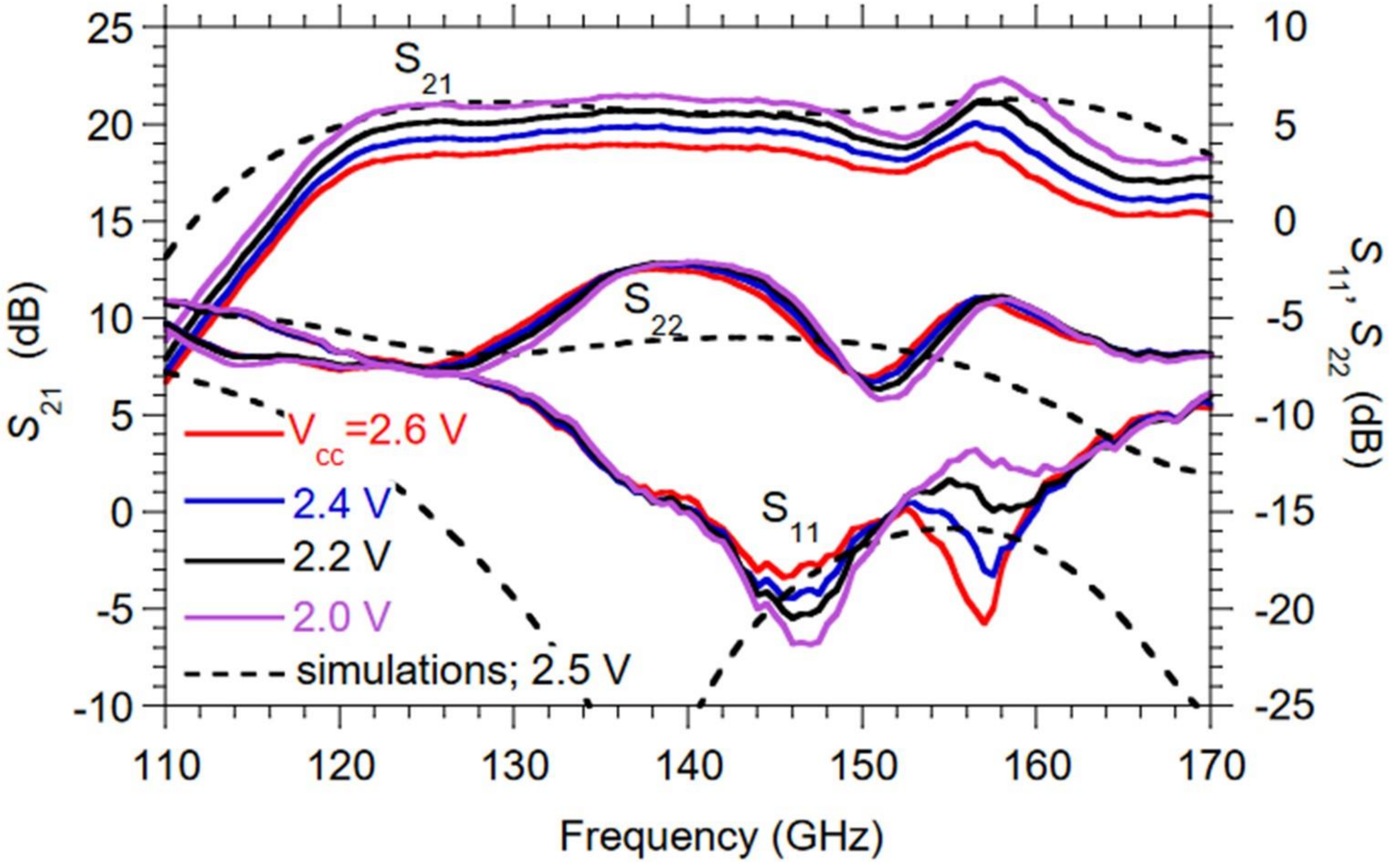


Measured Small-Signal Parameters

V_{cc}=2.4 V:
~20 dB midband gain
119–162 GHz bandwidth (-3 dB)

As V_{cc} increases:
→ more P_{DC} (more I_C, more V_{CE})
→ more heating
→ decreased gain S_{21} .

Bias currents will be greater under high-power operation.



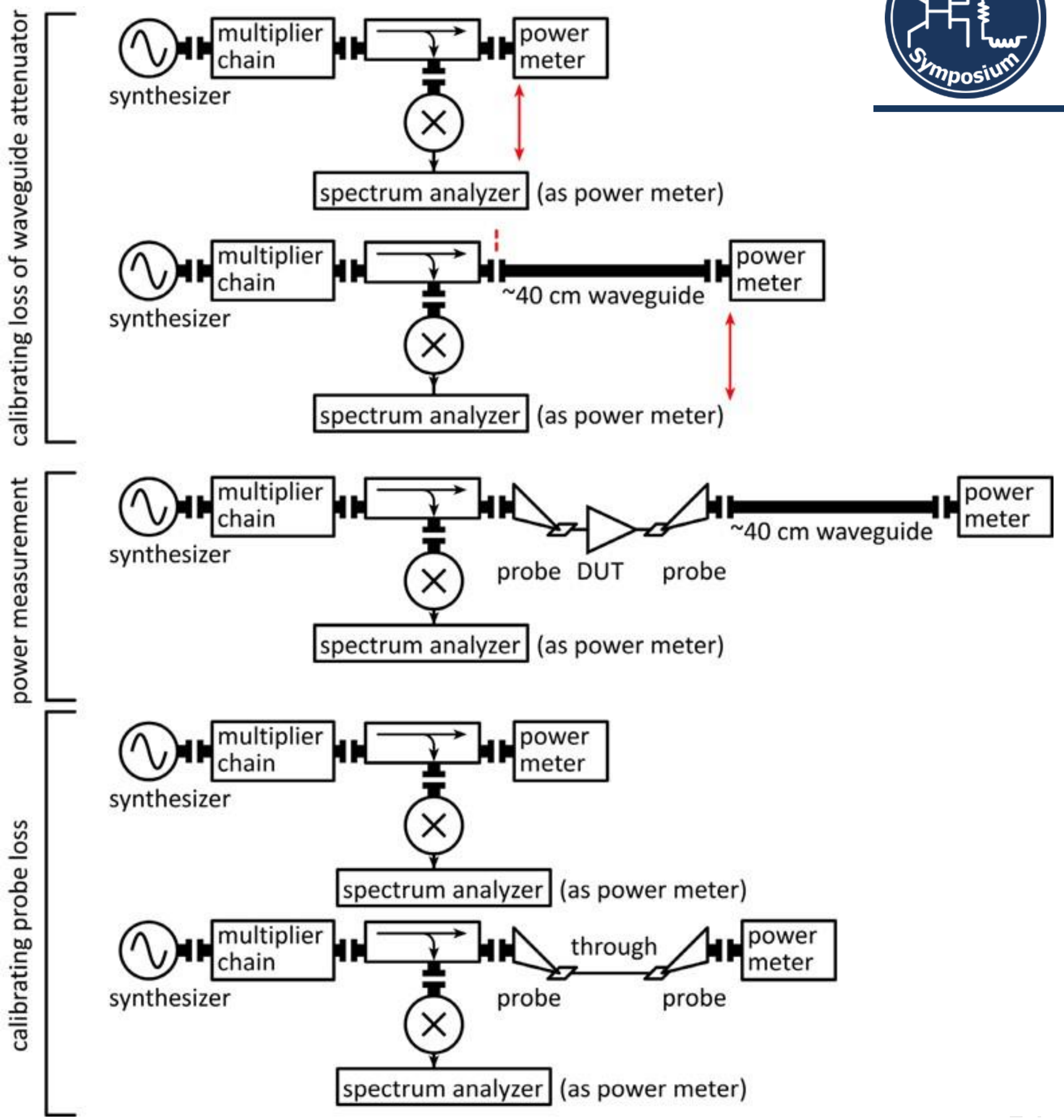
Power Measurements

Amplifier overloads power meter
Add 40 cm waveguide attenuator
Calibration: σ=0.33 dB (6 repeated measurements)

Amplifier output power measurement
IC bonded with high-K_{th} adhesive to Cu heat sink

Determining probe losses:
Measure loss of probe/line/probe (negligible line loss)
Weaknesses: division by 2, on-wafer structures near DUT
variability estimate: σ=1 dB (typical of D-band power data)

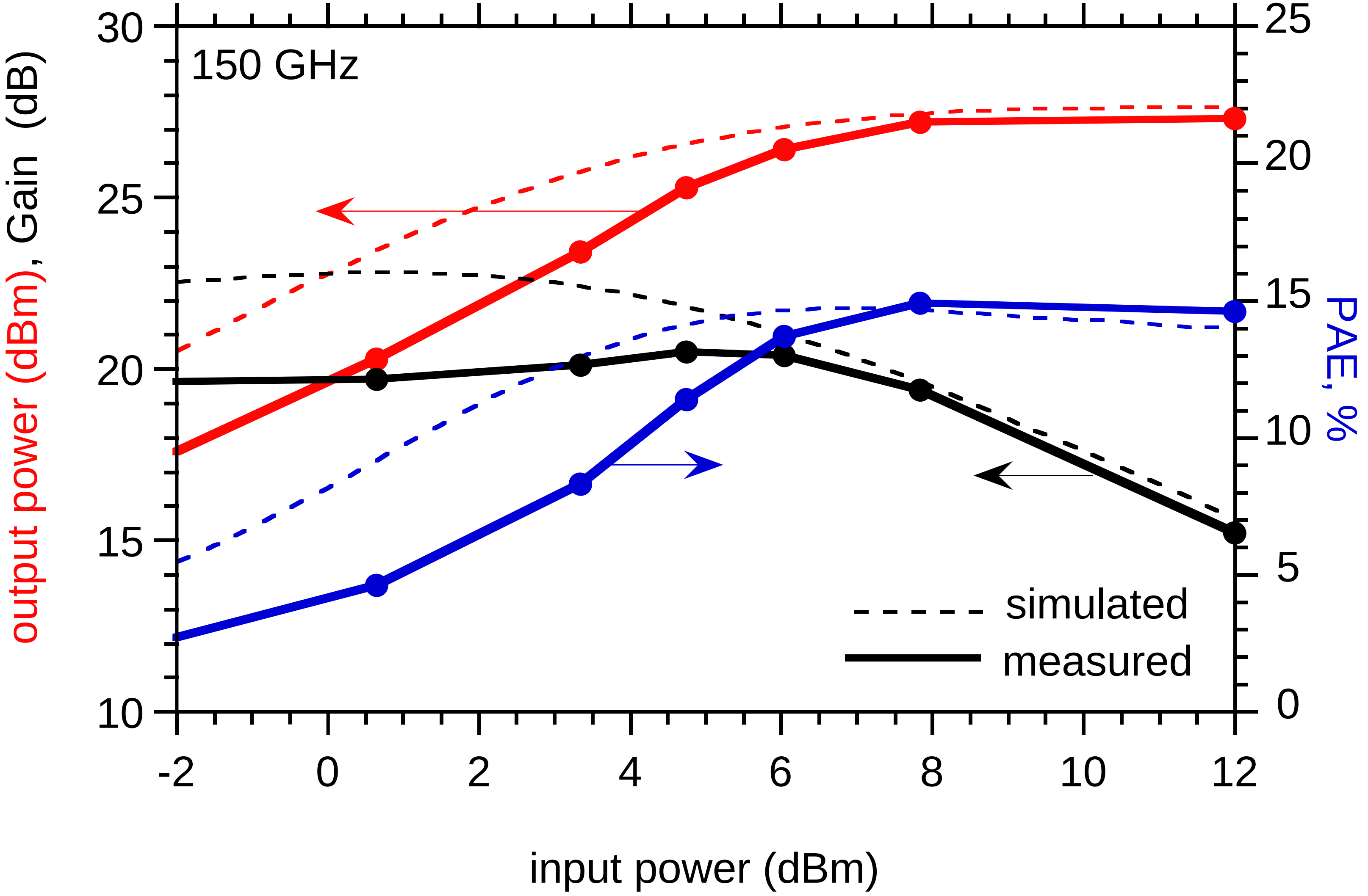
To be conservative, focus on 150 GHz data,
where probe loss correction is smallest (2.24 dB)



150 GHz Power Characteristics

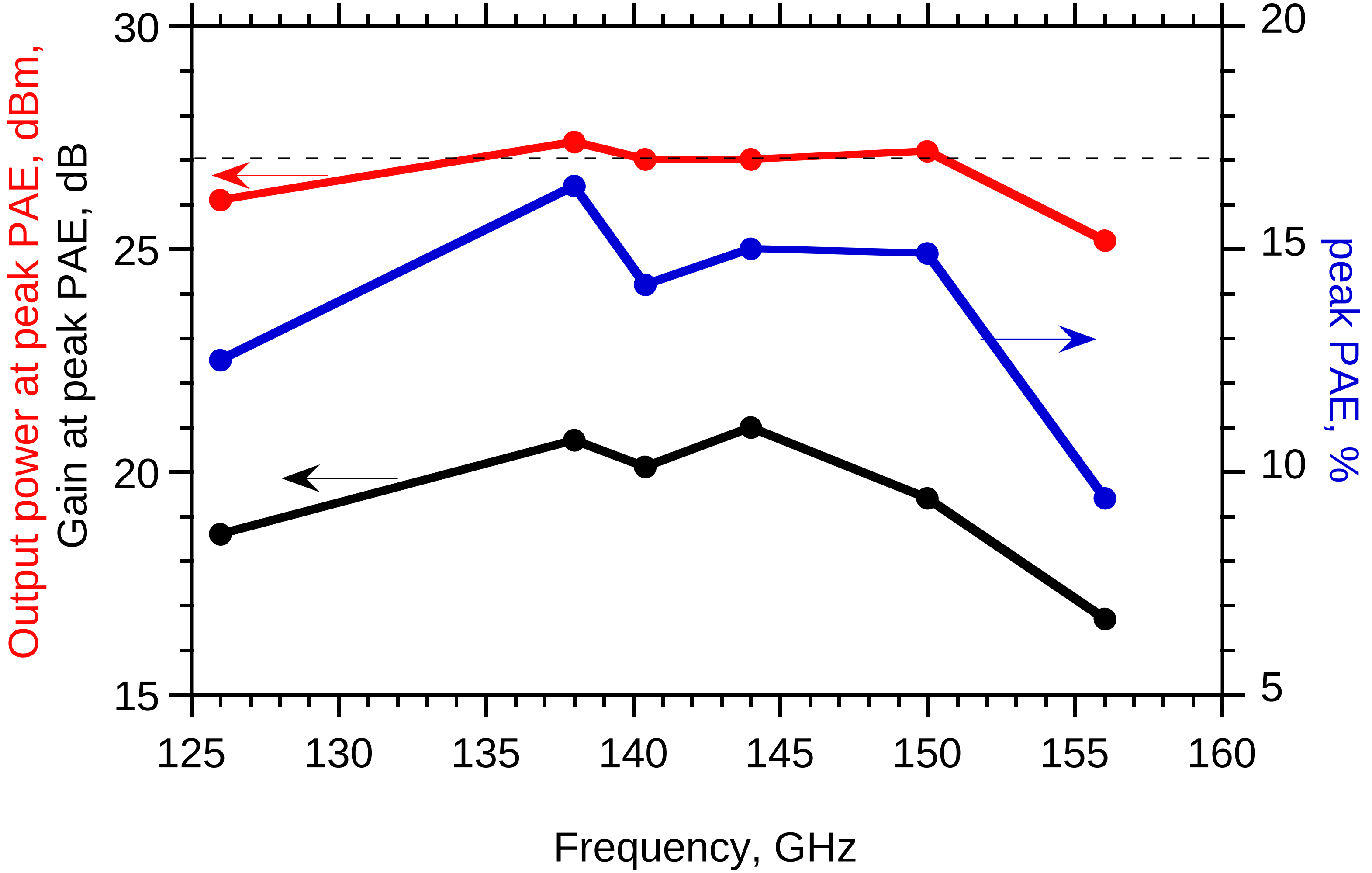
14.9% peak PAE

27.2 dBm output power at peak PAE



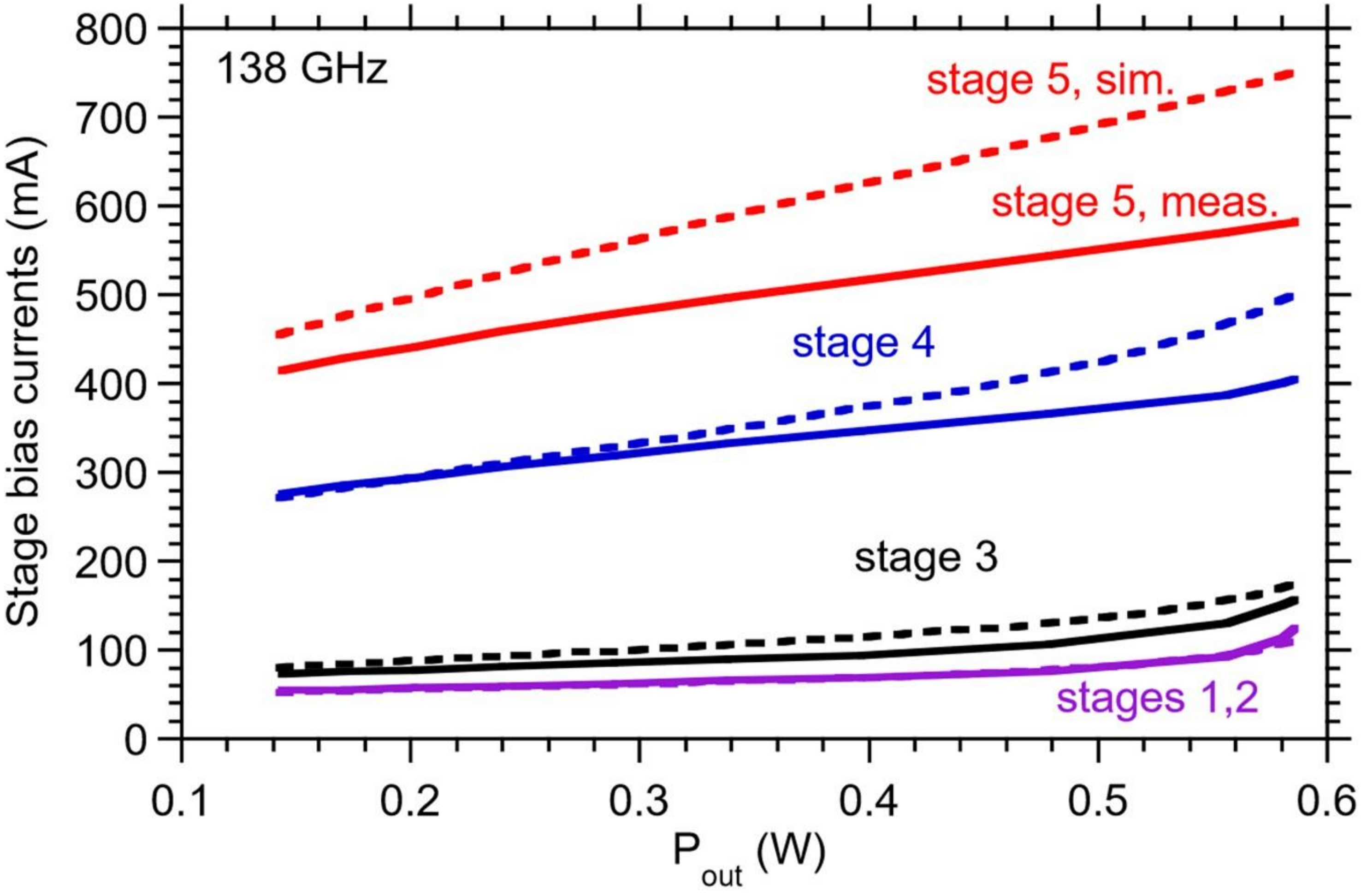
125-155 GHz Power Characteristics

$P_{out} > 26$ dBm
over 126-150 GHz



Adaptive Bias Circuit Operation: 138 GHz

IC shows expected
linear variation
of bias currents vs. RF power



High-Power InP D-band Amplifier

Record 27 dBm output power at 150 GHz; 14.9% associated PAE

> 26 dBm over 126-150 GHz

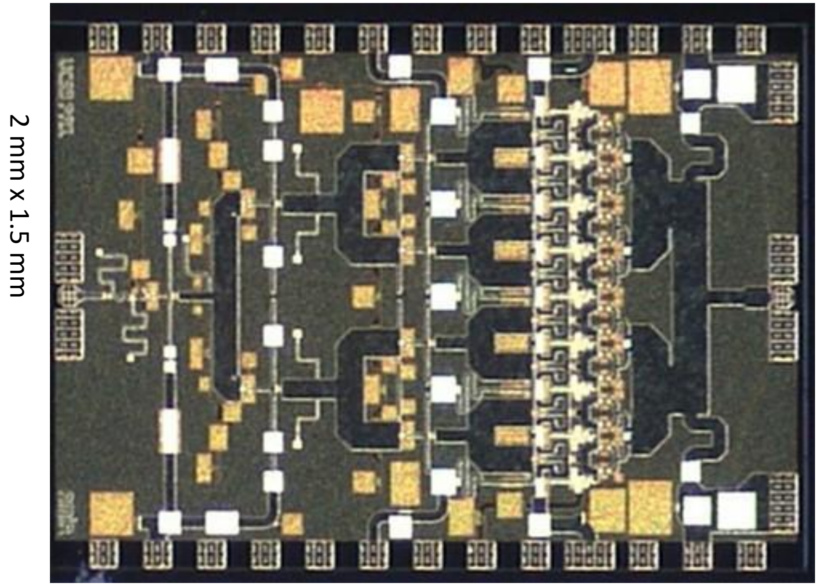
2 mm x 1.5 mm die; fits in 140 GHz, 0.6λ-pitch linear array

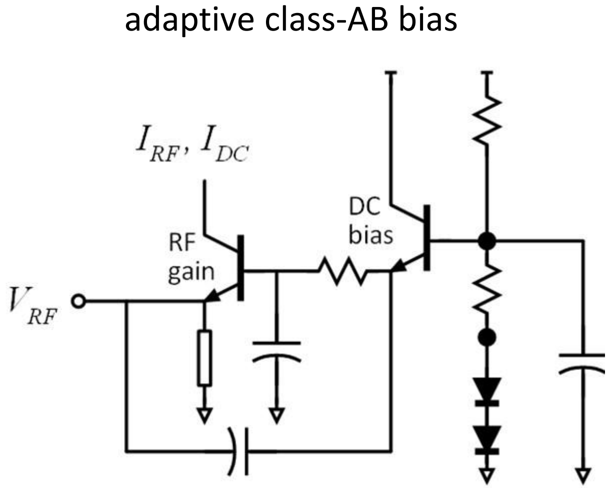
Teledyne 250 nm InP HBT technology.

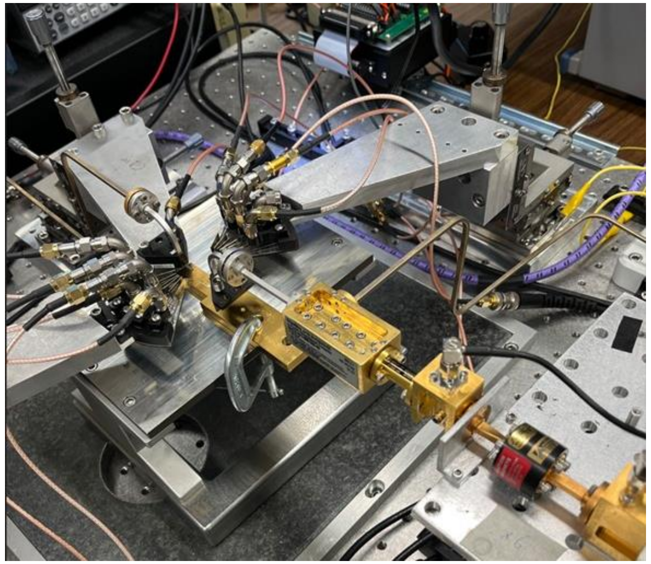
Adaptive bias circuits: class-AB bias, electrothermal stabilization.

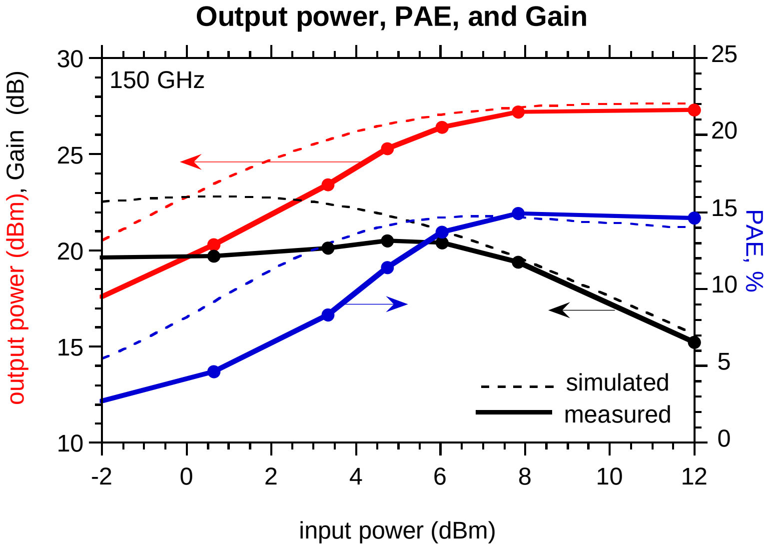
4x 6 μm HBT cell; no cell parasitics

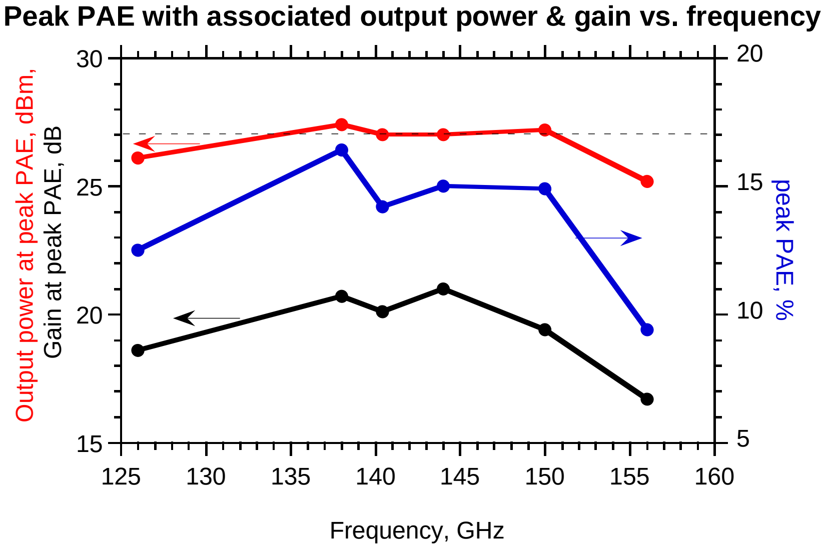
Questions ?

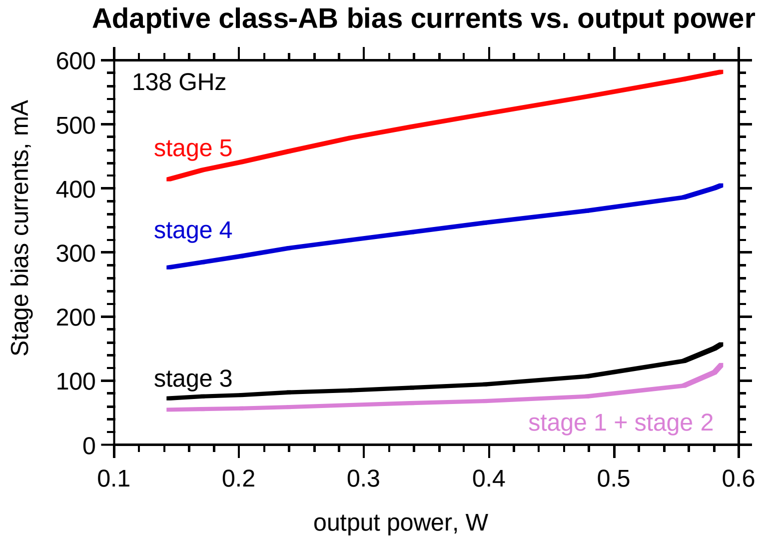

2 mm x 1.5 mm


adaptive class-AB bias
I_{RF}, I_{DC}
RF
gain
DC
bias
V_{RF}




Output power, PAE, and Gain
150 GHz
output power (dBm), Gain (dB)
PAE, %
simulated
measured
input power (dBm)
30
25
20
15
10
-2
0
2
4
6
8
10
12


Peak PAE with associated output power & gain vs. frequency
Output power at peak PAE, dBm,
Gain at peak PAE, dB
peak PAE, %
Frequency, GHz
125
130
135
140
145
150
155
160


Adaptive class-AB bias currents vs. output power
138 GHz
stage 5
stage 4
stage 3
stage 1 + stage 2
Stage bias currents, mA
output power, W
0.1
0.2
0.3
0.4
0.5
0.6

backup slides

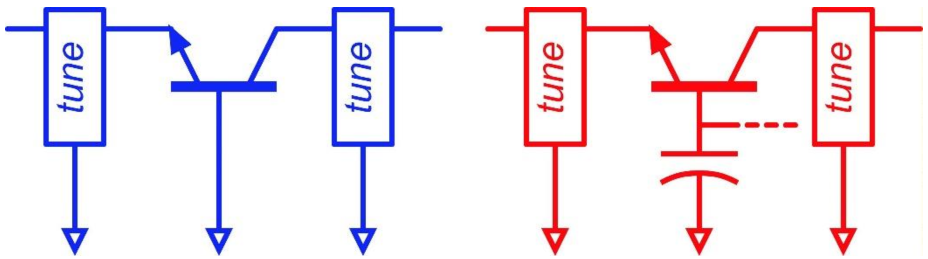
Capacitive Degeneration: Optimum Gain

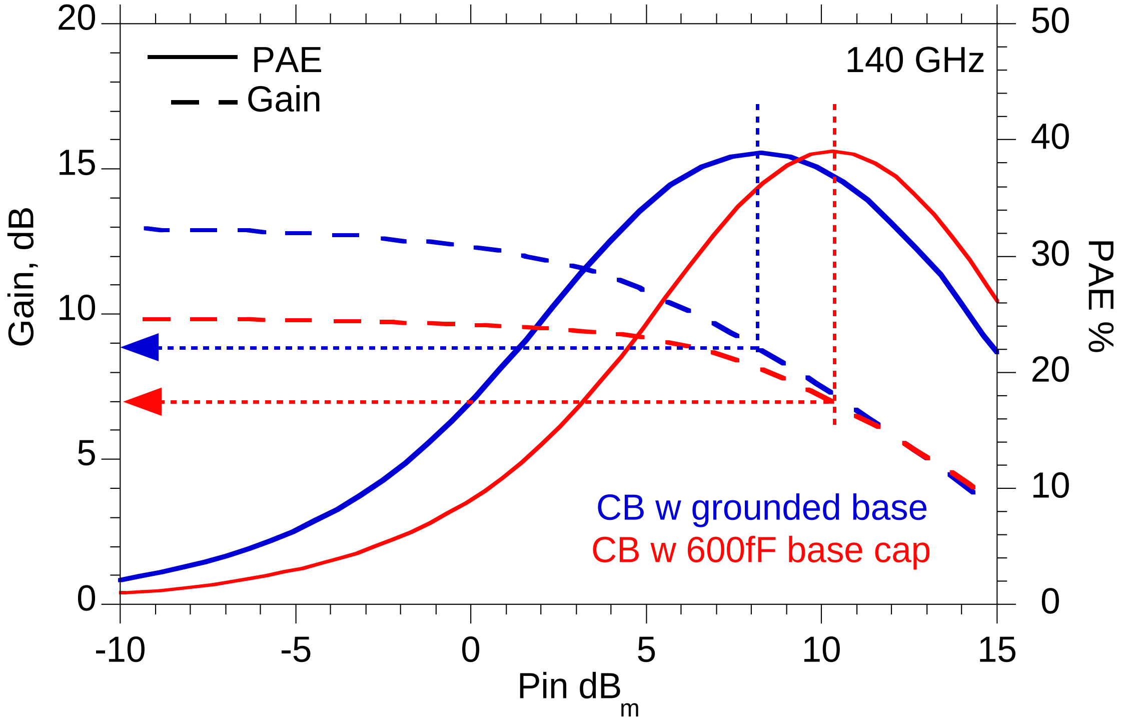
Capacitive degeneration:
    no effect on peak PAE….given lossless embedding

No capacitive degeneration:
    more gain compression @ P_{1dB}. ✗
    more gain @ P_{1dB} ✓
    input matching losses have less effect on PAE ✓

With capacitive degeneration:
    less gain compression @ P_{1dB}. ✓
    less gain @ P_{1dB} ✗
    input matching losses have more effect on PAE ✗

Design for greatest PAE @ P_{1dB}
balances these two considerations.





4x 6 μm HBT cell; no cell parasitics

9b.2

10:50 - 11:10 AM – D-Band Power Amplifier with 27dBm Peak Output Power and 14.9% PAE in 250-nm InP HBT Technology

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