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

mm-Wave PAs:
- **applications**: High resolution imaging, high speed communication
- **needed**: High power / High efficiency / Small die area (low cost)

**Extensive power combining**

Class E/D/F are poor @ mm-wave
- insufficient $f_{\text{max}}$
- 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: $P_{\text{OUT}} = N \times V \times I$
Parallel connection increases $P_{\text{OUT}}$

Load Impedance: $Z_{\text{OPT}} = \frac{V}{(N \times I)}$
Parallel connection decreases $Z_{\text{opt}}$

High $P_{\text{OUT}} \rightarrow$ Low $Z_{\text{opt}}$
Needs impedance transformation:
lumped lines, Wilkinson, ...

*High insertion loss* ✓
*Small bandwidth* ✓
*Large die area* ✓
**Series Power-Combining & Stacks**

**Parallel** connections: \( I_{out} = N \times I \)

**Series** connections: \( V_{out} = N \times V \)

Output power: \( P_{out} = N^2 \times V \times I \)

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 $\lambda/4$ Baluns: **Series** Combining

**Balun combiner:**

*Voltages add*

2:1 series connection

each source sees 25 $\Omega$

$\rightarrow$ double $I_{\text{max}}$ for each source

4:1 increased $P_{\text{out}}$

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**Standard $\lambda/4$ balun:**

$\lambda/4$ stub $\rightarrow$ open circuit

long lines $\rightarrow$ high losses

long lines $\rightarrow$ large die
Sub-$\lambda/4$ Baluns for Series Combining

What if balun length is $<<\lambda/4$? Stub becomes inductive!

Sub-$\lambda/4$ balun:
- stub $\rightarrow$ inductive
- tunes transistor $C_{\text{out}}$
- short lines $\rightarrow$ low losses
- short lines $\rightarrow$ small die

$V_1, V_2 \rightarrow 50\ \Omega$

$Z_{\text{stub}}$
Sub-λ/4 Baluns for Series Combining

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.
Each HBT loaded by $25\Omega$
HBT junction area selected so that $I_{\text{max}} = \frac{V_{\text{max}}}{25}$

Each HBT has some $C_{\text{out}}$.
Stub length picked so that $Z_{\text{stub}} = -\frac{1}{j\omega C_{\text{out}}}$ → tunes HBT

$$P_{\text{out}} = 4 \times \left( \frac{V_{\text{max}}^2}{8 \cdot 50\Omega} \right)$$
4:1 more power than without combiner.
Balun Configurations in PA ICs

- Step 1

2 (diff.) x 8 finger TR cells + GND (M₁)
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

$\rightarrow$ Well-balanced balun with short length ($\lambda/16$)
2:1 Balun Test Results

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

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

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

*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: 0.25\(\mu\)m x 6\(\mu\)m x 4-fingers

\[ BV_{CEO} = 4.5V, \quad I_{C,\text{max}} = 72mA \]

\[ P_{\text{out}} = 15.5\text{dBm} \]

\[ R_{\text{opt}} = 56\Omega \]

350GHz \(f_{\tau}\), 590GHz \(f_{\text{max}}\) @ \(J_E=6\text{mA}/\mu\text{m}^2\)

\(~13\text{dB MAG @ 85 GHz}\)
Identical input / output baluns
2-stage input matching networks
Active bias – thermal / class-AB
Single-Stage PA IC Test Results (86GHz)

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

Power per unit IC die area* = 294 mW/mm$^2$ (if pad area included)
= 723 mW/mm$^2$ (if pad area not included)
Two-Stage PA IC Test Results (86GHz)

17.5dB Gain, >200mW $P_{\text{SAT}}$, >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 1.3mm² Design Using 4:1 Baluns

Baluns for 4:1 series-connected power-combining

\[ Z_{\text{stub}} \quad Z_{\text{stub}} \quad Z_{\text{stub}} \quad Z_{\text{stub}} \]

\[ V_1 \quad V_2 \quad V_3 \quad V_4 \]

\[ 25 \Omega \quad 50 \Omega \quad 50 \Omega \]

\[ V_3 \text{ and } V_4 \text{ must be delayed by time delay } \tau \text{ relative to } V_1 \text{ and } V_2. \]

4:1 Two-Stage Schematic

4:1 Two-Stage Layout (1.2x1.1mm²)

Small-signal data looks good. Need driver amp for \( P_{\text{sat}} \) testing.
Sub-$\lambda/4$ Baluns for Series Combining

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

2:1 baluns $\rightarrow$ 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
Thanks for your attention!

Questions?

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