30% PAE W-band InP Power Amplifiers using Sub-quarter-wavelength Baluns for Series-connected Power-combining

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mm-Wave Power Amplifier: **Challenges**

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mm-Wave PAs:

applications: High resolution imaging, high speed communication

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 f_{max} ,

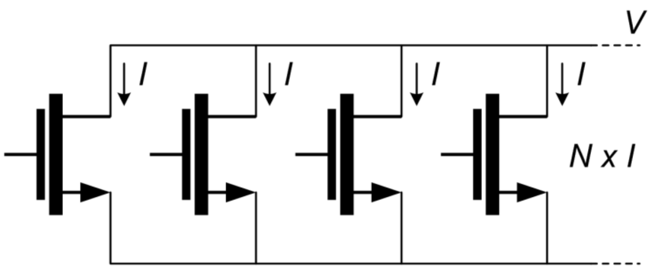
high losses in harmonic terminations

efficiency must instead come from combiner

Efficient power-combining

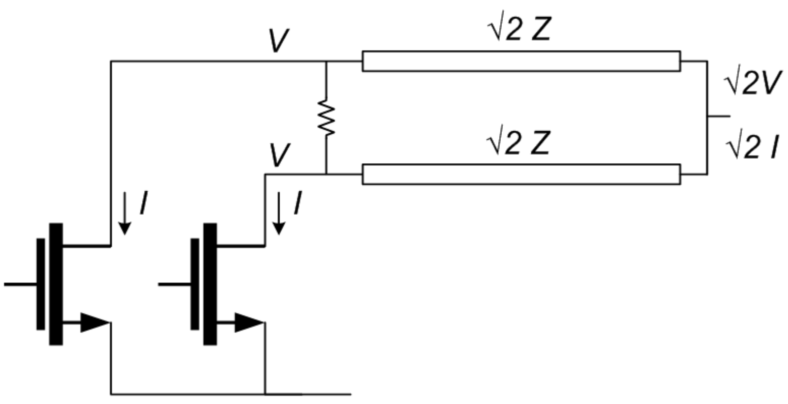
Goal: efficient, compact mm-wave power-combiners

Parallel Power-Combining



Output power: P_{OUT} = **N** x V x I
Parallel connection increases P_{OUT} ✓

Load Impedance: Z_{OPT} = V / (**N** x I)
Parallel connection decreases Z_{opt} ✗

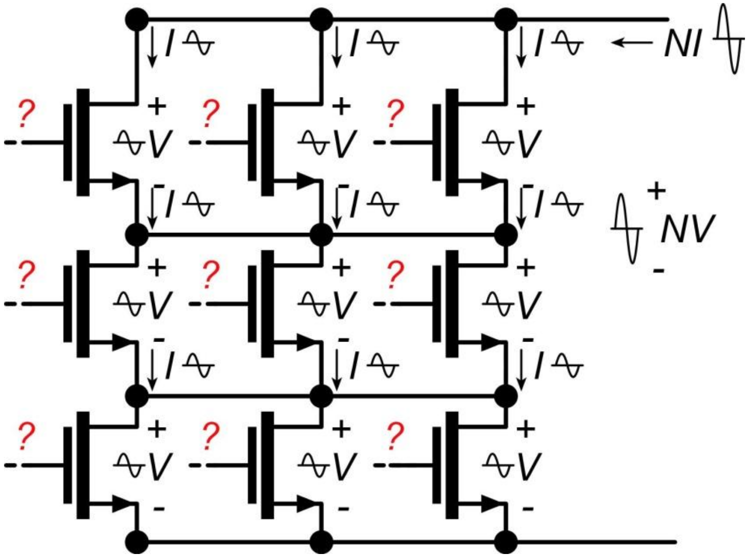


High P_{OUT} → Low Z_{opt}

Needs impedance transformation:
lumped lines, Wilkinson, ...

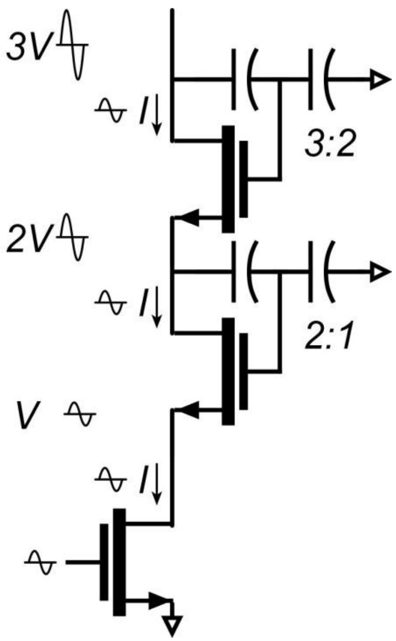
High insertion loss ✗
Small bandwidth ✗
Large die area ✗

Series Power-Combining & Stacks



Parallel connections: I_{out}=N x I
Series connections: V_{out}=N x V

Output power: P_{out}=**N^2** x V x I
Load impedance: Z_{opt}=V/I ✓
Small or zero power-combining losses ✓
Small die area ✓
How do we drive the gates ?

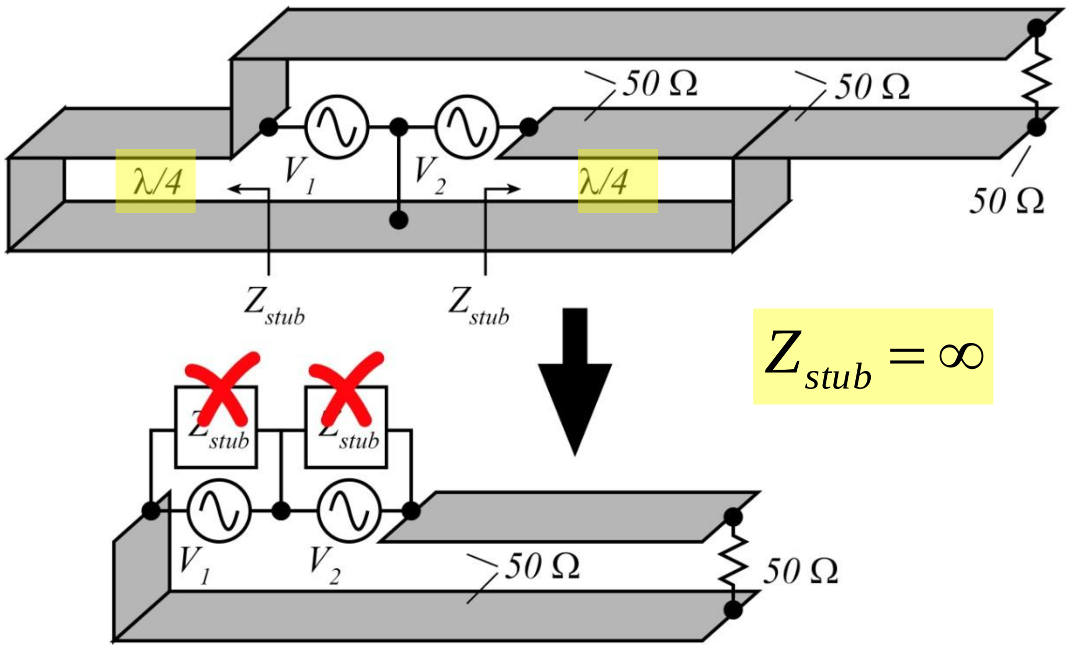


Local voltage feedback:
drives gates, sets voltage distribution

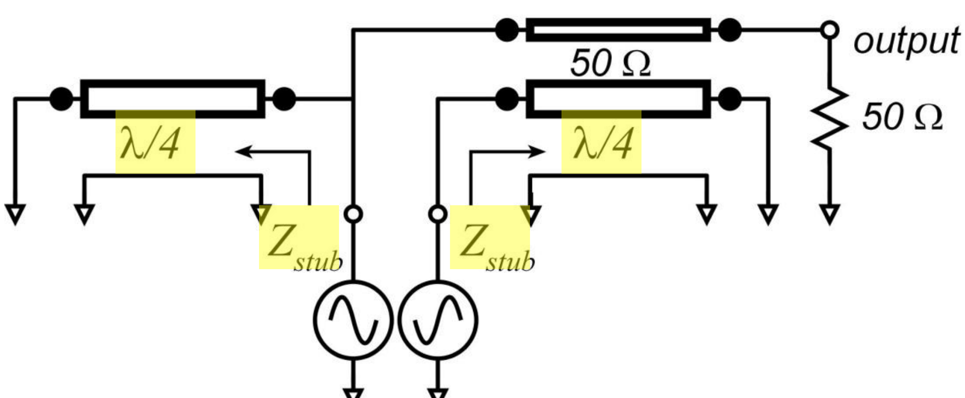
Design challenge:
need uniform RF voltage distribution
need ~unity RF current gain per element

...needed for simultaneous compression of all FETs.

Standard λ/4 Baluns: **Series** Combining



Balun combiner:
voltages add
2:1 series connection ✓
each source sees 25 Ω
→ double I_{max} for each source
4:1 increased P_{out} ✓



Standard λ/4 balun :
λ/4 stub→ open circuit
long lines→ high losses ✗
long lines → large die ✗

Sub-λ/4 Baluns for **Series** Combining

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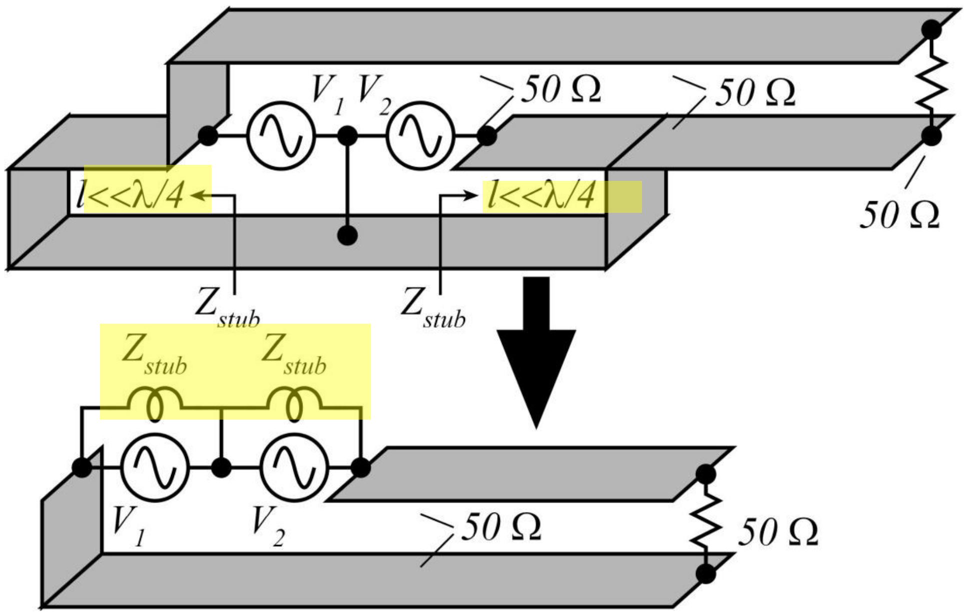


What if balun length is <<λ/4 ?

Stub becomes inductive !

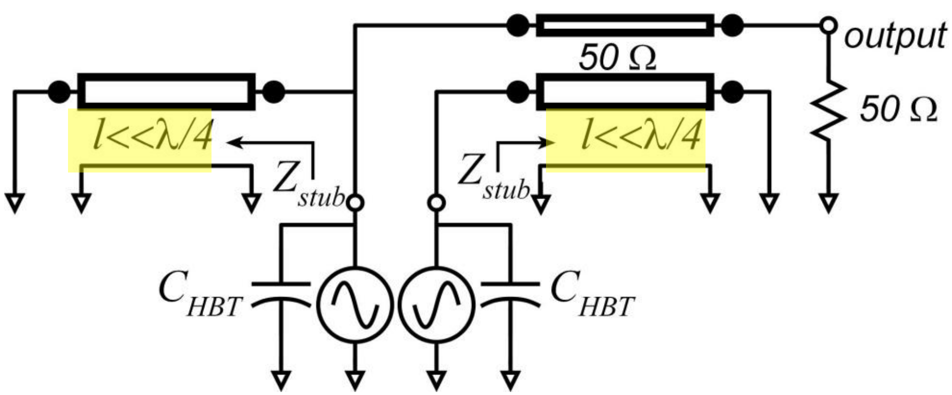
Sub-λ/4 balun :

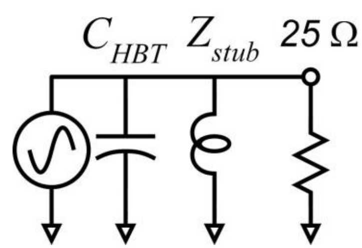
stub→ inductive

tunes transistor C_{out} !

short lines→ low losses

short lines → small die





Sub-λ/4 Baluns for **Series** Combining

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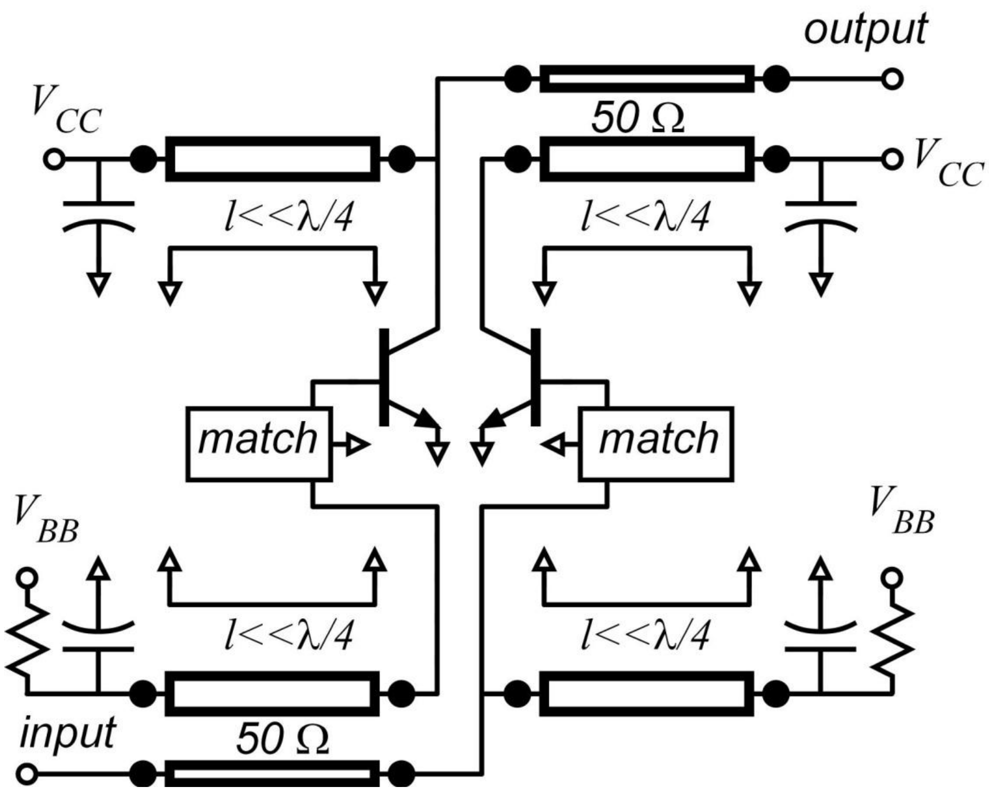


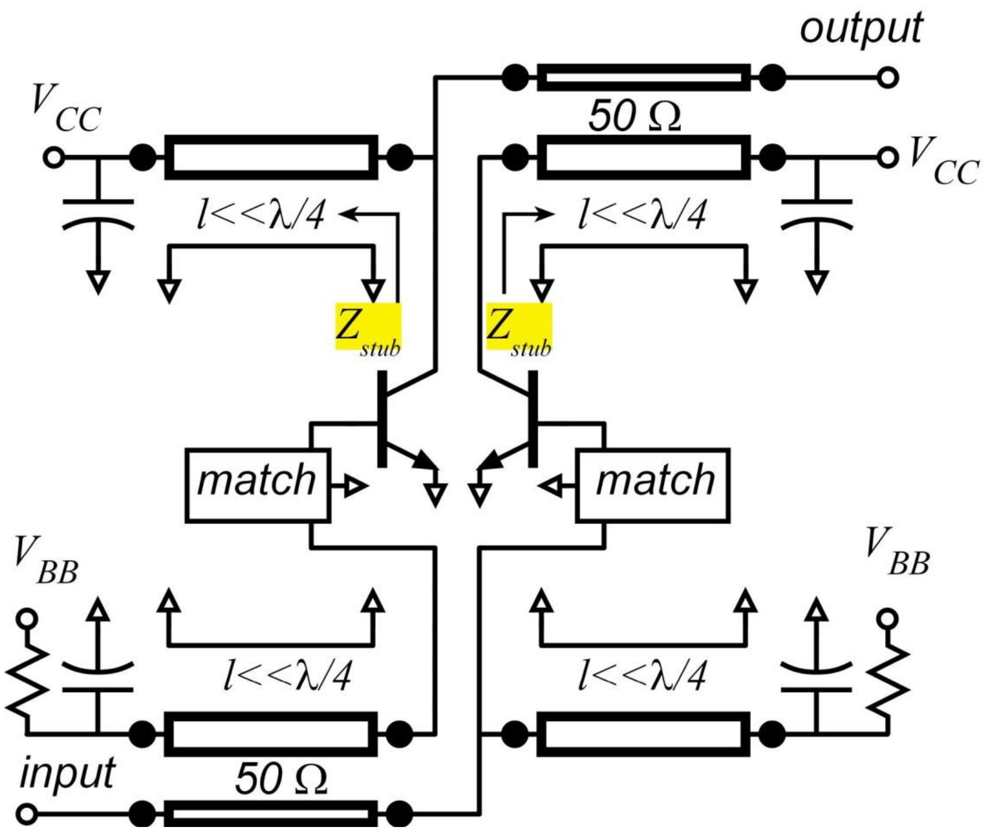
2:1 baluns:
2:1 series connection

Each device loaded by 25Ω
→ HBTs are 2:1 larger than needed for 50Ω load.
→ 4:1 increased P_{out}.

Sub λ/4 balun: inductive stub
balun inductive stub tunes HBT C_{out}.

Similar network on input.

Sub-λ/4 Balun Series-Combiner: Design



Each HBT loaded by 25Ω

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

Each HBT has some C_{out} .

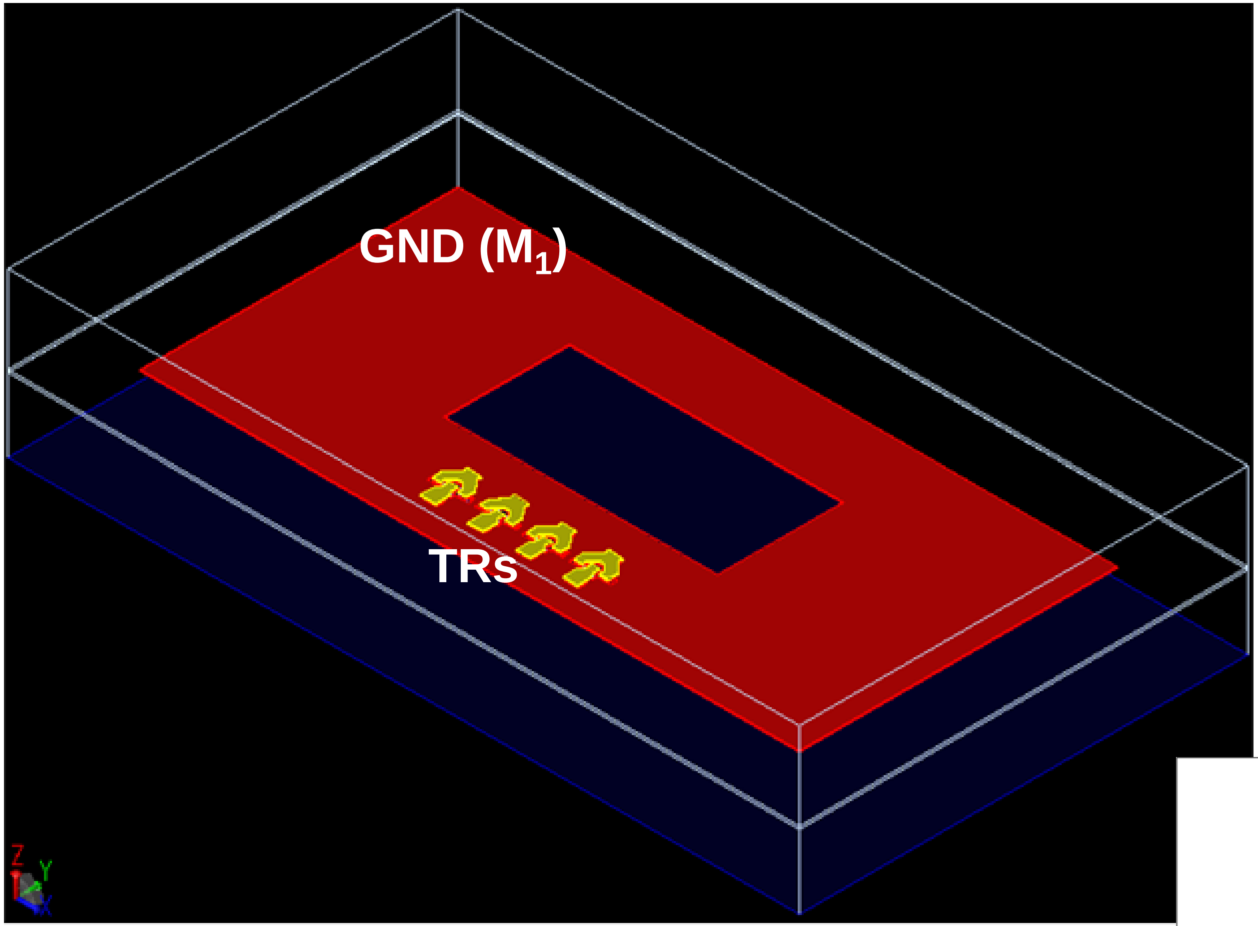
Stub length picked so that $Z_{stub}=-1/j\omega C_{out}$ → tunes HBT

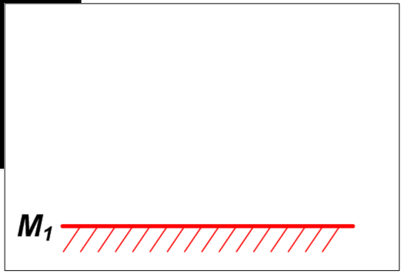
$$P_{out} = 4 \times \left(\frac{V_{max}^2}{8 \cdot 50\Omega} \right)$$

4:1 more power than without combiner.

Balun Configurations in PA ICs

- Step 1

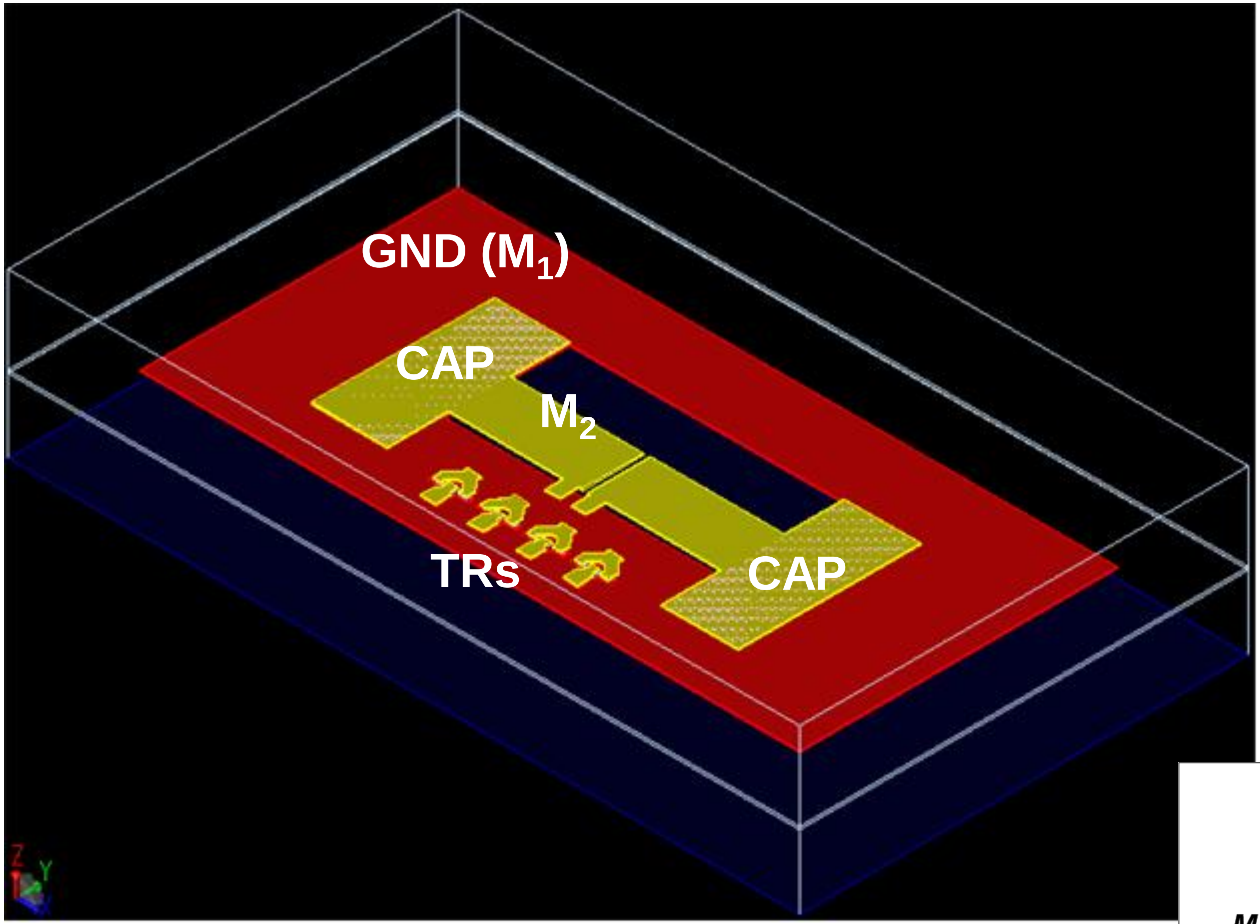


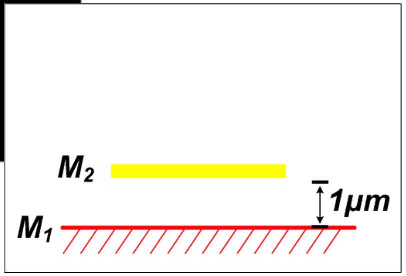


2 (diff.) x 8 finger TR cells + GND (M_1)

Balun Configurations in PA ICs

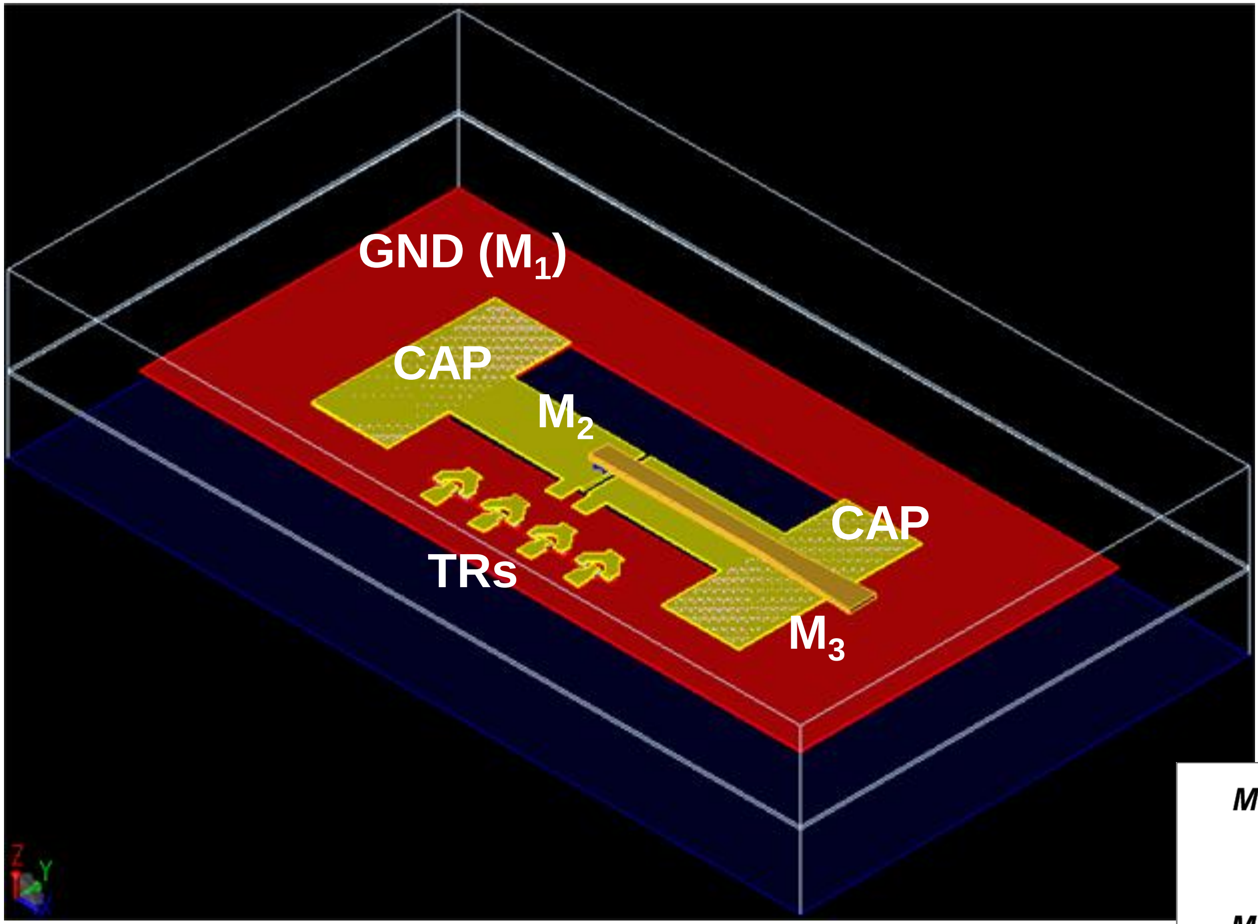
- Step 2

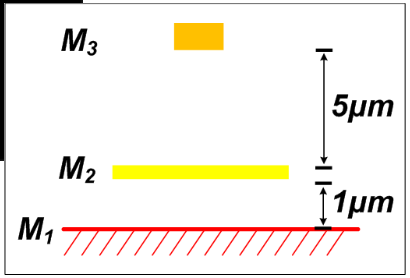




Balun Configurations in PA ICs

- Step 3



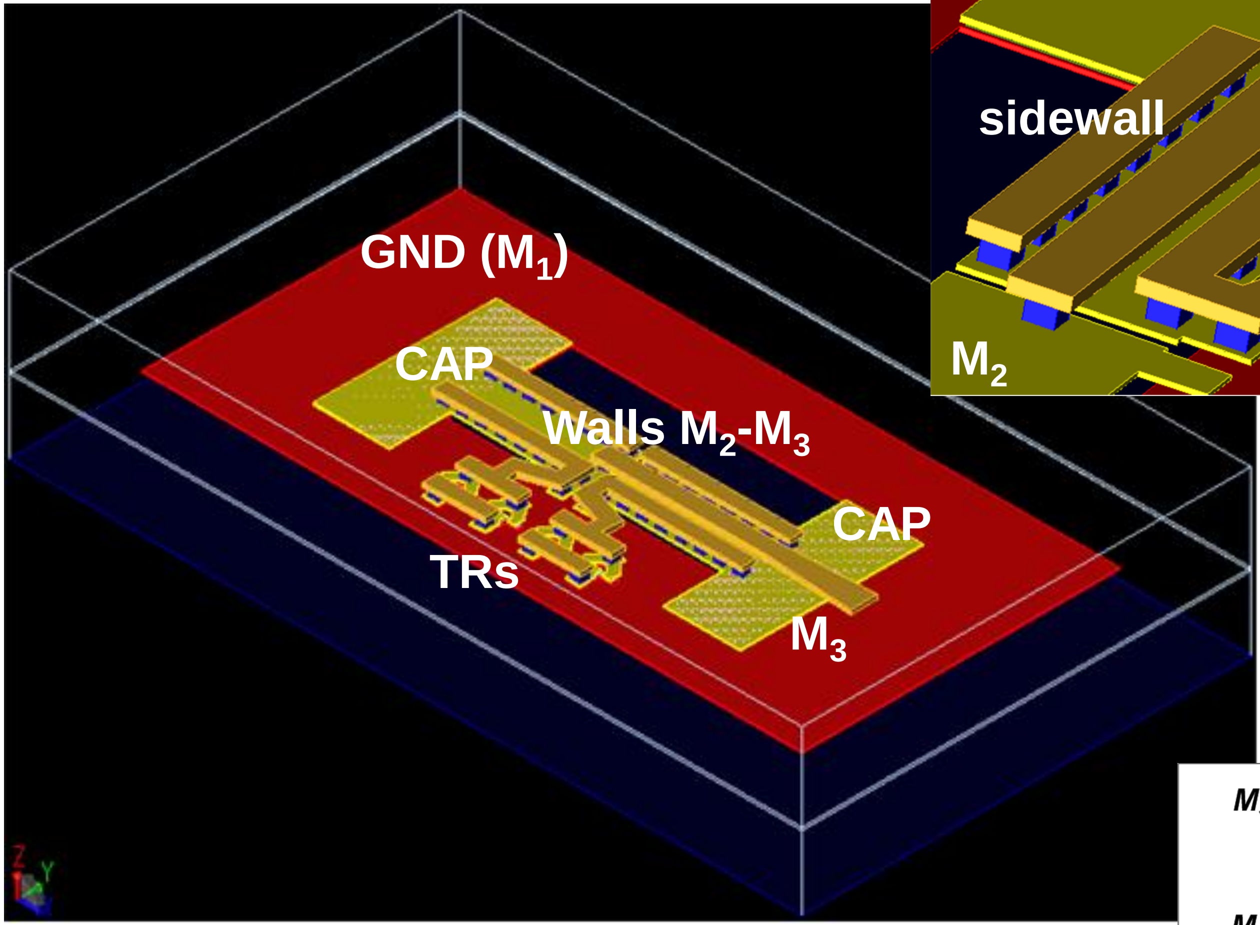


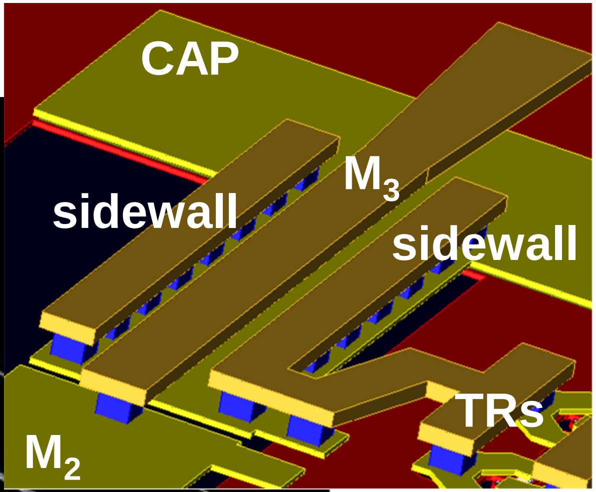
M_2–M_3 Microstrip transmission lines

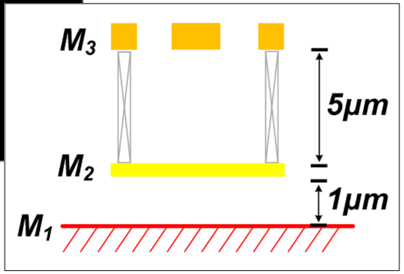
But, E-fields between M_3-M_1 are not negligible !!

Balun Configurations in PA ICs

- Step 4





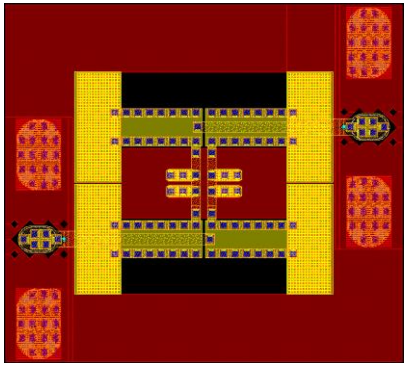


M_3–M_1 E-field shield using sidewalls

→ Well-balanced balun with short length (λ/16)

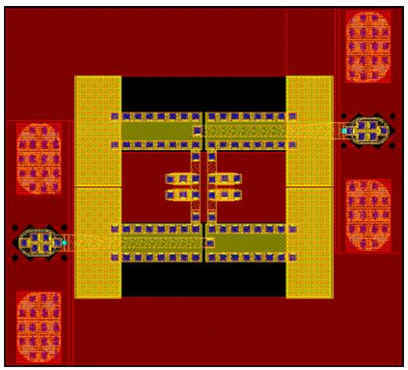
2:1 Balun Test Results

v1



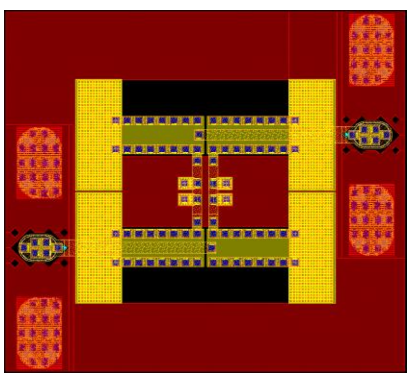
$\underline{C_P = 103fF}$
$\underline{F_C = 81GHz}$
I.L. = -1.1dB
S21 = -1.76dB

v2



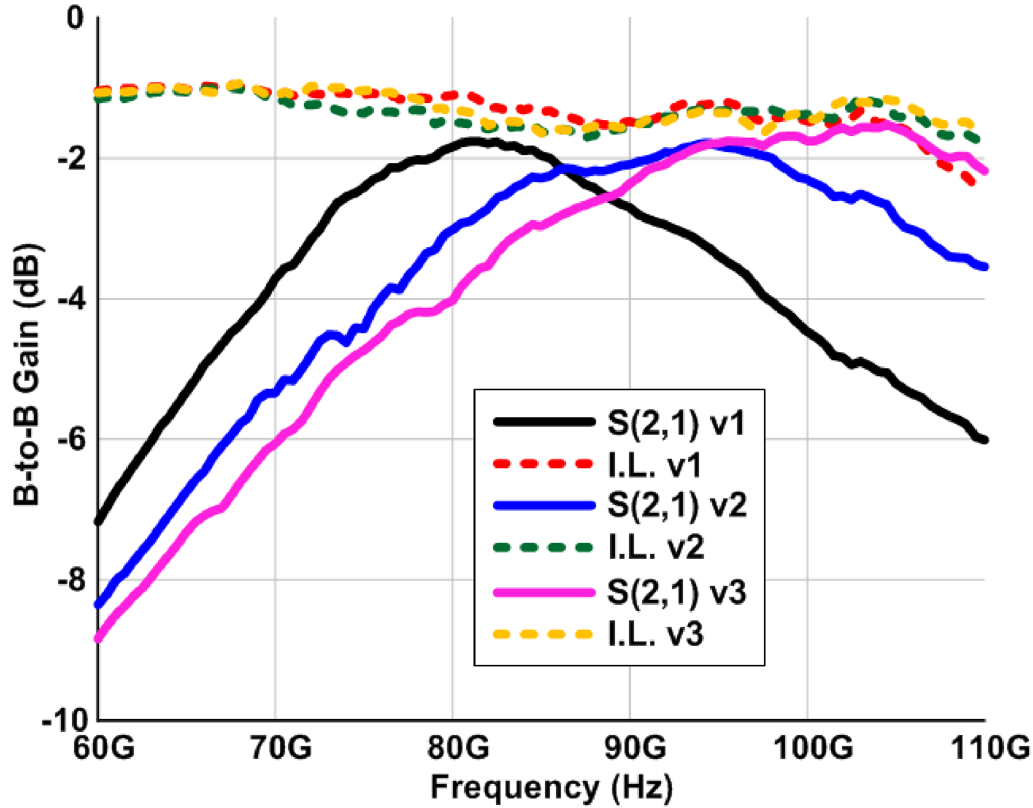
$\underline{C_P = 78fF}$
$\underline{F_C = 94GHz}$
I.L. = -1.2dB
S21 = -1.79dB

v3



$\underline{C_P = 65fF}$
$\underline{F_C = 103GHz}$
I.L. = -1.2dB
S21 = -1.56dB

Back-to-back measured S-parameters



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

0.6~0.8 dB single-pass insertion loss (used for 4:1 power combining)

InP HBT (Teledyne 250nm HBT)

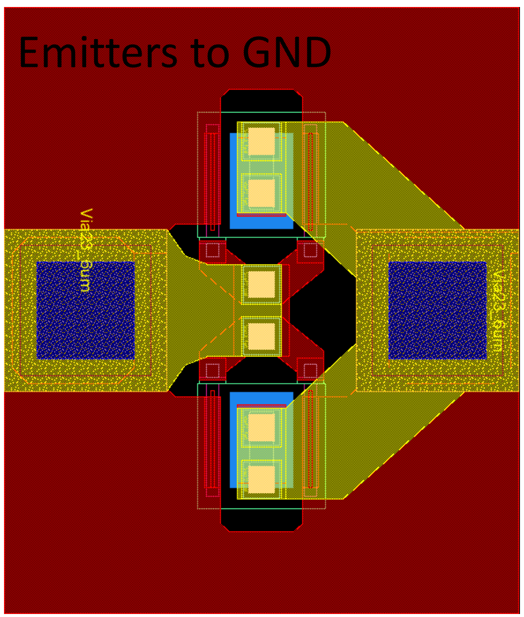
cell: 0.25µm x 6µm x 4-fingers

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

P_{out} = 15.5dBm

R_{opt} = 56Ω

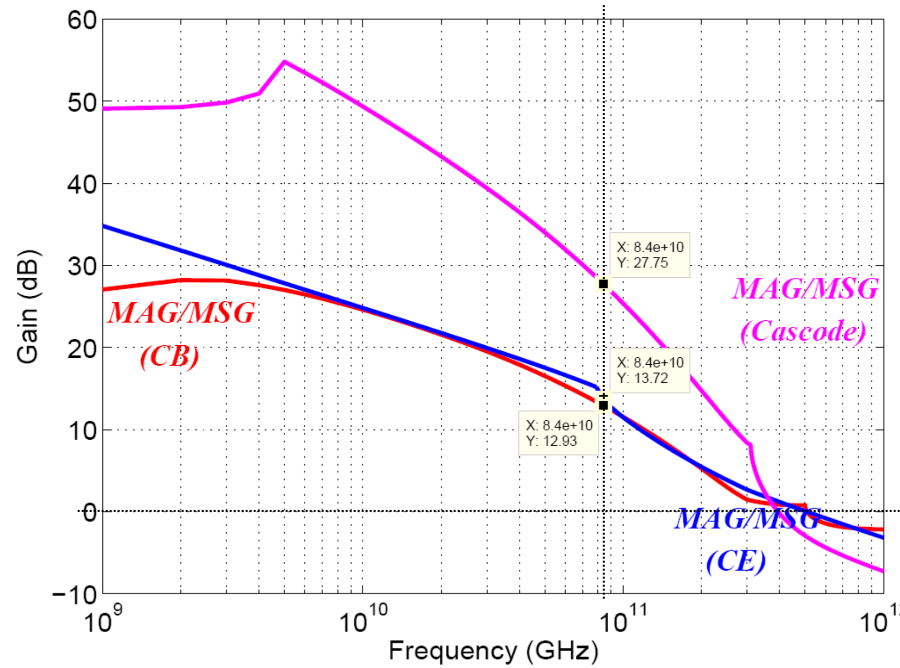
Base



Collector

Courtesy: Teledyne Science Company

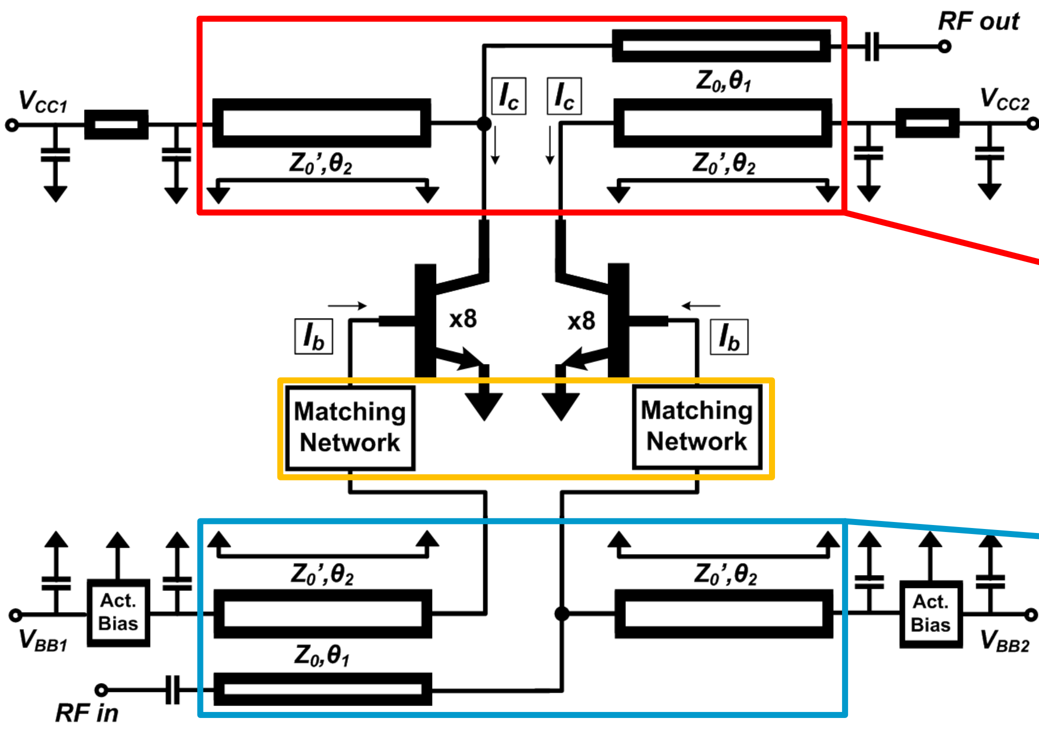
MAG/MSG including EM-Momentum

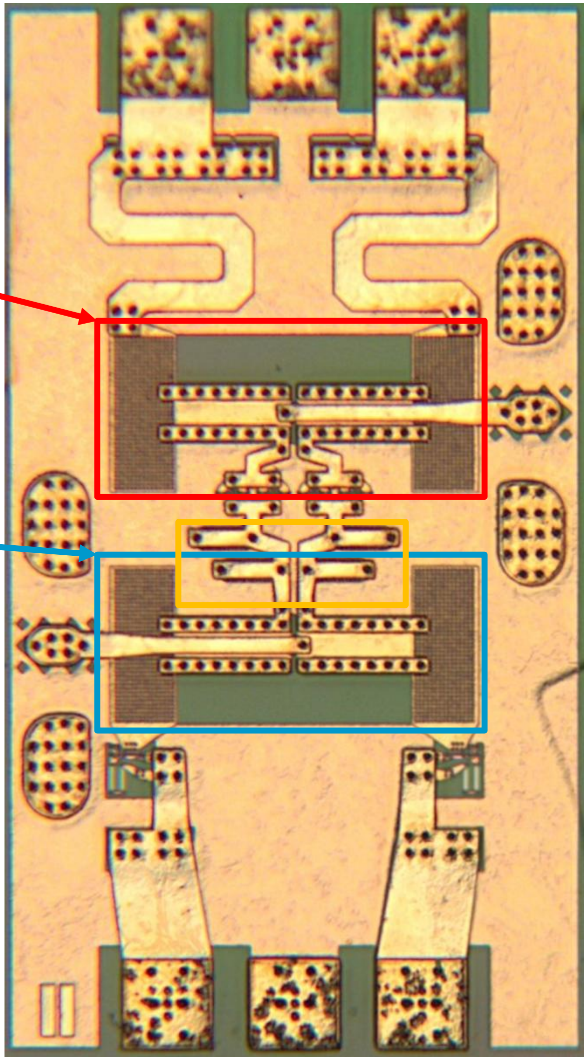


350GHz f_τ, 590GHz f_{max}@ J_E=6mA/µm^2

~13dB MAG @ 85 GHz

PA Designs Using 2:1 Balun





Identical input / output baluns

2-stage input matching networks

Active bias – thermal / class-AB

Single-Stage PA IC Test Results (86GHz)

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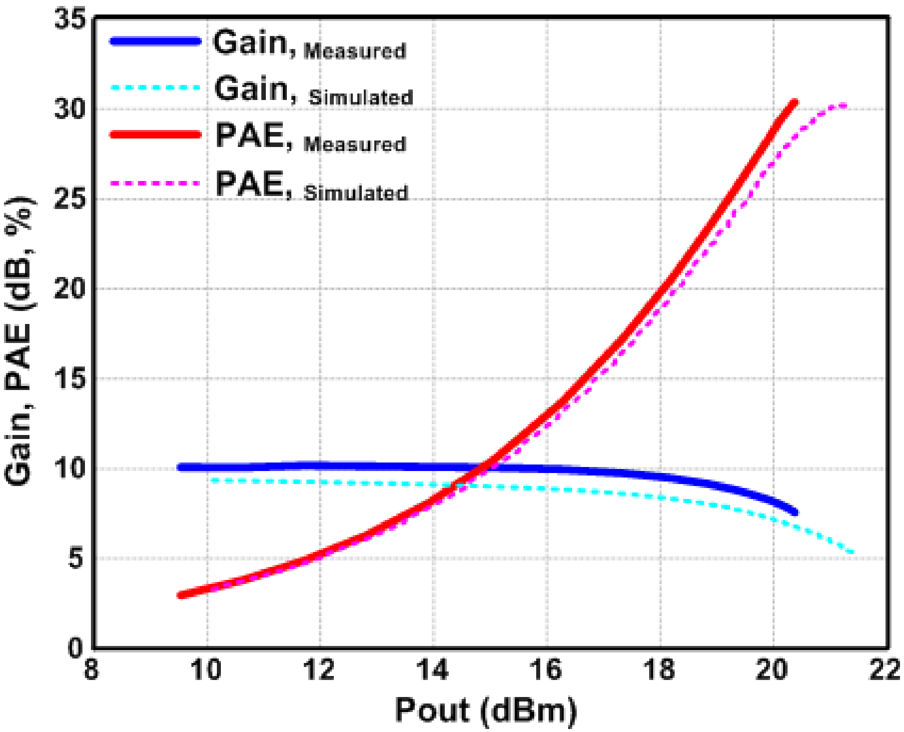

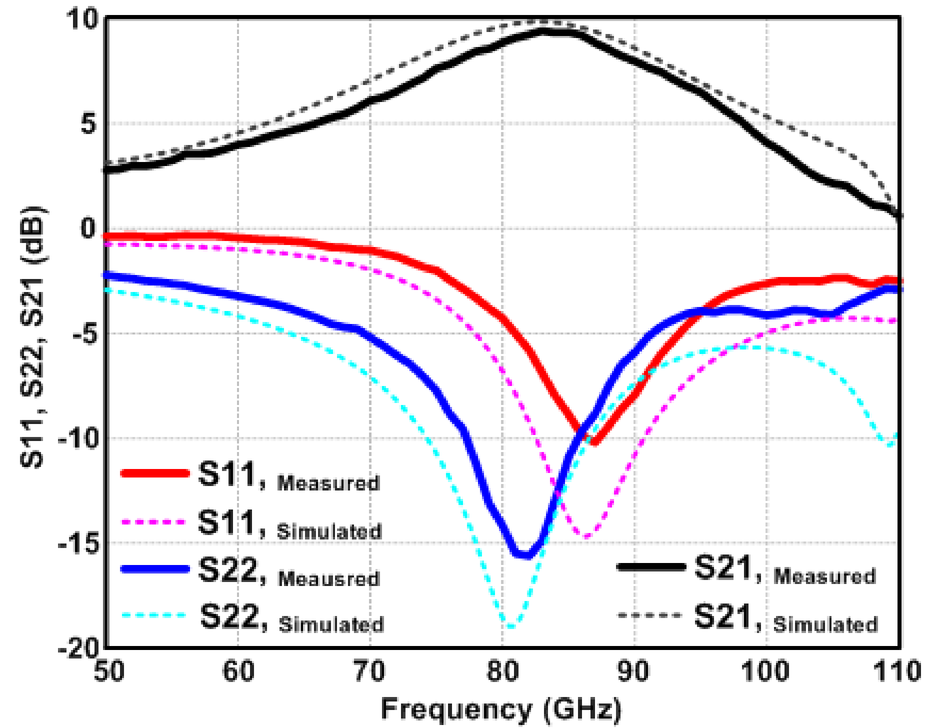

10dB Gain, >100mW P_{SAT}, >30% PAE, 23GHz 3dB-bandwidth

Power per unit IC die area* =294 mW/mm² (if pad area included)

=723 mW/mm² (if pad area not included)

Two-Stage PA IC Test Results (86GHz)

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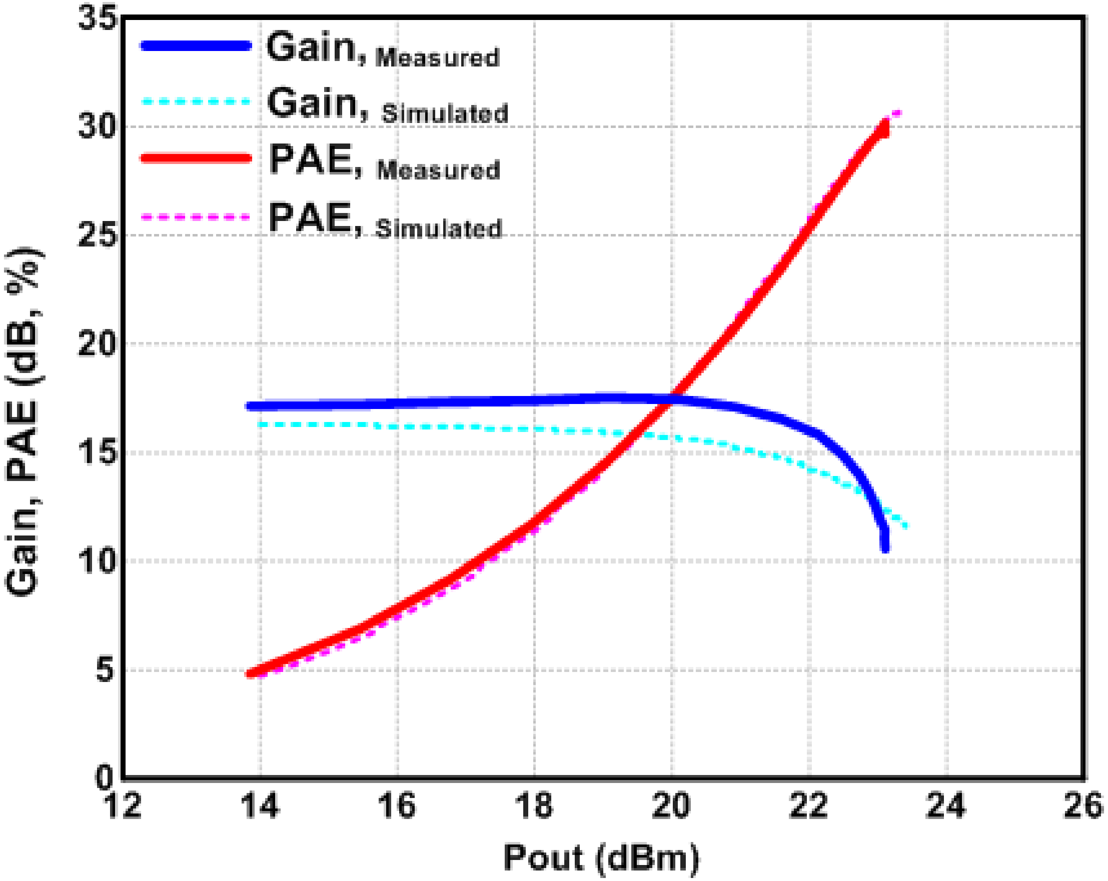

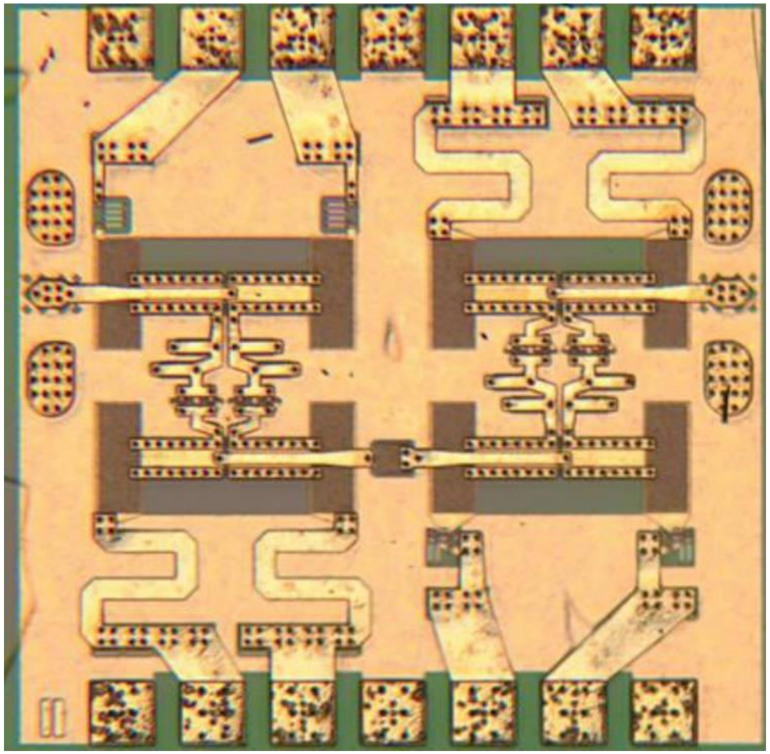

17.5dB Gain, >200mW P_{SAT}, >30% PAE

Power per unit IC die area* =307 mW/mm² (if pad area included)
=497 mW/mm² (if pad area not included)

800 mW 1.3mm^2 Design Using 4:1 Baluns

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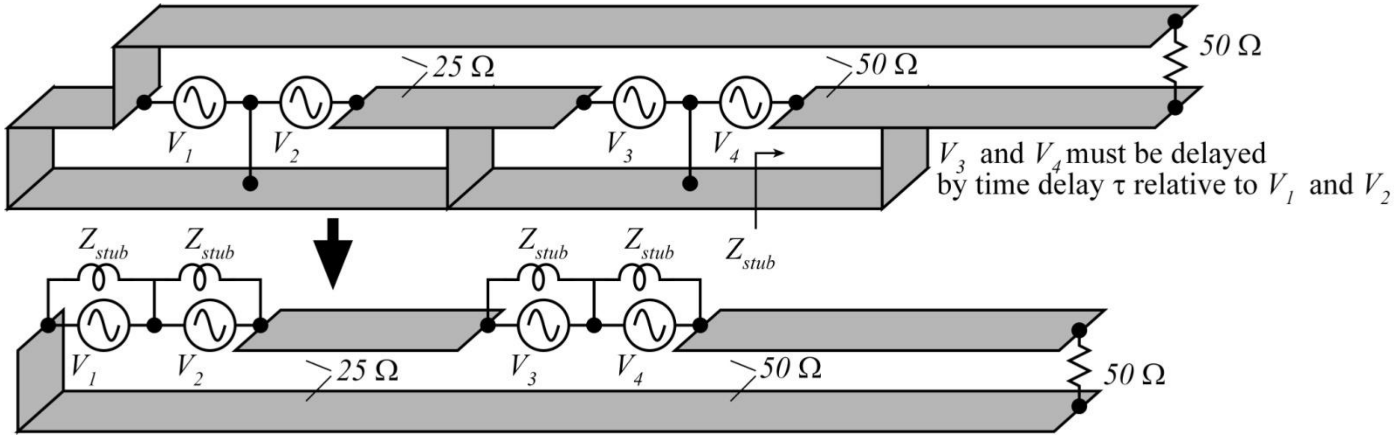
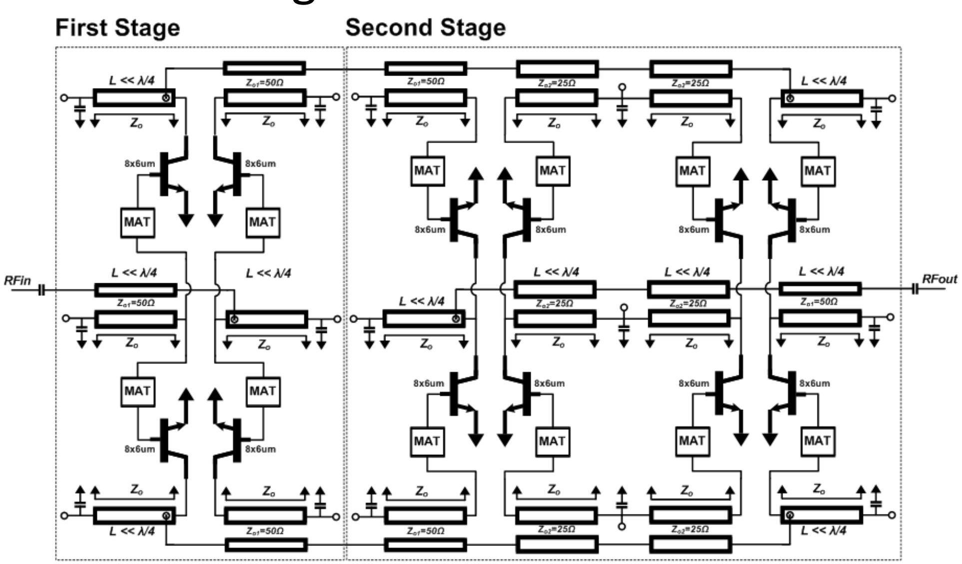
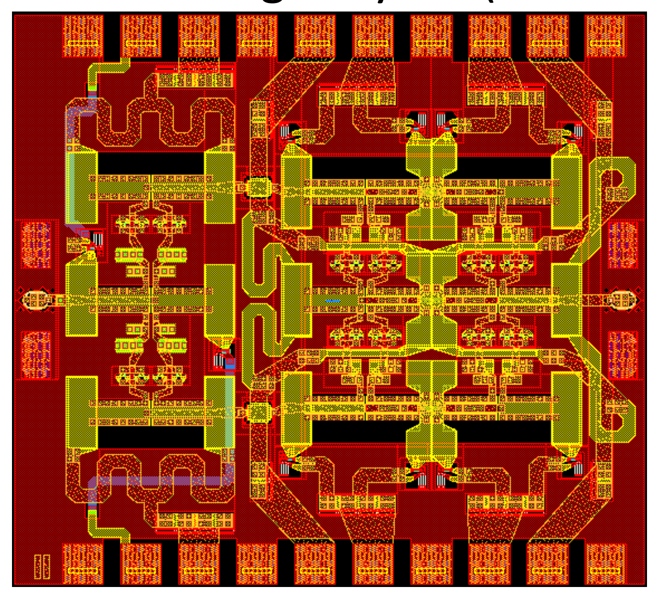
Baluns for 4:1 series-connected power-combining



4:1 Two-Stage Schematic



4:1 Two-Stage Layout (1.2x1.1mm^2)



Small-signal data looks good. Need driver amp for P_{sat} testing.

Sub-λ/4 Baluns for Series Combining

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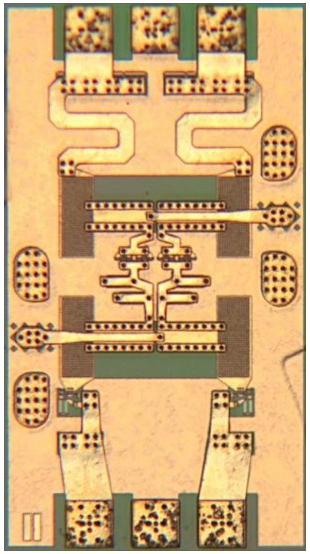
Series combining using sub-λ/4 baluns
- Low-loss (~0.6 dB @85GHz) → high efficiency
- Compact→ small die area

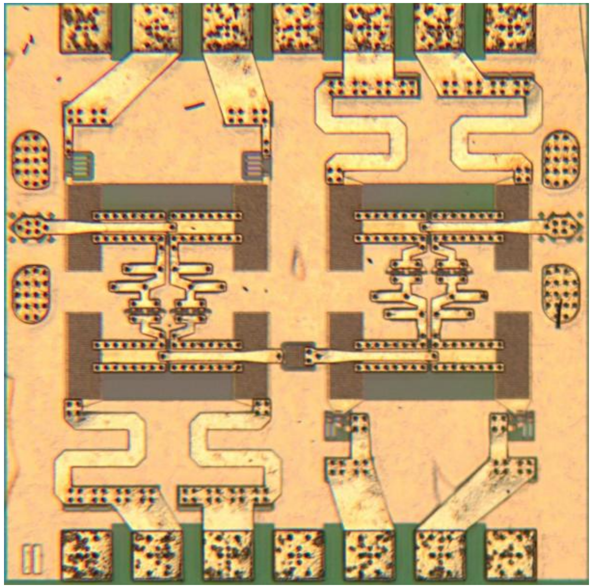
2:1 baluns→ effective 2:1 series connection
- 4:1 increase in output power.

W-band power amplifiers using 2:1 baluns
- Record >30% PAE @ 100mW, 200mW
- Record 23 GHz 3-dB bandwidth
- Record 723mW/mm^2 power density

Completed new designs in test
- Higher-efficiency ~200 mW, 85 GHz designs
- 4:1 balun design: goal 800 mW, 85 GHz, 1.3 mm^2
- 220 GHz 4:1 balun design has been taped out



450 x 820 um^2



825 x 820 um^2

Thanks for your attention!

Questions?

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