TU3B-1

An 81 GHz, 470 mW, 1.1 mm^2 InP HBT Power Amplifier with 4:1 Series Power Combining using Sub-quarter-wavelength Baluns

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Outline

- Motivation, Challenge
- Power-combining Techniques in mm-Wave
- Proposed Baluns (2:1 and 4:1 Series Combiners)
- Power Amplifier Designs (2:1 and 4:1)
- Measurement Results and Comparisons
- Conclusion

mm-Wave Power Amplifier: **Challenges**

mm-Wave PAs:

Applications: High speed communications, high resolution images

Needed: High power / High efficiency / Small die area (low cost)

***Extensive** power combining*

***Compact** power-combining*

$$\mathrm{PAE} = \eta_{\substack{\text{drain/}\\ \text{collector}}} \left(1 - \frac{1}{\mathrm{Gain}}\right) \cdot \eta_{\substack{\text{power-}\\ \text{combiner}}}$$

Class E/D/F are poor @ mm-wave

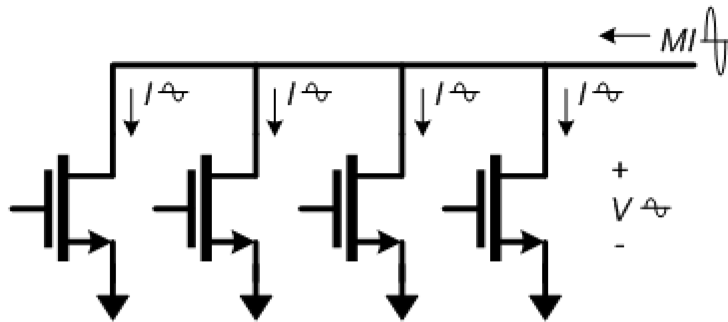
insufficient gain ~f_{max},

high losses in harmonic terminations

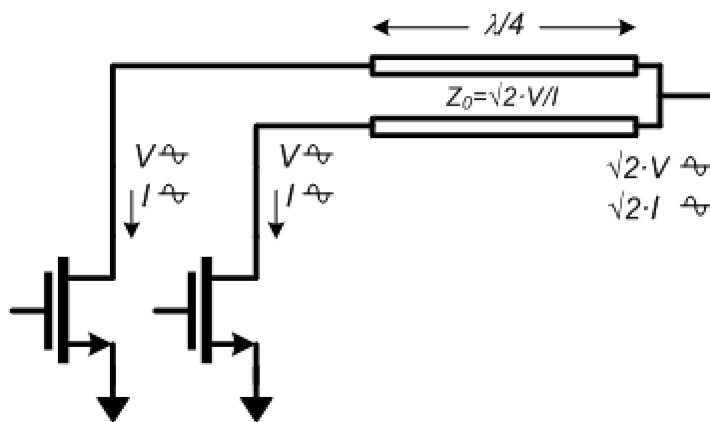
***Efficient** power-combining*

Goal: efficient, compact mm-wave power-combiners

Parallel Power-Combining



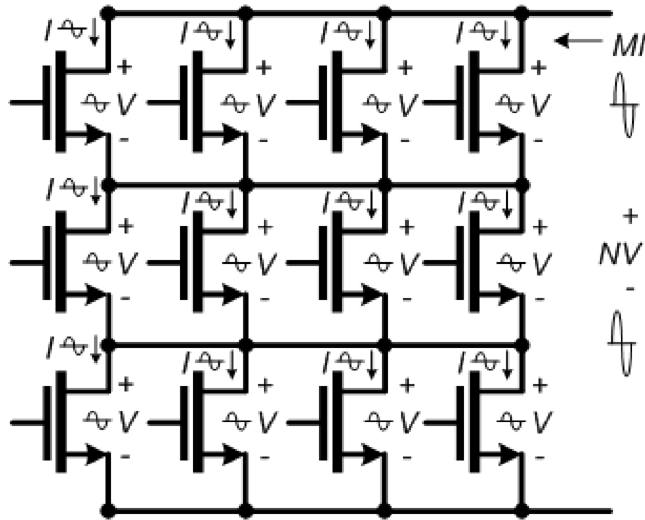
Output power: $P_{OUT} = V \times (\mathbf{M} \times I)$
Parallel connection **increases** P_{OUT}
Load Impedance: $R_{OPT} = V / (\mathbf{M} \times I)$
Parallel connection **decreases** R_{OPT}



High P_{OUT} using low V_{DD} → Low R_{OPT}
Needs impedance transformation:
Wilkinson or lumped lines …

→ ***High insertion loss***
→ ***Small bandwidth***
→ ***Large die area***

Series Power-Combining & Stacks



Parallel connections: I_{OUT} = **M** x I

Series connections: V_{OUT} = **N** x V

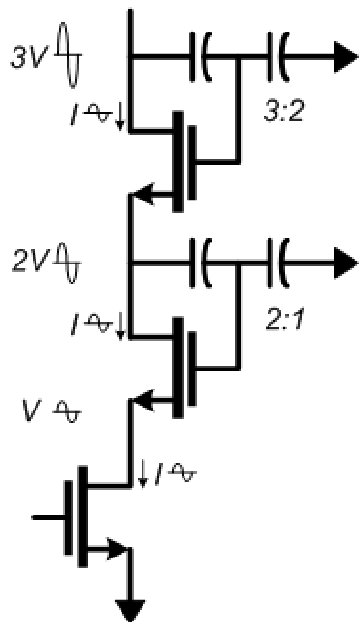
Output power: P_{OUT} = **(N·M)** x V x I

Load impedance: R_{OPT} = **(N/M)** x V/I

Small or zero power-combining losses

Small die area

BUT, how do we drive the gates **?**



Local voltage feedback:

drives gates, sets voltage distribution

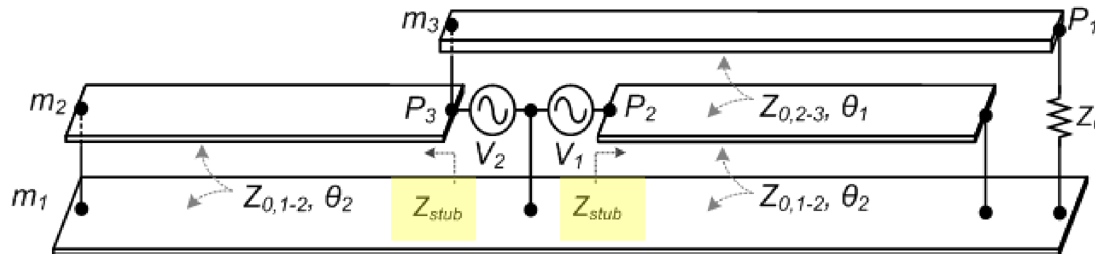
Design challenge:

need uniform RF voltage distribution

need ~unity RF current gain per element

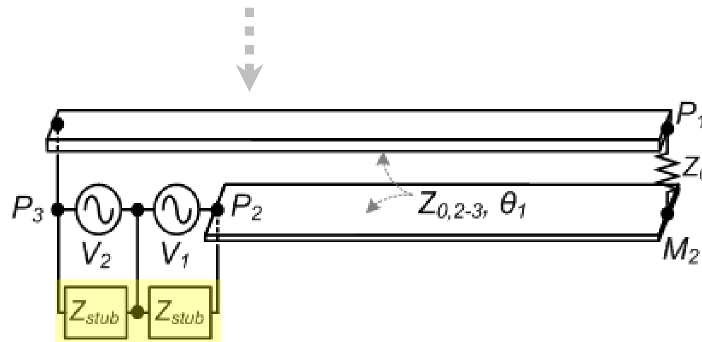
...needed for simultaneous compression of all FETs.

Proposed λ/4 Baluns



Balun structure

Simplified model



$$Z_{stub} = jZ_{0,1-2} \tan\theta_2$$

$$if \;\; \theta_2 = \lambda/4, \;\; Z_{stub} = \infty$$

Our proposed balun with λ/4 lines

Three-conductor transmission-lines

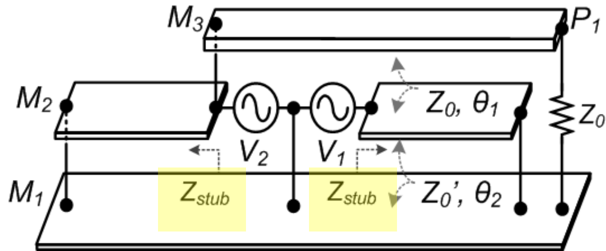
→ Two separate transmission lines *(m_3-m_2, m_2-m_1)*

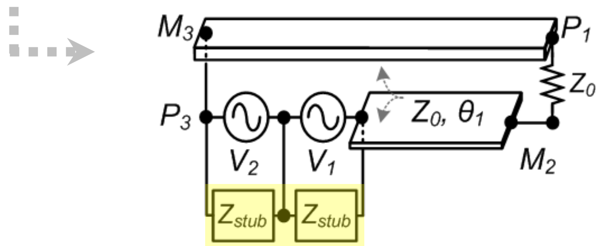
Fields between *m_3 and m_1* isolated!

λ/4 line stub → ***Z_{stub}* = open**

BUT, still long line → *high loss and large die area* ☹

Proposed Sub-λ/4 Baluns



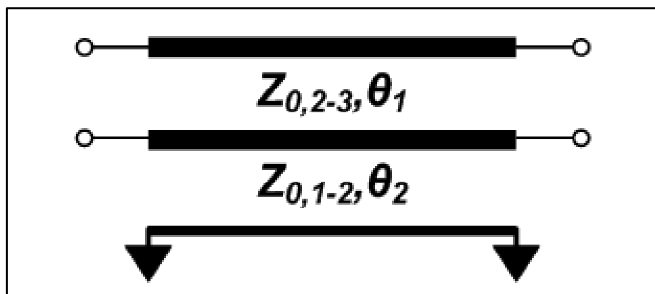


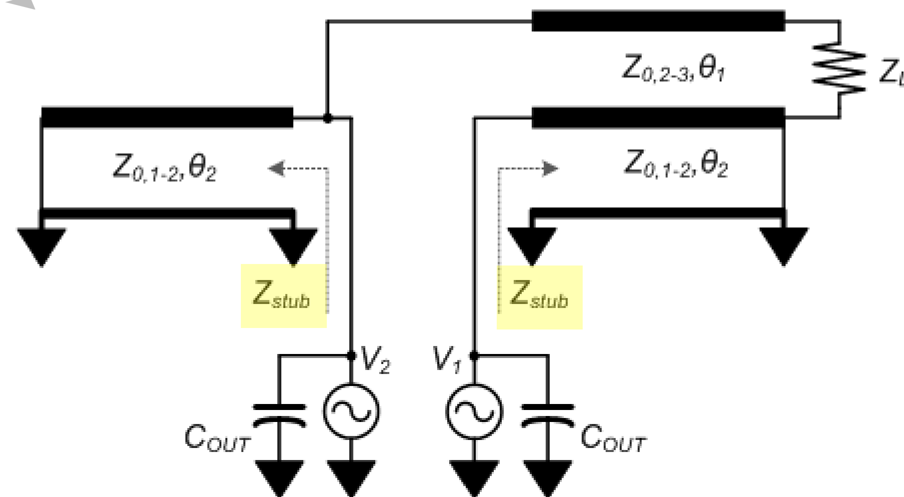
What if balun length is << λ/4 ?
→ Stub line becomes **inductive**!

Sub-λ/4 balun:
Inductive stub line
Tunes transistor C_{OUT} !!
Short line → *Low losses* ☺
→ *Small die area* ☺

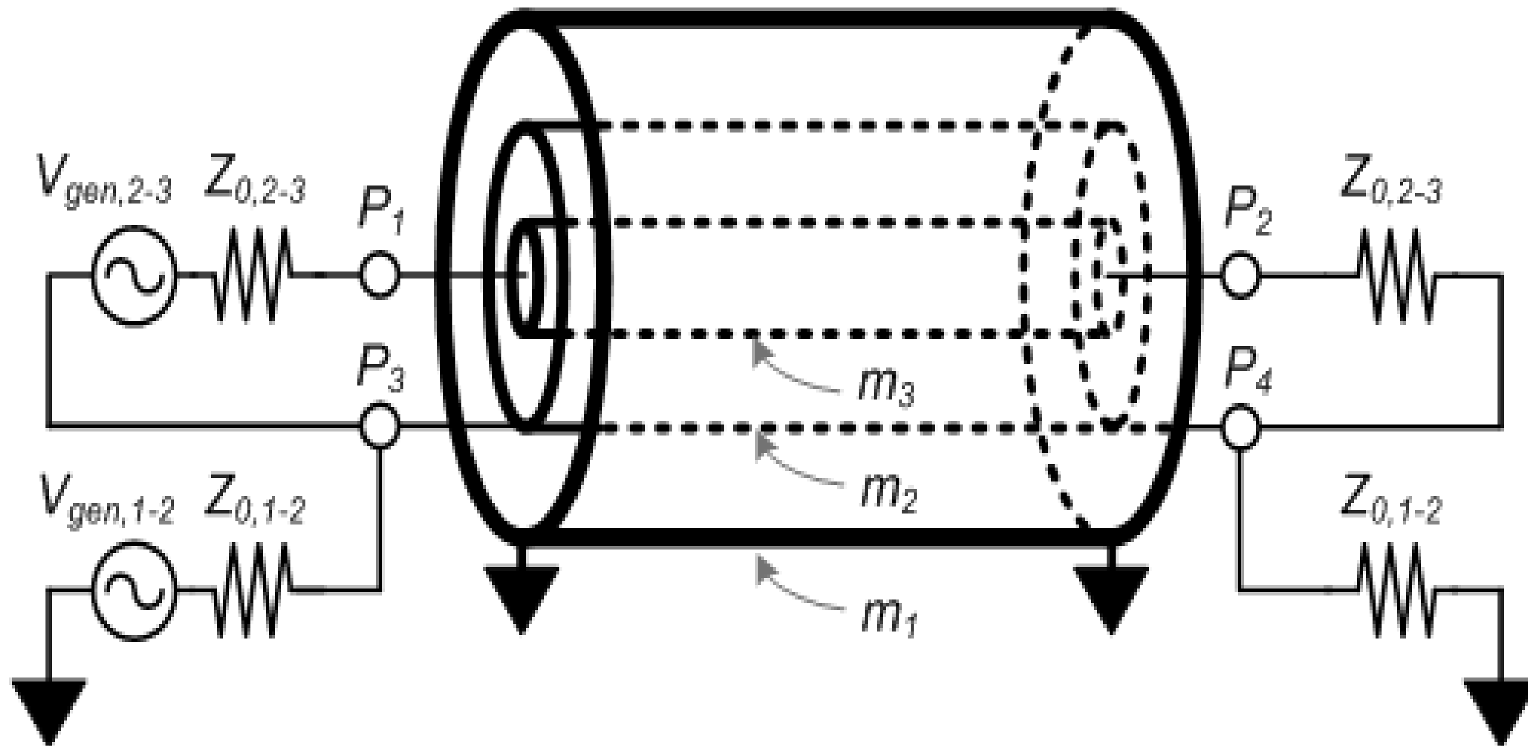
$$if \;\; \theta_2 << \lambda / 4, \;\; Z_{stub} \rightarrow inductive$$

*Symbol:
Three-conductor transmission line





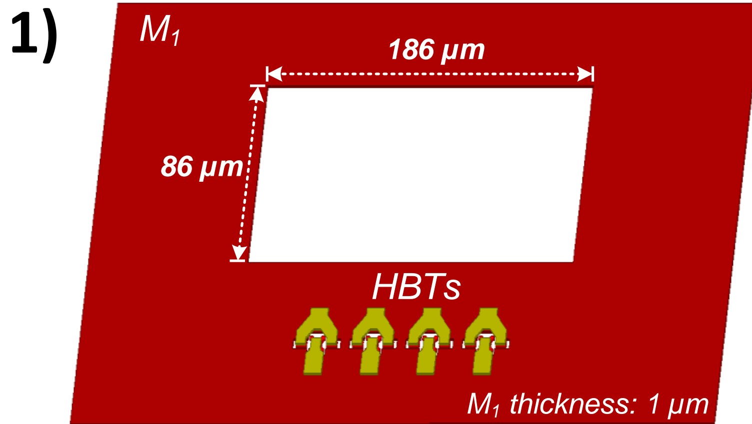
Ideal Tri-axial Line



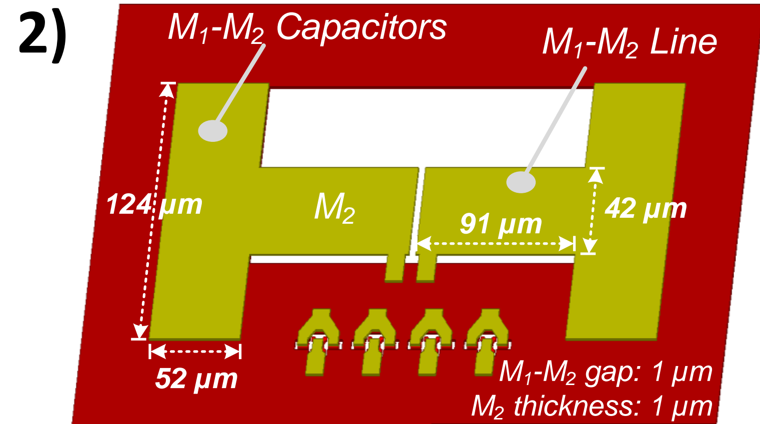
Two separate transmission lines (m_3-m_2, m_2-m_1)
→ E, H fields between m_3 and m_1 perfectly shielded

Baluns in **Real ICs**

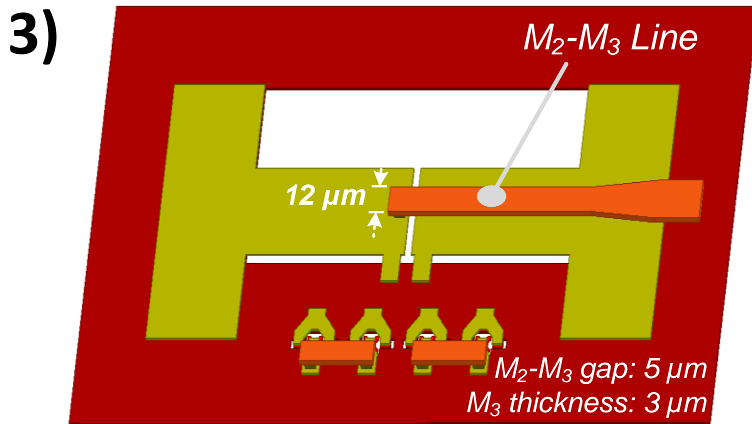
1)



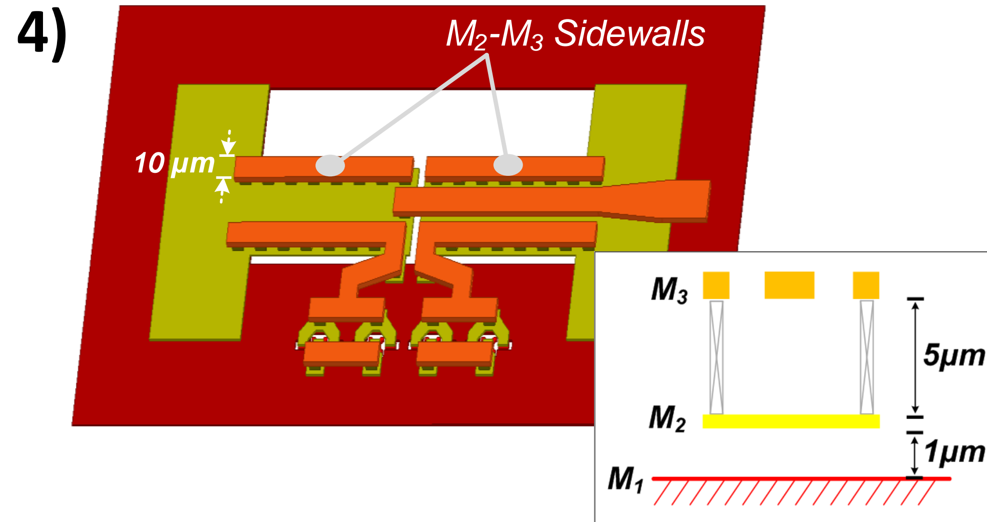
2)



3)



4)



1) M_1 as a GND

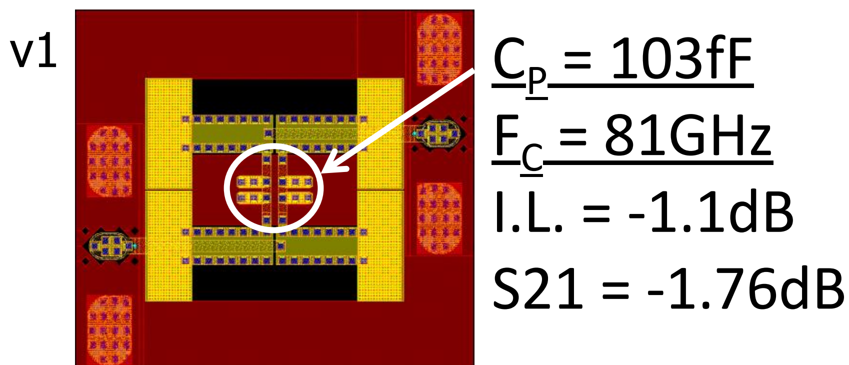
2) Slot-type transmission lines (M_1-M_2), AC short (2 pF MIM)

3) Microstrip line (M_2-M_3), E-field shielding **NOT** negligible

4) **Sidewalls** between M_3-M_1 (Faraday cages), **λ/16 length**

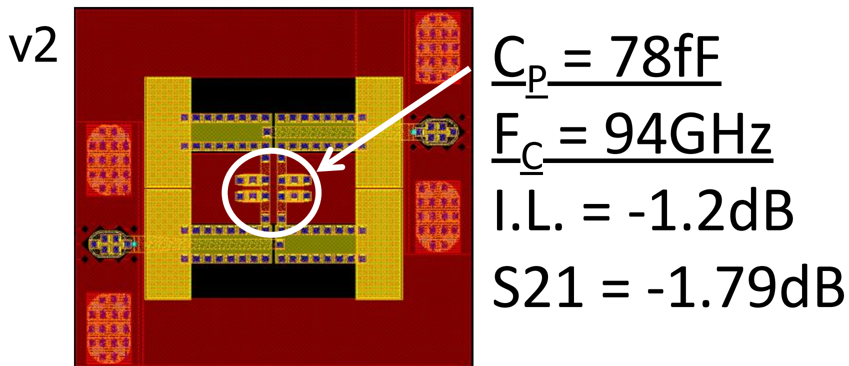
2:1 Balun B-to-B Test Results

v1



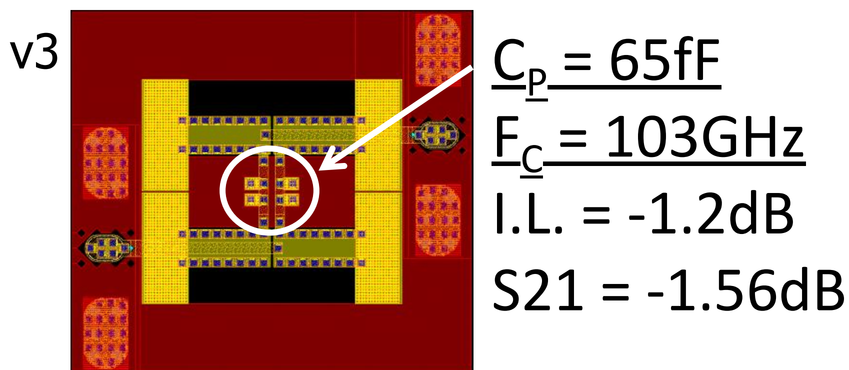
C_P = 103fF
F_C = 81GHz
I.L. = -1.1dB
S21 = -1.76dB

v2



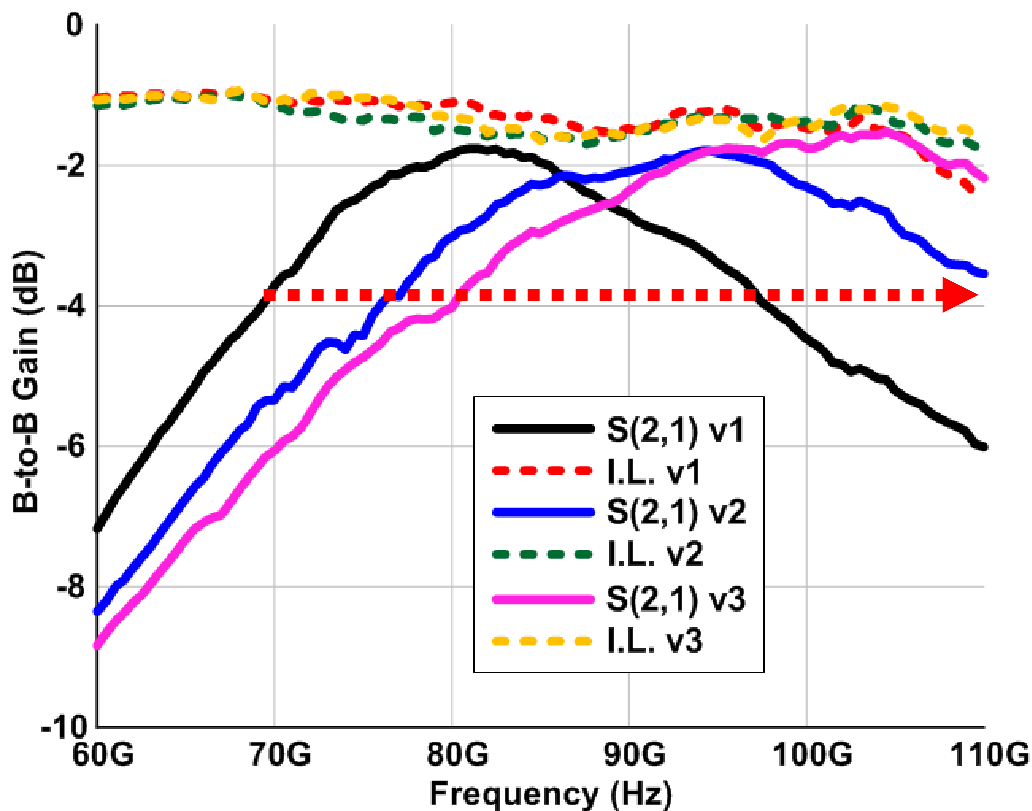
C_P = 78fF
F_C = 94GHz
I.L. = -1.2dB
S21 = -1.79dB

v3



C_P = 65fF
F_C = 103GHz
I.L. = -1.2dB
S21 = -1.56dB

Back-to-back measured S-parameters



**Does not de-embed losses of PADs , capacitors, and interconnection lines*

< 0.6dB single-pass insertion loss, 0.16 dB/2.7° imbalance

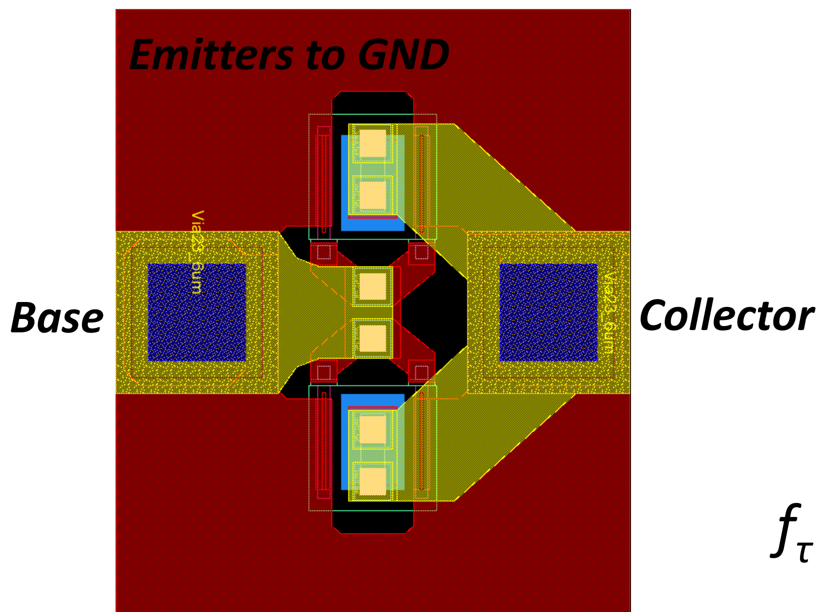
Teledyne *0.25 μm* HBTs

Cell: 4-fingers x 0.25 μm x 6 μm

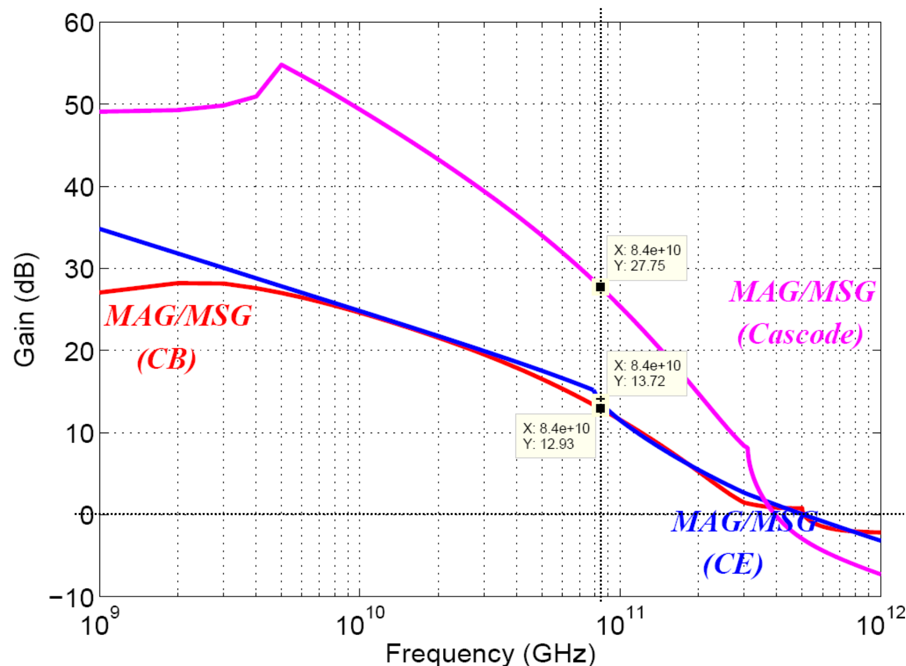
BV_{CEO} = 4.5 V, $I_{C,max}$ = 72 mA

P_{OUT} = 15.5 dBm

R_{OPT} = 56 Ω



MAG/MSG including EM-Sim. results



f_τ=285 GHz, f_{max}=525 GHz

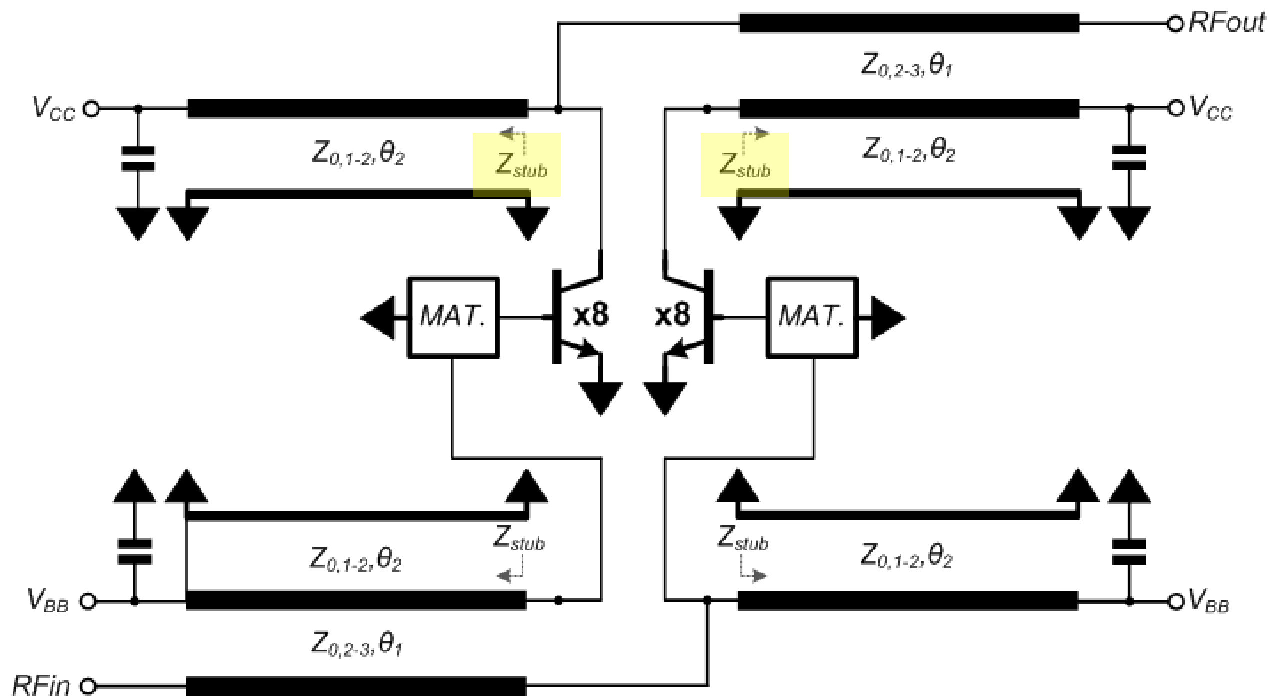
@ J_E=4.2 mA/μm^2 and V_{CE}=2.5 V

12~13dB MAG @ 86 GHz

[Z. Griffith et al, IPRM 2012]

Multi-finger 250nm InP HBTs for 220GHz mm-Wave Power Multi-finger 250nm InP HBTs for 220GHz mm-Wave Power

Sub-λ/4 Baluns: **PA Design**



Each HBT loaded by 25 Ω

HBT junction area selected so that $\mathbf{I_{max}=V_{max}/25\ \Omega}$

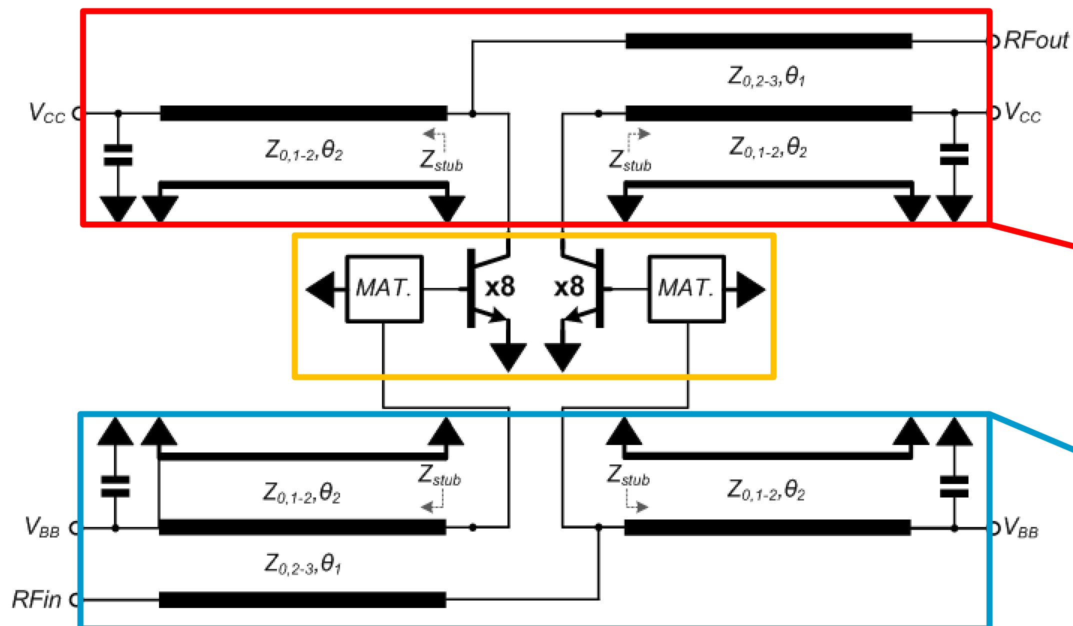
Each HBT has some C_{OUT}

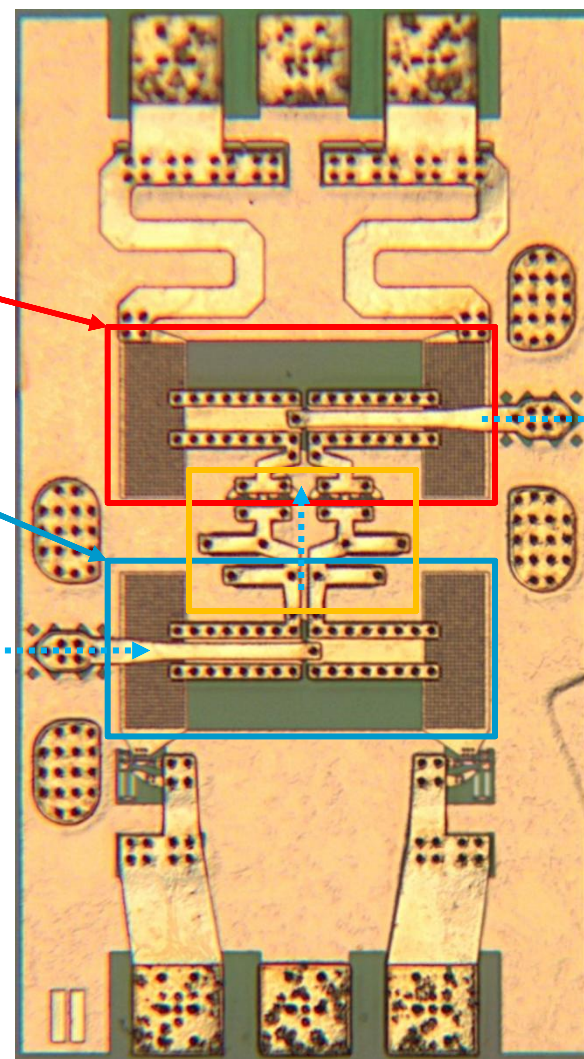
Stub length picked so that $\mathbf{Z_{stub}=-1/j\omega C_{OUT}}$ → tunes HBT

$$P_{out} = 4 \times \left(\frac{V_{max}^2}{8 \cdot 50\Omega} \right)$$

4:1 more power than without the combiner.

4:1 PA Designs Using **2:1 Balun**





Identical input / output baluns

2-section *LC* input matching network

Active bias: Thermal stability & class-AB

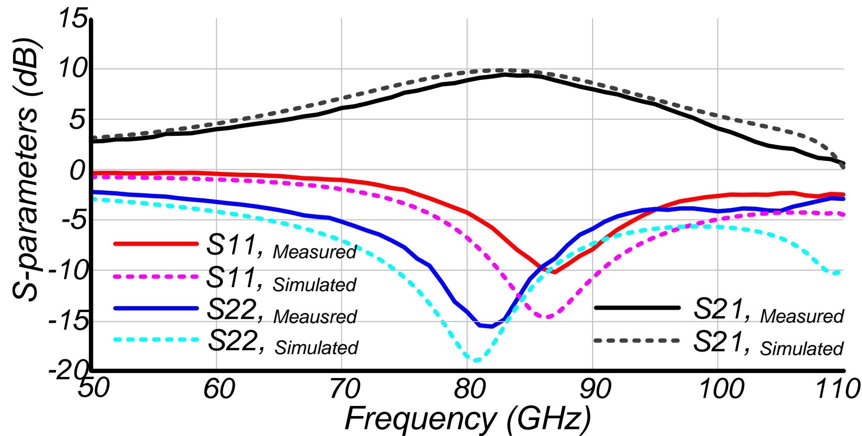
IC size: 450 x 820 um^2

[H. Park et al, CSICS 2013]

30% PAE W-Band InP Power Amplifiers Using Sub-Quarter-Wavelength Baluns for Series-Connected Power-Combining

Single-Stage PA IC Test Results (86GHz)

Small signal measurements



x4 larger output power than 50 Ohm R_{OPT} device

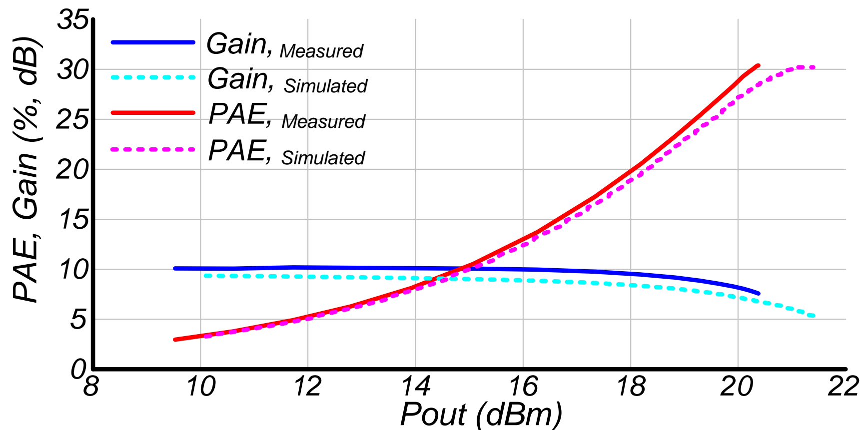
***Gain:* 10 dB**

***P_{SAT}:* >100 mW @2.5V**

***PAE:* >30 %**

***3-dB BW:* 23 GHz**

Large signal measurements



Power density (power/die area)

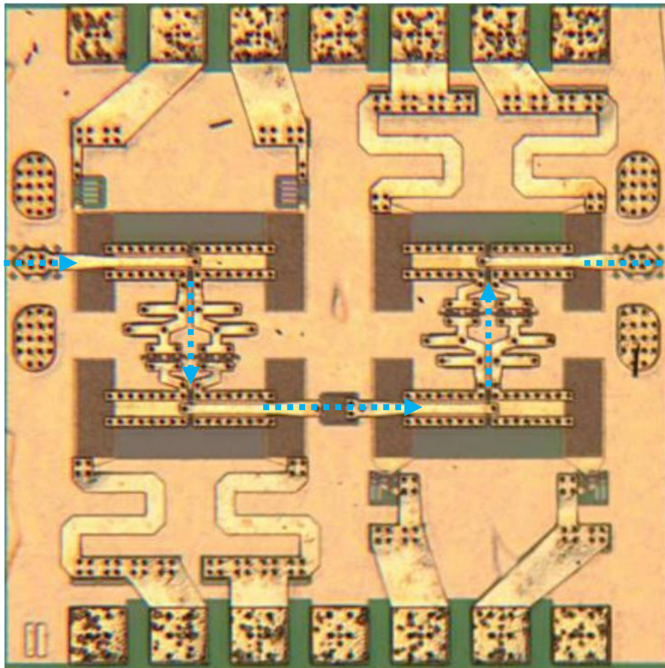
= 294 mW/mm² (including RF pads)

= 1210 mW/mm² (core area)

[H. Park et al, CSICS 2013]

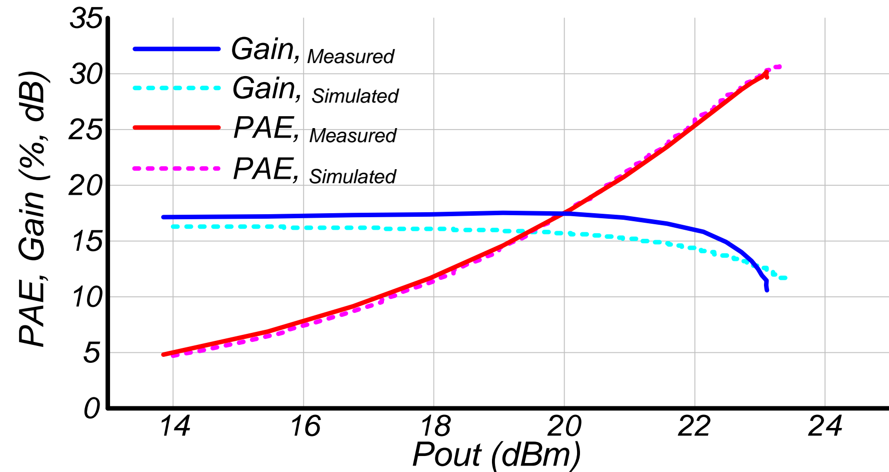
30% PAE W-Band InP Power Amplifiers Using Sub-Quarter-Wavelength Baluns for Series-Connected Power-Combining

Two-Stage PA IC Test Results (86GHz)



IC size: 825 x 820 um^2

Large signal measurements



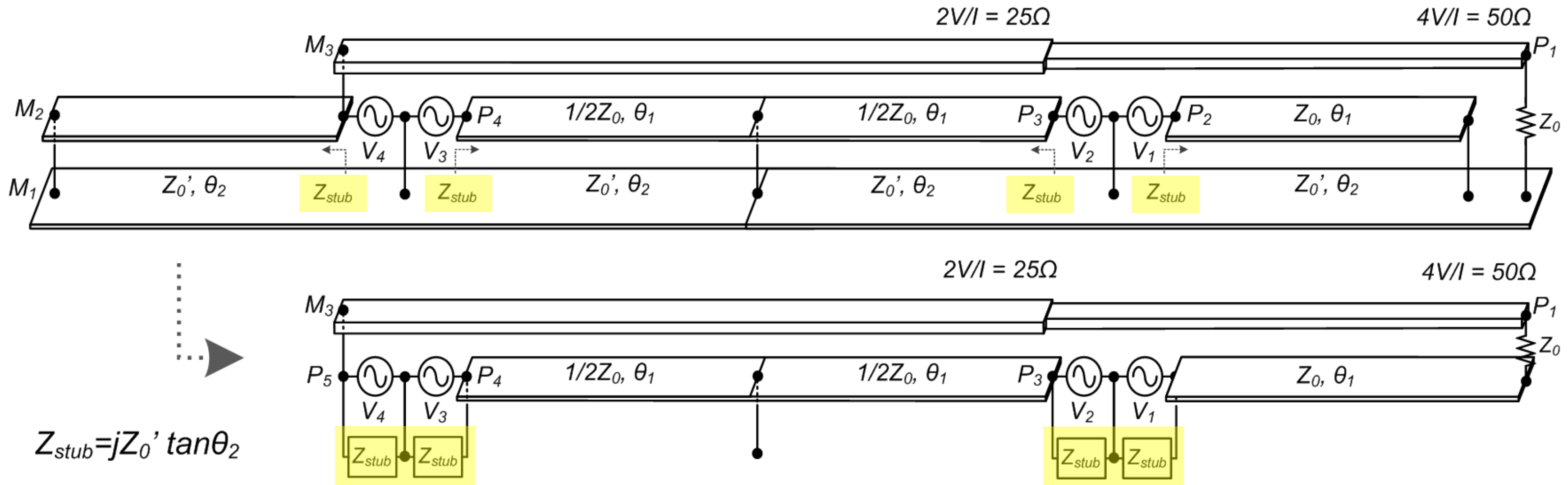
Gain: 17.5 dB
P_{SAT}: >200 mW @ 3.0 V
PAE: >30 %

Power density (power/die area)
= 307 mW/mm^2 (including RF pads)
= 927 mW/mm^2 (core area)

[H. Park et al, CSICS 2013]
30% PAE W-Band InP Power Amplifiers Using Sub-Quarter-Wavelength Baluns for Series-Connected Power-Combining

16:1 PA Using 4:1 Baluns

4:1 series-connected power-combining



Each HBT loaded by 12.5Ω

HBT junction area selected so that $I_{max}=V_{max}/12.5\Omega$

$$P_{out} = 16 \times \left(\frac{V_{max}^2}{8 \cdot 50\Omega} \right)$$

Each HBT has some C_{OUT}

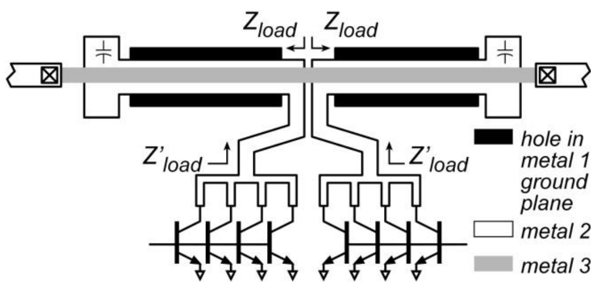
Stub length picked so that $Z_{stub}=-1/j\omega C_{out}$ → tunes HBT

16:1 more power than without combiner.

PA IC Schematic (2-stages)

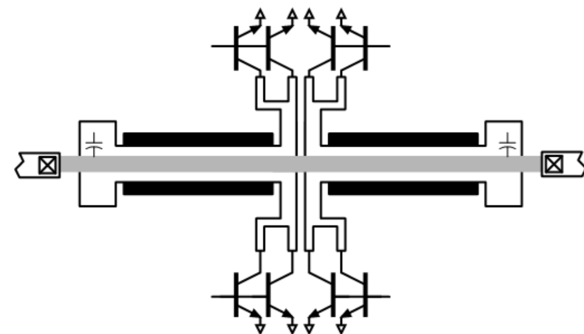
2-stage PA using 2:1 and 4:1 baluns

1st stage **2nd stage**



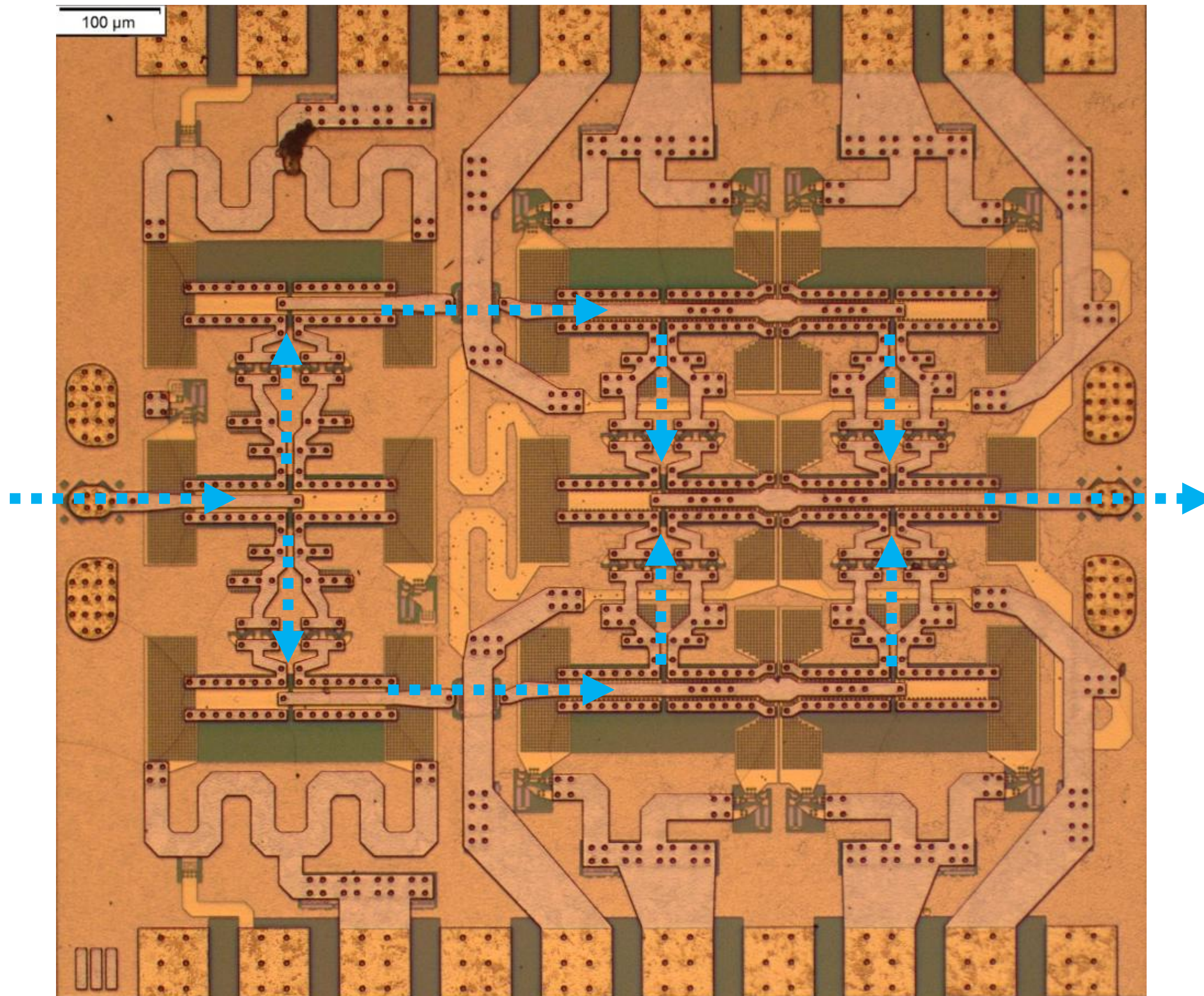
Long lead lines

$Z_{load} \neq Z'_{load}$



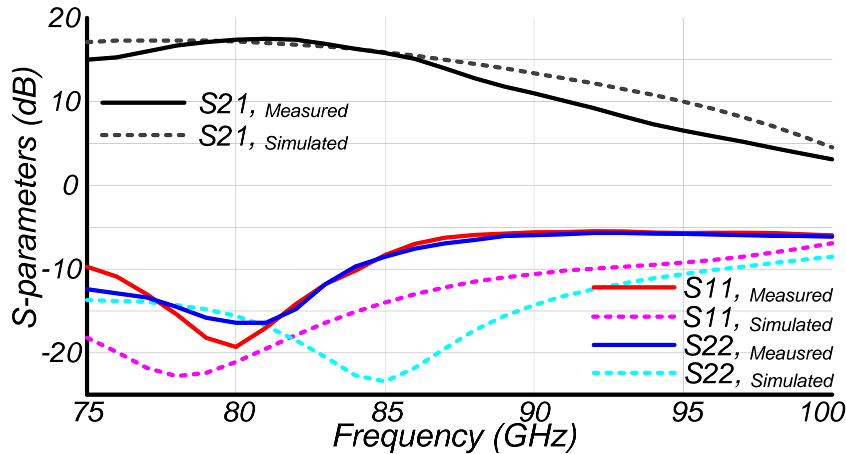
PA IC Die Image (2-stages)

IC Size: 1.08 x 0.98 mm^2



PA IC Test Results (81 GHz)

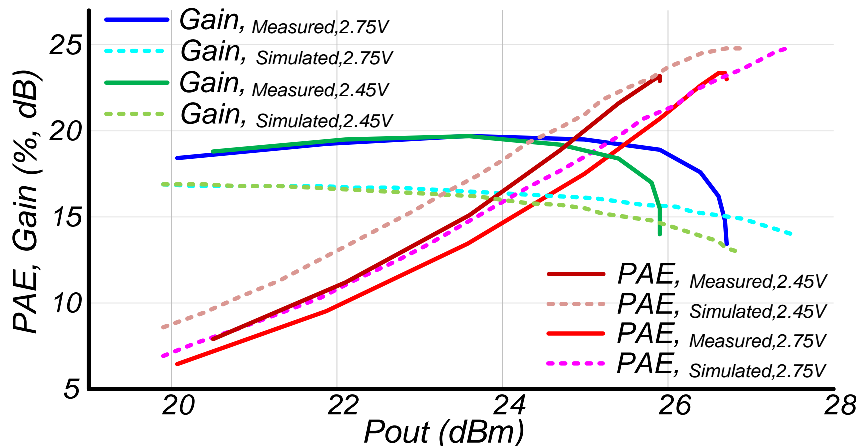
Small signal measurements



x16 larger output power than 50 Ohm R_{OPT} device

Gain: 17.8dB
Output Power: 470mW @2.75 V
PAE: 23.4%

Large signal measurements



Power density (power/die area)
= 443 mW/mm² (including pads)
= 1020 mW/mm² (only core area)

mm-Wave **Power Combiners**

Ref.	Tech.	Type	N-way	Freq. (GHz)	IL (dB)	Size (mm^2)
This work	0.25 µm InP HBT	Sub-λ/4 TL	2:1	86 (60-105)	**0.52** (0.68)	**0.03**
This work	0.25 µm InP HBT	Sub-λ/4 TL (ring)	2:1	86 (60-110)	**0.50** (0.63)	**0.04**
This work	0.25 µm InP HBT	Sub-λ/4 TL	4:1	87 (75-103)	**0.91** (1.32)	**0.06**
2012 Yi	0.13 µm BiCMOS	TF	4:1	60 77/79	0.73* 1.20*	0.015
2013 Thian	0.18 µm BiCMOS	TF	8:1	83.5 (70.5-85)	1.25 (0.80*)	0.02#
2010 Chen	65 nm CMOS	TF	4:1	60	0.63*	0.02#
2010 Law	90 nm CMOS	Wilkinson	2:1	60	0.54	0.08
2014 Zhao	40 nm CMOS	Series/ parallel TF	4:1	75 (65-90)	0.92* (1.0)	0.05#
2007 Niknejad	90 nm CMOS	TL	4:1	60 (55-65)	1.09* (1.25*)	-
2007 Liu	0.18 µm CMOS	Marchand	2:1	57	3.40	0.55
2005 Hamed	InGaP/GaAs	Marchand	2:1	(15-45)	(1.50)	0.40

*Simulation results, #Area estimated by chip image. IL: insertion loss, TF: transformer, and TL: transmission-line. Parentheses in the frequency and insertion loss columns indicate worst-case insertion loss over the indicated bandwidth.

mm-Wave **Power Amplifiers**

Ref.	Tech. f_{max} / f_τ (GHz)	Freq. (GHz)	BW (GHz)	Max. S_{21} (dB)	P_{out} (dBm)	Peak PAE (%)	V_{CC} or V_{DD} (V)	Size (mm^2)	mW /mm^2
This work	0.25 µm InP HBT 525 / 285	86	23	9.4	**20.4**	**30.4**	2.5	0.37 0.09*	294 **1210***
This work	0.25 µm InP HBT 525 / 285	86	33	10.2	**20.8**	**35.0**	2.5	0.43 0.14*	285 **858***
This Work	0.25 µm InP HBT 525 / 285	81	>11.5	17.5	**26.7**	**23.4**	2.75	1.06 0.46*	443 **1020***
2011 Brown	0.14 µm GaN HEMT	91	7+	16.0	30.8	>20.0	17.5	2.25	530
2012 Micovic	0.14 µm GaN HEMT 230 / 97	95	10+	18.0+	31.5+	20.5+	12.0	-	-
2012 Yi	0.13 µm BiCMOS 270 / 240	62 84	>10 >8	20.6 27.0	20.1 18.0	18.0 9.0	1.8 2.5	0.72 0.68	142 93
2013 Agah	45 nm SOI CMOS	89	10+	10.3	15.8	11.0	2.8	0.37 0.05*	103 760*
2013 Thian	0.18 µm BiCMOS 250 / 170	78	8.9	18.3	14	2.0	3.2	0.85*	29*
2010 Chen	65nm CMOS	60	9	20.3	18.6	15.1	1.0	0.28*	256*
2010 Law	90nm CMOS	60	8	20.6	19.9	14.2	1.2	1.76	55
2014 Zhao	40nm CMOS	80	15.2	18.1	20.9	22.3	0.9	0.19*	647*

*IC core area (excluding DC feed lines and RF pads), +Value estimated from figure, c)Corporate transmission-line power-combiners, s)Stacked PA.

Conclusion

Sub-λ/4 baluns for series-power-combining using a low V_{BV} device

Low-loss **<0.6dB** @ 2:1 balun, **<0.92dB** loss @ 4:1 balun

→ High power, high efficiency, compact PA IC designs

W-band power amplifiers using the 2:1 & 4:1 baluns

	2:1	4:1
Record	**>30 % PAE** @ 100 mW, 200 mW,	**23.4 % PAE @470 mW**
Record	23 GHz 3-dB bandwidth,	>10GHz 3-dB BW
Record	**1210 mW/mm²** power density,	**1020 mW/mm²**

Future directions

220GHz PA designs using the sub-λ/4 baluns

SiGe PA designs with the optimized balun structures

Phased arrays at K/V/E/W bands

Thanks for your attention!

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