Par4CR

MARIE CURIE ACTIONS

PEOPLE

Optimization of power combining of broadband power amplifier cells

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Where innovation starts

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- Introduction
- Broadband active cell
- Power cells
- Power combining power cells
- Combined performance power cells + combiner
- Conclusion

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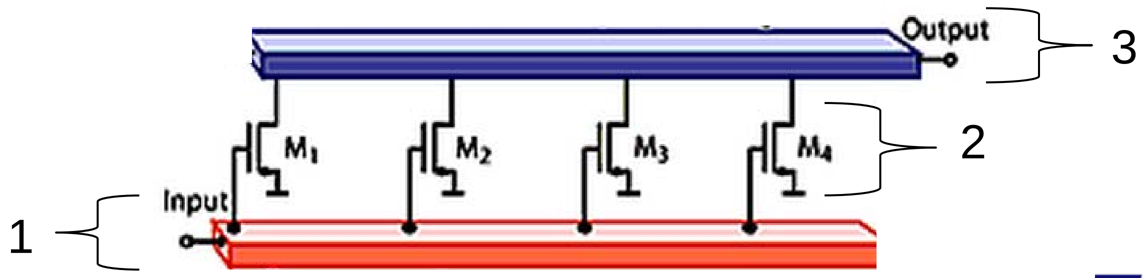
Introduction

- **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

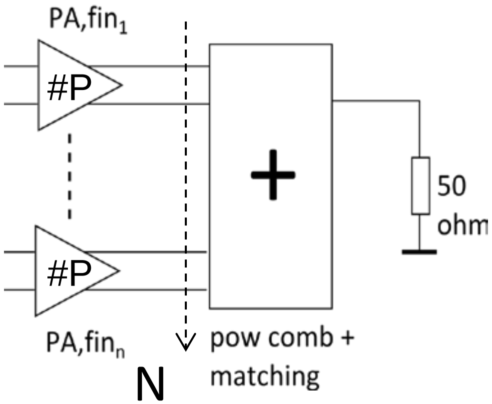
- **Performance device scales not linear with its area due to impact interconnect**

  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:** $$P_{o,\max} \approx \frac{V_{sw,\max}}{2 * R} = \frac{V_{sw,\max}}{2 * 50}$$
- **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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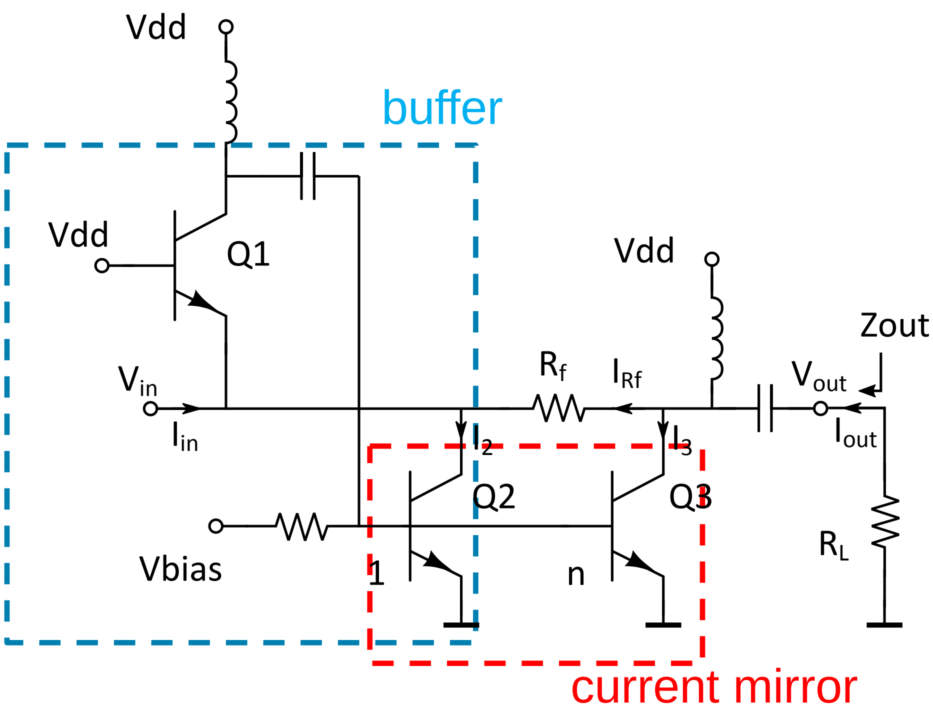
Broadband active cell

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



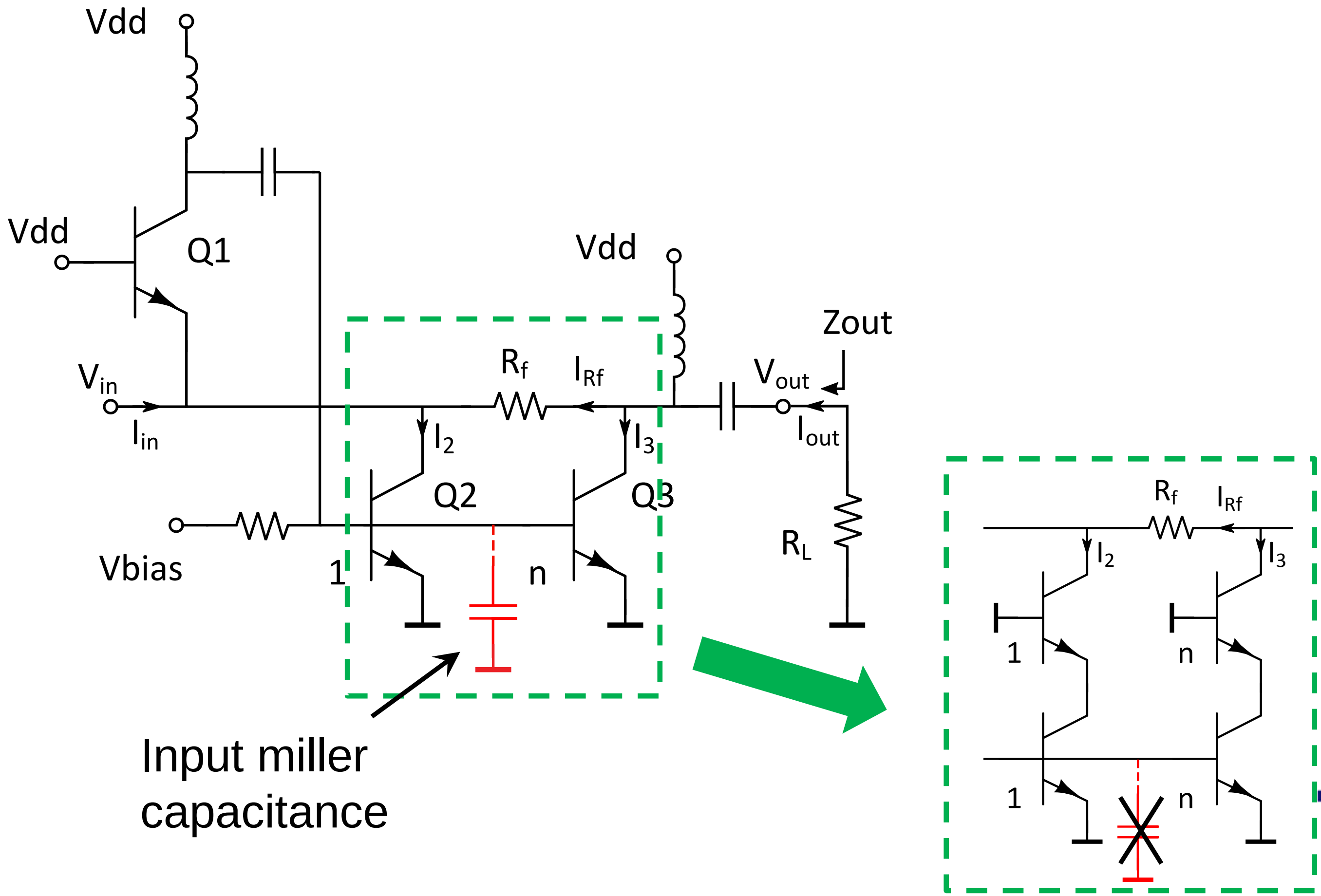
$$R_{out} = \frac{R_f}{n+1}$$

$$\frac{Iout}{Iin} = \frac{n}{1+\frac{R_L}{R_{out}}}$$

Bjork, D.; Carlsson M.; "Method of using integrated power amplifier," U.S. patent 8018284 B2, Sep. 13, 2009.

Loop gain enhancement

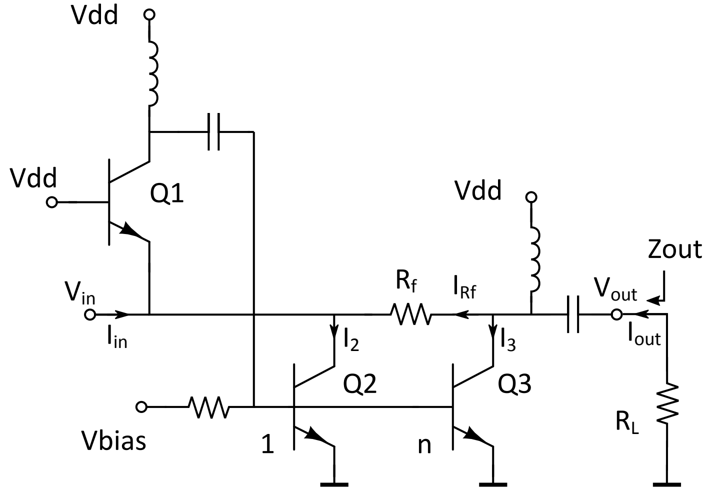
- **Use cascoded devices for current mirror to reduce miller effect and enhance loop gain buffer**



$$R_{out} \approx \frac{R_f}{n+1}$$

$$\frac{Iout}{Iin} \approx \frac{n}{1+\frac{R_L}{R_{out}}}$$

Conjugate + Load-line match

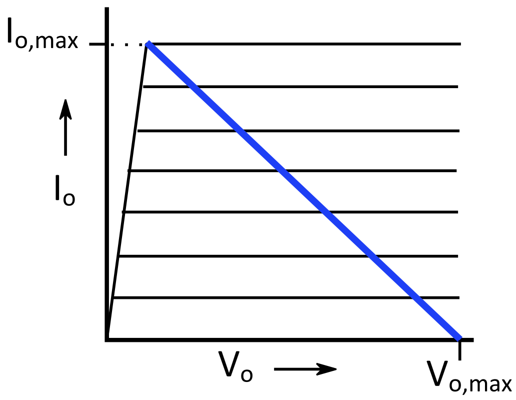


For conjugate match:

$$R_{out} = R_L$$

$$R_L = \frac{R_f}{n+1}$$

$$\boxed{\rightarrow R_f = R_L\left(n+1\right)}$$



Combined with class A load-line match:

$$R_{L,opt} = \frac{V_{Q3,\mathrm{rf,max}}}{I_{\mathrm{out,rf,max}}} = \frac{V_{Q3,\mathrm{rf,max}}}{I_{Q3,\mathrm{rf,max}}}\frac{R_{L,opt} + Rf}{R_f}$$

$$\boxed{R_{L,opt} = \frac{V_{Q3,\max}}{I_{Q3,\max}}\frac{n+2}{n+1}}$$

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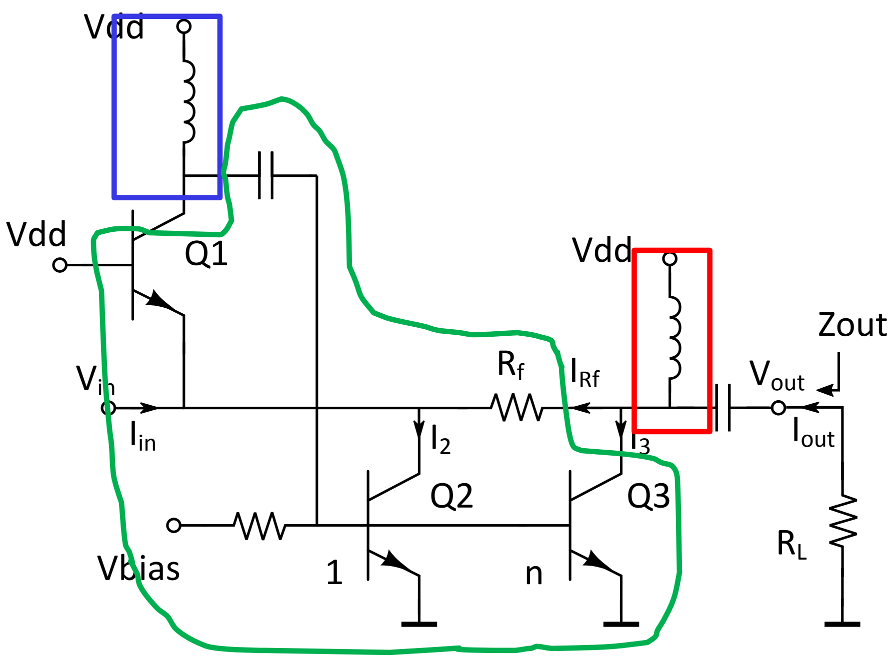
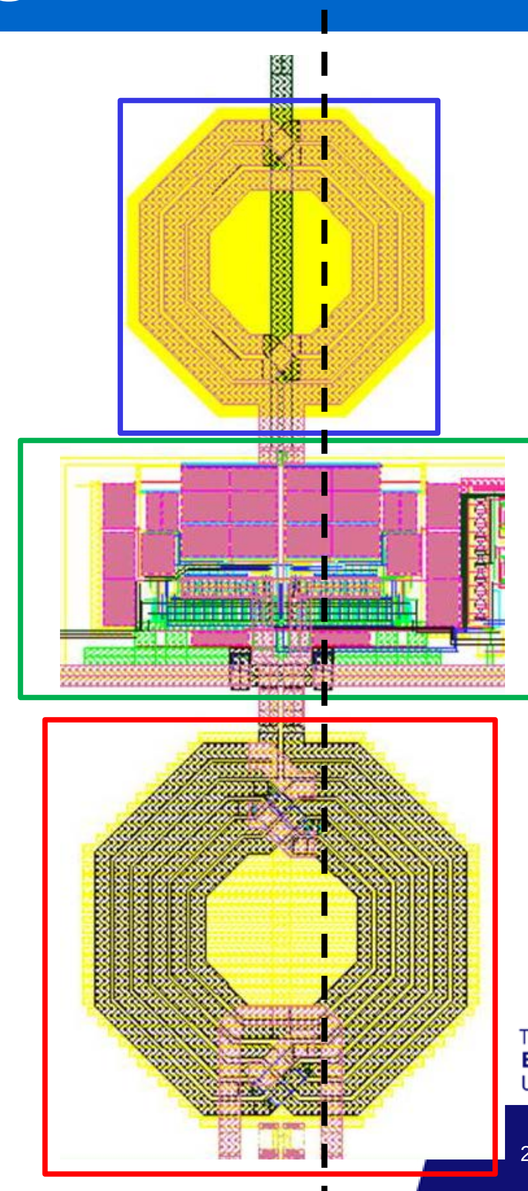
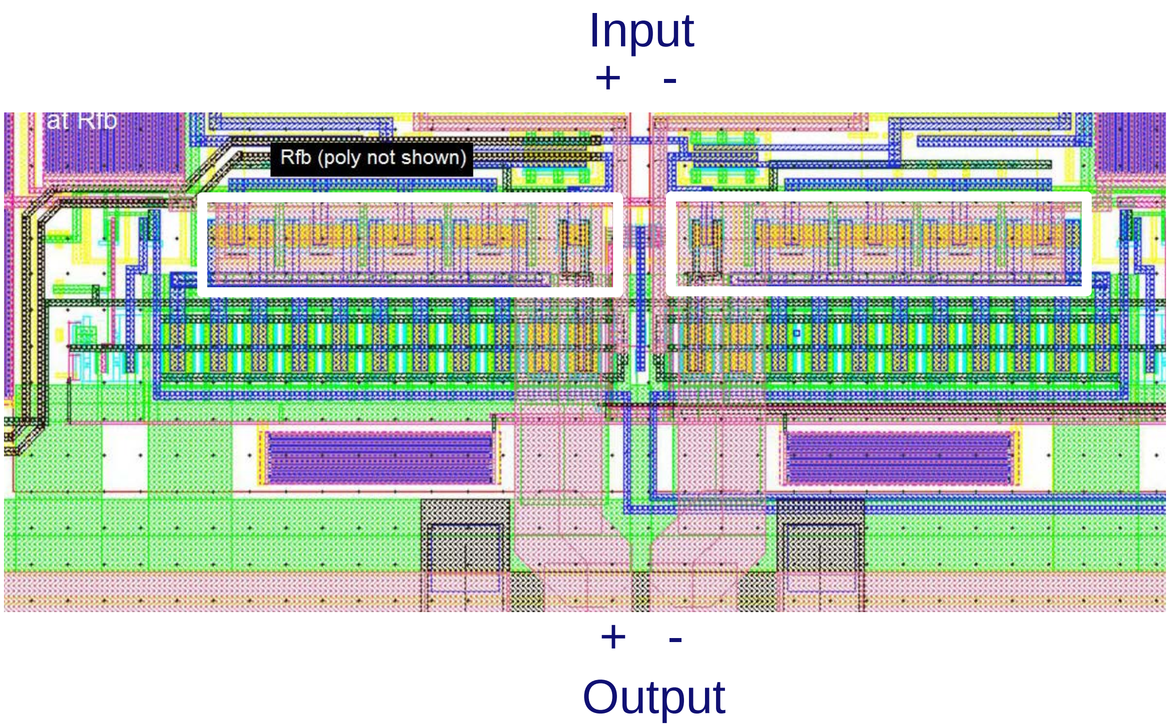
Status-quo: Implementation power cell with biasing + matching

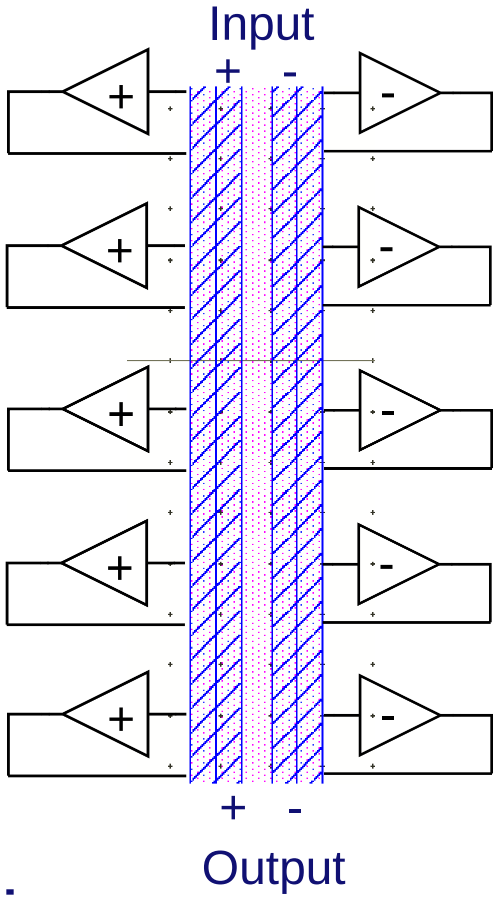
- **Differential design**
  - Use two single-ended broadband cells
  - Transformer BalUn at output





Status quo: Implementation power cell



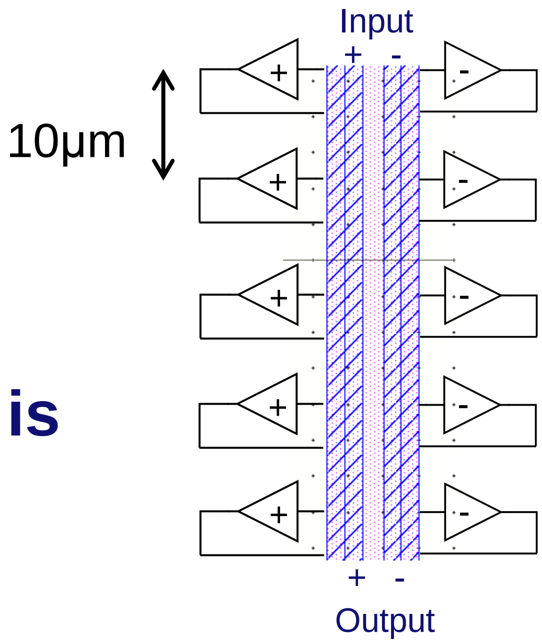


- **Active cells will be put in parallel in vertical direction**

Power cells

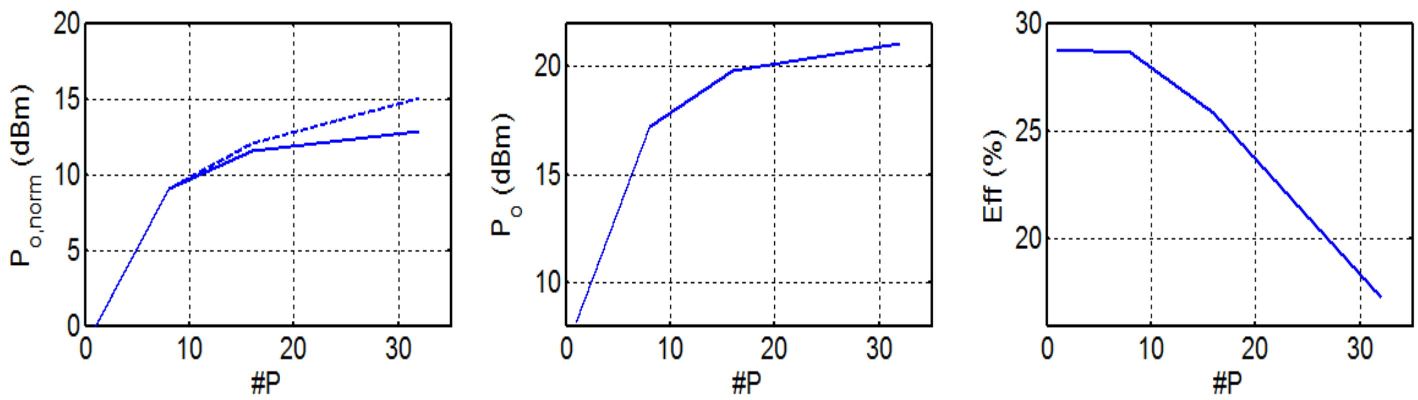
- **Power cells created containing 8, 16 or 32 active cells**
- **Initial load terminations set to:**

$$R_{L,opt,P} = \frac{V_{\mathrm{Q3,max}}}{I_{Q3,\mathrm{max}}} \frac{n+2}{n+1} \frac{1}{P}$$



- **Increase initial values R_f, R_L if V_{max} is not reached**
- **Conditions:**
  - pitch=10um (EL=0.14°)
  - freq=5..6GHz (f_c=5.5GHz)

Performance different power cells



- **At #P≥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)

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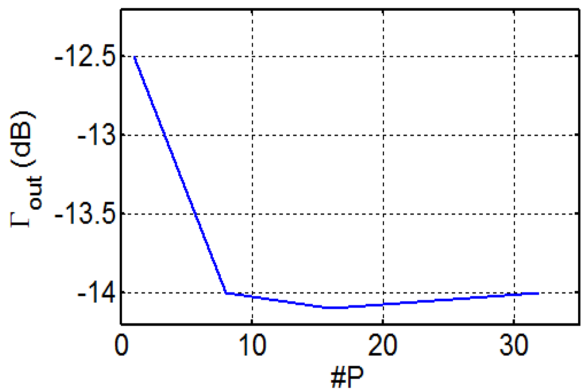
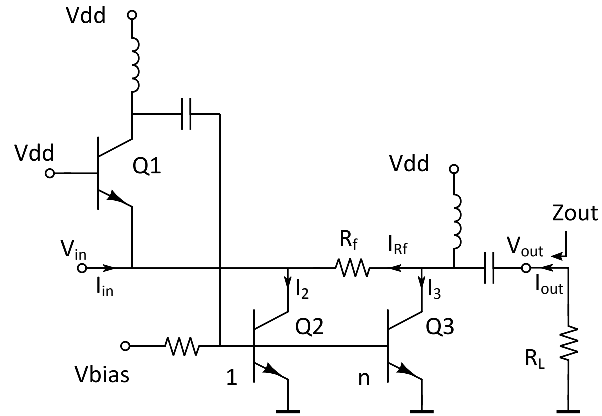
Performance different power cells





$$\boxed{\frac{Iout}{Iin} \approx \frac{n}{1+\dfrac{R_L}{R_{out}}}}$$

- **Less 'perfect' conjugate match increases output current and hence P_o and efficiency**

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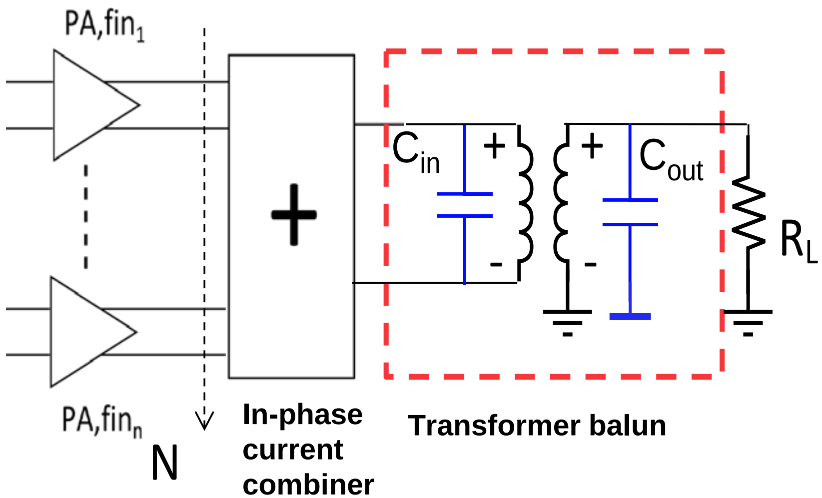
Power combiner

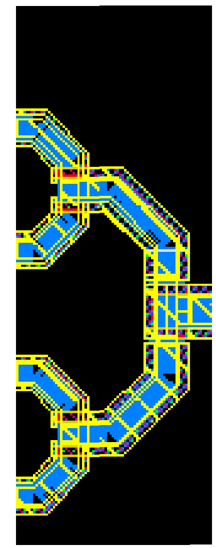
- **Performs combining, matching and single-ended to differential conversion**

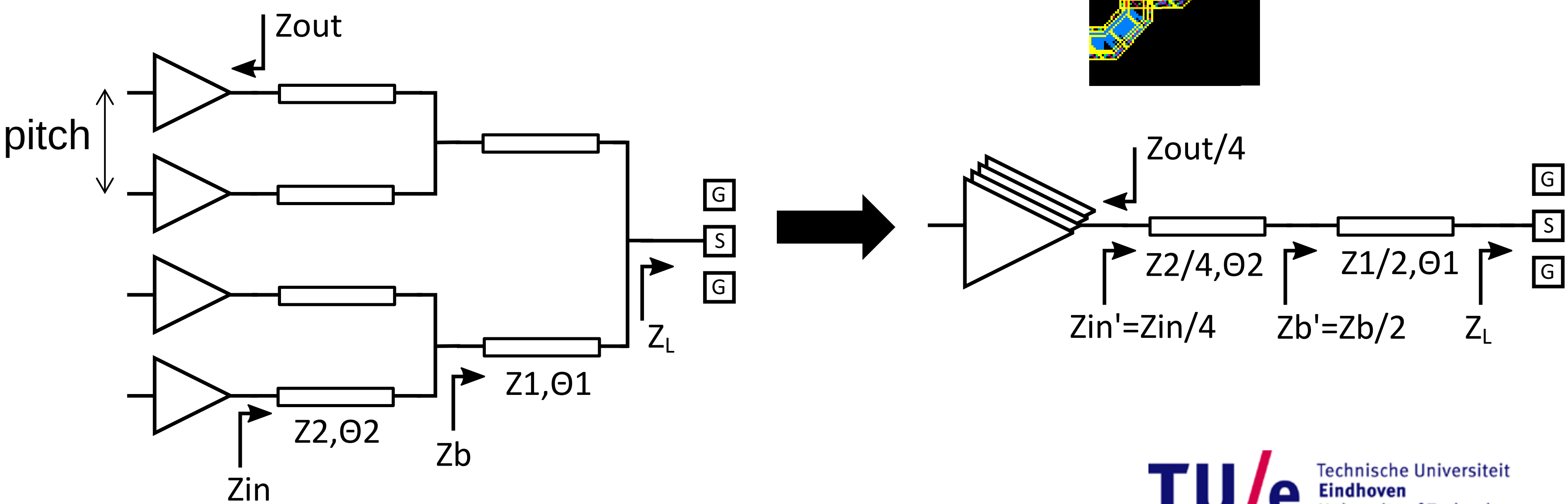


- **Consists of in-phase current combiner with transformer BalUn**

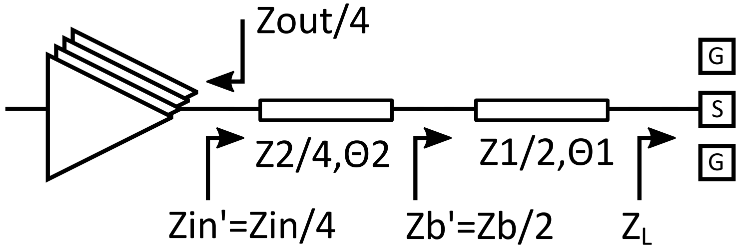
In-phase current combining

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





In-phase current combining



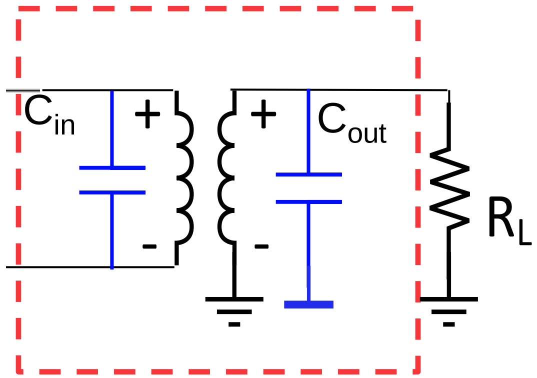
$$Z_{in}' \approx Z_2' \frac{Z_b' + jZ_2' \tan(\Theta_2)}{Z_2' + jZ_b' \tan(\Theta_2)} \qquad Z_b' \approx Z_1' \frac{Z_L + jZ_1' \tan(\Theta_1)}{Z_1' + jZ_L \tan(\Theta_1)}$$

$$\eta_{nw} = \eta_{nw,1} \cdot \eta_{nw,2}$$

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

Transformer BalUn

- **Data-based transformer model from technology lib**
- **Additional input and output capacitance included to improve matching**
- **Design parameters: {D_{inr}, turn ratio, C_{in},C_{out}}**



Power combiner optimization routine

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

- **Output power maximization:**

$$P_o = P_{\mathrm{in,comb},opt} \cdot \underbrace{PMF \cdot \eta_{nw}}_{\eta_{\mathrm{eff}}}$$

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

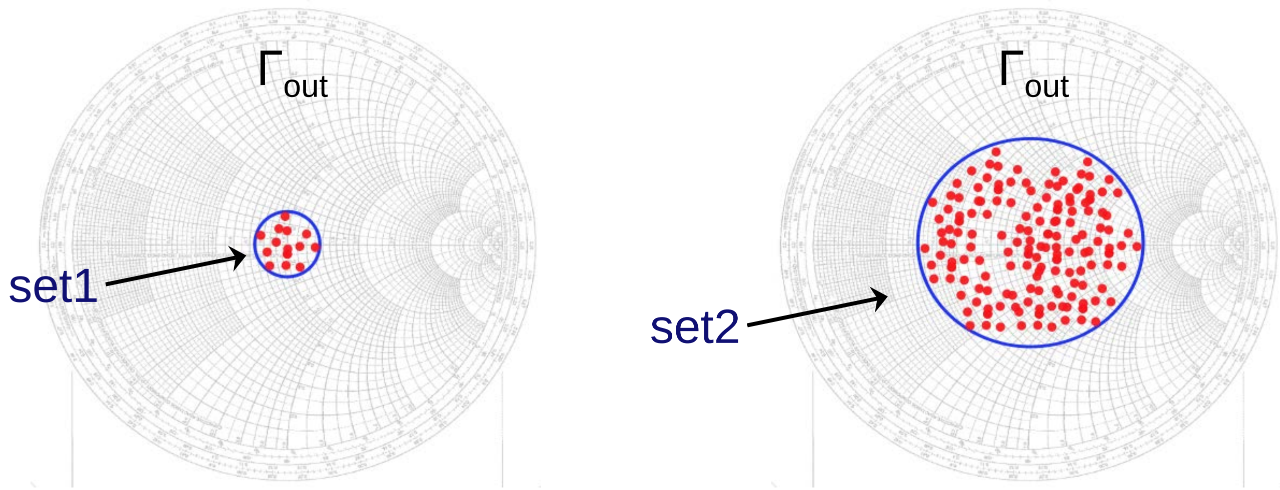
η_{eff} : effective efficiency

  - **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**

   Γ_{out} < -15dB (→ set1) and Γ_{out} < -5dB (→ set2)



3. **Search within set1 (set2) for design parameters that maximizes η_{eff} (=PMF*η_{nw})**

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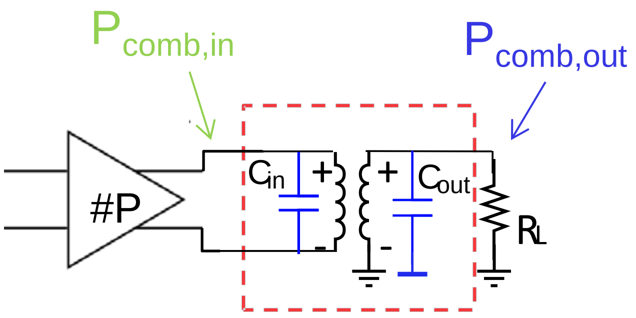
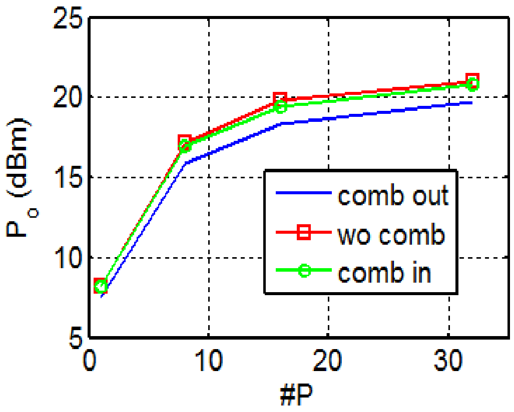
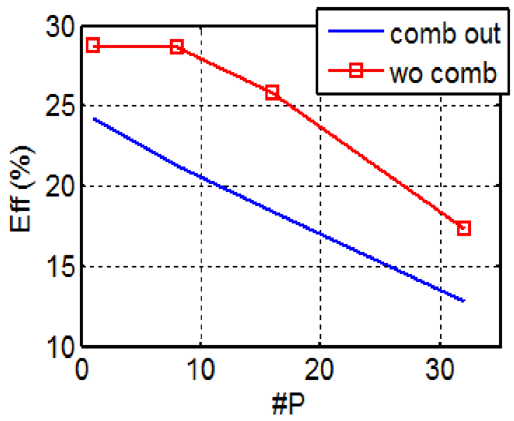
Combined performance power cells and combiner at N=1 with Γ_{out}< -15dB





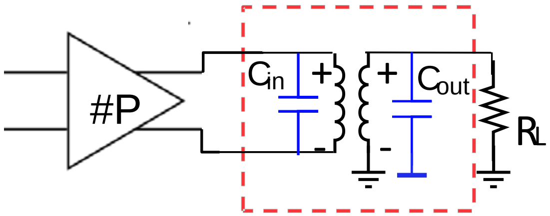


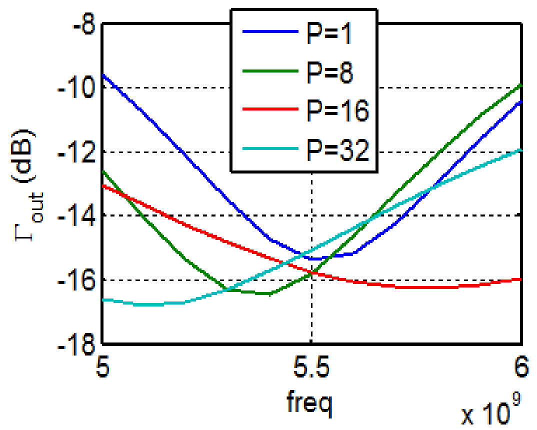
- $P_{comb,in}$ ≈ $P_{wo,comb}$ **so** $PMF = \dfrac{P_{in,comb,del}}{P_{in,comb,opt}} \approx 1$

  → η_{eff} (=PMF*η_{nw}) dominated by η_{nw}

- **η_{nw} reduces as #P goes up**

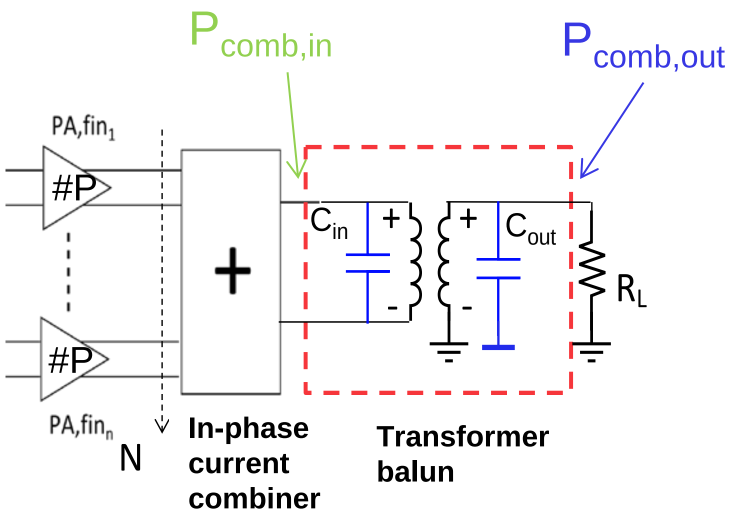
Combined performance power cells and combiner at N=1 with Γ_{out}< -15dB

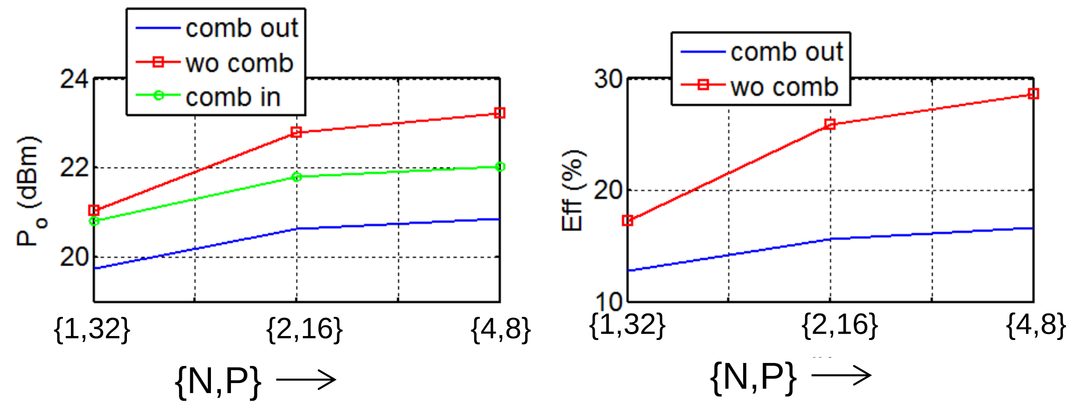




- Γ_{out} < -15dB at f_c=5.5GHz (as forced by optim routine)
- Γ_{out} < -9.8dB over entire bandwidth

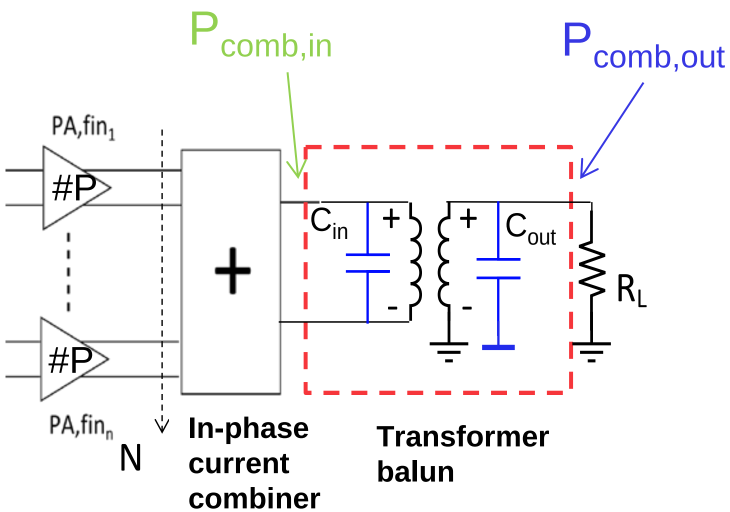
Combined performance power cells and combiner at P*N=32 with Γ_{out}< -15dB

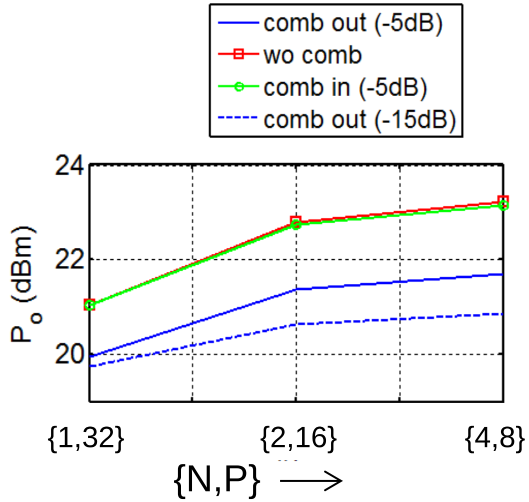


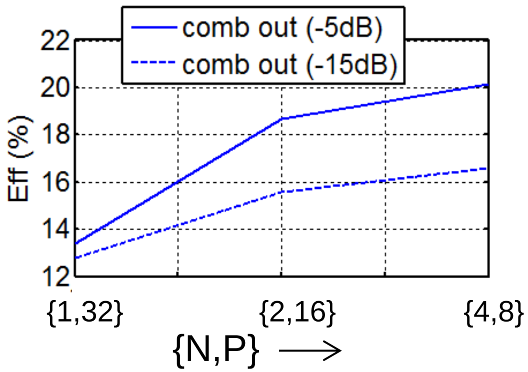


- **Improved performance as N goes up**
- **At {P,N}={2,16} and {4,8}: $P_{comb,in}$ < $P_{wo,comb}$ so PMF<1**
  - **Load impedance mismatched irt optimum load-line impedance R_{opt}**
  - **Due to losses, low required R_{opt} and Γ_{out}< -15dB requirement**

Combined performance power cells and combiner at P*N=32 with Γ_{out}< -5dB







- Γ_{out} requirement loosened from -15dB to -5dB
- $P_{comb,in} \approx P_{wo,comb}$ so PMF≈1 → 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**

Acknowledgement

- **Catena in Sweden**
- **The European Union for providing this exchange opportunity**

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Questions?