Optimization of power combining of broadband power amplifier cells

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Introduction

• Applications like cognitive radio and WiFi require a (broadband) power amplifier (PA)
  – Bandwidth and output impedance depend on devices’ behavior

• Silicon submicron transistors are commonly used to implement PA due to low cost and high integration capability
  – Devices have low breakdown voltage
  – Enhance output power by putting devices in parallel
Introduction

- Performance device scales not linear with its area due to impact interconnect
  1. Non-equal input signals at devices (mag & phase)
     - Attenuation
     - Standing wave (reflections)
  2. Non-equal operation of devices
     - Non-equal currents
     - Non-equal effective terminations
  3. Non-linear scaling of output current with device-size
Introduction

- Output matching required as:
  \[ P_{o,\text{max}} \approx \frac{V_{sw,\text{max}}}{2 \times R} = \frac{V_{sw,\text{max}}}{2 \times 50} \]

- One large device cell (power cell) complicates:
  - Output matching
    - Impact on efficiency
    - Impact on bandwidth
  - Heat distribution

- Therefore power combining is often used

What’s optimal combination of devices/power cell and number of combining power cells?
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Broadband active cell

- Employs feedback to define output impedance and gain over large bandwidth
- Buffer presents virtual ground at $V_{in} \rightarrow I_{Rf} = V_{out}/R_f$
- $I_{Rf}$ is fed into Q2 and copied to Q3 with factor $n$ by current mirror

\[
R_{out} = \frac{R_f}{n + 1}
\]

\[
\frac{I_{out}}{I_{in}} = \frac{n}{1 + \frac{R_L}{R_{out}}}
\]

Loop gain enhancement

- Use cascoded devices for current mirror to reduce miller effect and enhance loop gain buffer
Conjugate + Load-line match

For conjugate match:

\[
R_{out} = R_L
\]

\[
R_L = \frac{R_f}{n+1}
\]

\[
\rightarrow R_f = R_L(n+1)
\]

Combined with class A load-line match:

\[
R_{L,\text{opt}} = \frac{V_{Q3,\text{rf,max}}}{I_{\text{out,rf,max}}} = \frac{V_{Q3,\text{rf,max}}}{I_{Q3,\text{rf,max}}} \left( \frac{R_{L,\text{opt}} + R_f}{R_f} \right)
\]

\[
R_{L,\text{opt}} = \frac{V_{Q3,\text{max}}}{I_{Q3,\text{max}}} \frac{n+2}{n+1}
\]
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Status-quo: Implementation power cell with biasing + matching

- **Differential design**
  - Use two single-ended broadband cells
  - Transformer BalUn at output
Active cells will be put in parallel in vertical direction
Power cells

• Power cells created containing 8, 16 or 32 active cells

• Initial load terminations set to:

\[ R_{L,\text{opt},P} = \frac{V_{Q3,\text{max}}}{I_{Q3,\text{max}}} \left( \frac{n + 2}{n + 1} \right) \]

• Increase initial values \( R_f, R_L \) if \( V_{\text{max}} \) is not reached

• Conditions:
  • pitch=10um (EL=0.14°)
  • freq=5..6GHz (\( f_c = 5.5 \text{GHz} \))
Performance different power cells

- At $#P \geq 16$, performance deviates from ‘ideal’ linear scaling due to impact interconnect
  - Output current scales not linear with $#P$ and hence $P_o$ reduces compared with ‘ideal’ linear scaling
  - Efficiency reduces as $P_o$ scales not linear but $P_{dc}$ does (class A)
Performance different power cells

- Less ‘perfect’ conjugate match increases output current and hence $P_o$ and efficiency
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Power combiner

- Performs combining, matching and single-ended to differential conversion

- Consists of in-phase current combiner with transformer BalUn
In-phase current combining

- Adding currents to enhance power
- Scales well with number of stages
- Example: N=4

\[
\begin{align*}
Z_{in}' &= Z_{in}/4 \\
Z_{b}' &= Z_{b}/2 \\
Z_{L} &= Z_{L}
\end{align*}
\]
In-phase current combining

- Including physical layout constraints due to pitch between cells
- Data-based TL model from technology lib
- Design parameters: \( \{Z_i, \Theta_i\} \)

\[
Z_{in}' \approx Z_2 \frac{Z_b' + jZ_2' \tan(\Theta_2)}{Z_2' + jZ_b' \tan(\Theta_2)}
\]

\[
Z_b' \approx Z_1 \frac{Z_L + jZ_1' \tan(\Theta_1)}{Z_1' + jZ_L \tan(\Theta_1)}
\]

\[
\eta_{nw} = \eta_{nw,1} \cdot \eta_{nw,2}
\]
Transformer BalUn

- Data-based transformer model from technology lib
- Additional input and output capacitance included to improve matching
- Design parameters: \{D_{\text{in}}, \text{turn ratio}, C_{\text{in}}, C_{\text{out}}\}
Power combiner optimization routine

• Exhaustive search routine implemented in Matlab to obtain maximum output power and efficiency
• Constraint: $\Gamma_{\text{out}@fc} < \Gamma_{\text{out,threshold}}$
• Optimization parameters: \{$Z_i, \Theta_i, D_{\text{inr}}, \text{turn ratio, } C_{\text{in}}, C_{\text{out}}$\}

• Output power maximization:

$$P_o = P_{\text{in,comb,\emph{opt}}} \cdot PMF \cdot \eta_{nw}$$

PMF: Power Mismatch Factor = $\frac{P_{\text{in,comb,del}}}{P_{\text{in,comb,\emph{opt}}}}$

$\eta_{\text{eff}}$: effective efficiency

– PMF depicts impedance mismatch between actual load impedance and optimum impedance for load-line match
Optimization routine sequence

1. Prepare data for exhaustive search
2. Search for design parameters that give 
   $\Gamma_{\text{out}} < -15\text{dB}$ ($\rightarrow$ set1) and 
   $\Gamma_{\text{out}} < -5\text{dB}$ ($\rightarrow$ set2)
3. Search within set1 (set2) for design parameters that 
   maximizes $\eta_{\text{eff}} (=\text{PMF} \ast \eta_{\text{nw}})$
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Combined performance power cells and combiner at N=1 with $\Gamma_{out} < -15$dB

- $P_{comb,in} \approx P_{wo,comb}$ so $PMF = \frac{P_{in,comb,del}}{P_{in,comb,opt}} \approx 1$

  $\Rightarrow \eta_{eff} (= PMF \times \eta_{nw})$ dominated by $\eta_{nw}$

- $\eta_{nw}$ reduces as #P goes up
Combined performance power cells and combiner at N=1 with $\Gamma_{\text{out}} < -15\text{dB}$

- $\Gamma_{\text{out}} < -15\text{dB}$ at $f_c = 5.5\text{GHz}$ (as forced by optim routine)
- $\Gamma_{\text{out}} < -9.8\text{dB}$ over entire bandwidth
Combined performance power cells and combiner at $P*N=32$ with $\Gamma_{\text{out}} < -15\text{dB}$

- Improved performance as $N$ goes up
- At $\{P,N\} = \{2,16\}$ and $\{4,8\}$: $P_{\text{comb,in}} < P_{\text{wo,comb}}$ so $\text{PMF} < 1$
  - Load impedance mismatched irt optimum load-line impedance $R_{\text{opt}}$
  - Due to losses, low required $R_{\text{opt}}$ and $\Gamma_{\text{out}} < -15\text{dB}$ requirement
Combined performance power cells and combiner at $P*N=32$ with $\Gamma_{out} < -5\text{dB}$

- $\Gamma_{out}$ requirement loosened from $-15\text{dB}$ to $-5\text{dB}$
- $P_{\text{comb,in}} \approx P_{\text{wo,comb}}$ so PMF$\approx1 \rightarrow P_o$ and efficiency improve
Conclusions

- Performance power cells containing different number of active cells investigated

- Optimization routine for power combiner implemented to obtain design parameters for optimum output power and efficiency

- Combined performance power cells + combiner investigated
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Questions?