A 140GHz power amplifier with 20.5dBm output power and 20.8% PAE in 250-nm InP HBT technology

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mm-wave Communication (140-1000 GHz)

• Objective
  – Support high data rate communication.
  – Spatial multiplexing for high capacity.
  – Cover long distance.

• Benefits (140-1000 GHz)
  – Large available spectrum, high data rate.
  – Shorter $\lambda$: more channels for the same array size.

• Challenge
  – Atmospheric attenuation is high $P_R \alpha \frac{\lambda^2}{R^2} e^{-\alpha R}$. 
PA Requirements and Link Budget

- CMOS chips drive high efficiency InP power amplifiers.
- CMOS’s output power is ~2dBm.
- **20.5dBm** output power per element extends the link range to ~50m.
- Required gain ~20dB.
- Massive MIMO arrays require high efficiency PAs to avoid thermal destruction or complex heatsink.

### Calculated Data

- **Tx Antenna Gain**: 22.7 dBi
- **Rx Antenna Gain**: 13 dBi
- **Link range**: 50 m
- **Required output power per element**: 20.5dBm
- **Friss Path Loss**: 73 dB
- **Rx Noise Figure**: 8.5 dB
- **Rx BW**: 5 GHz
- **Bit rate**: 10 Gb/s
- **System Margin**: 15 dB
- **No of elements, Tx (λ/2 spacing)**: 32
- **No of elements, Rx (λ/2 spacing)**: 4

Calculated data are based on [https://www.ece.ucsb.edu/Faculty/rodwell/Classes/ece218c/ECE218c.htm](https://www.ece.ucsb.edu/Faculty/rodwell/Classes/ece218c/ECE218c.htm)
250nm InP HBT Process (Teledyne*)

- $f_{\text{max}} = 650\text{GHz}$.
- $BV_{CEo} = 4.5\text{V}$.
- $J_{\text{max}} = 3\text{mA/µm}$.
- Four Au interconnect.
- MIM cap (0.3fF/µm2).
- TFR (50Ω/square).

Unit Cell Comparison

- Comparison between CE, grounded CB and CB with base capacitor
- Simulation is done under same bias condition
- Large signal simulation is more relevant in power amplifier
- CB with base capacitor shows the highest $O_{P_{1dB}}$ with associated PAE

<table>
<thead>
<tr>
<th></th>
<th>Gain*, dB</th>
<th>PAE**, %</th>
<th>$P_{out}$**, dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE</td>
<td>10.7</td>
<td>15.4</td>
<td>12.0</td>
</tr>
<tr>
<td>Grounded CB</td>
<td>13.1</td>
<td>22.4</td>
<td>13.5</td>
</tr>
<tr>
<td>CB with 600 cap</td>
<td>9.8</td>
<td>29.7</td>
<td>15.2</td>
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</table>

*under opt load line condition without compression **at 1dB gain compression

At 140GHz

$P_{out}$ gain, and PAE for CE, grounded CB, and CB with base capacitor.
Unit Cell Comparison

- **Common emitter**
  - Lowest OP\(_{1\text{dB}}\) and Soft compression
  - Less sensitive to base inductance errors
- **Common base with grounded base**
  - Higher gain and OP\(_{1\text{dB}}\)
  - Requires \(-\)ve supply -> huge efficiency drop (large DC current in Re)
  - Bias is very sensitive without Re due to exponential relation (I\(_{\text{CE}}\) vs V\(_{\text{BE}}\))
  - Sensitive to base inductance errors
- **Common base with base capacitance**
  - Highest PAE and OP\(_{1\text{dB}}\) due to capacitance feedback linearization
  - Capacitance help stabilization (not shown)
  - Stable bias: negligible efficiency due to R\(_{b}\); base current is very small
  - Gain drops with smaller capacitance

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CB viewed as stacked PA cell*

- $C_{CB}$ and $C_{base}$ creates negative feedback
- This negative feedback
  - Linearize the amplifier: higher PAE and OP$_{1dB}$
  - Allows voltage swing on the base: with proper design, the output swing increases yielding in higher output power
  - Drops the output impedance: improves S22

PAE invariance*

- Assuming lossless matching network
- Internal voltages and currents are constant by proper load and base impedances*

\[ 2(n - 1)\omega P_{add} C_{base} = X_1 X_2 \sin(Y_1 - Y_2) \]  
(derivation not shown)

- The added power per stage is kept constant for the same internal voltages and currents.

\[ P_{out} = P_{add} + P_{in} \]

\[ X_1 \] is the magnitude of \( I_1 \)
\[ X_2 \] is the magnitude of \( I_2 \)
\[ Y_1 \] is the angle of \( I_1 \) in radians
\[ Y_2 \] is the angle of \( I_2 \) in radians

Power Amplifier Cell

- Common base with base capacitance
- Capacitance dropped slightly
  - More power and hard compression
  - Lower output impedance (better S22)
- Shunt stub tunes the transistor parasitics
- Two cells are combined and driven by a single driver -> better PAE
- ADS and HFSS are used for the interconnect and matching circuit simulations
Driver design

- Higher base capacitance:
  - more gain
- Input ant output are 50Ω matched
- Staggered matching for wider bandwidth

Driver cell
Combiner Design

• Transmission line combiner instead of Wilkinson
• Proposed combiner
  – Low loss and very compact
  – Smaller BW compared to Wilkinson
• Wilkinson
  – Bulky, high loss and skinny line
  – Higher BW

Proposed combiner

Wilkinson combiner
PA block diagram

- Three linearized common base stages
- Low loss and compact transmission line combiner
- First driver scaled to sustain good PAE
- Independent bias for each stage to monitor the current and optimize the PAE

Chip micrograph

Block diagram

1.08mmx0.63mm
Measurement results

- Wide band operation
- 1dB BW=20GHz
- 3dB BW=43GHz

<table>
<thead>
<tr>
<th>$V_{CC1}$</th>
<th>$V_{CC2}$</th>
<th>$V_{CC3}$</th>
<th>$V_{BB1}$</th>
<th>$V_{BB2}$</th>
<th>$V_{BB3}$</th>
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<tbody>
<tr>
<td>2.5V</td>
<td>2.5V</td>
<td>1.5V</td>
<td>1.94V</td>
<td>1.36V</td>
<td>1.1V</td>
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</table>

<table>
<thead>
<tr>
<th>$I_{CC1}$</th>
<th>$I_{CC2}$</th>
<th>$I_{CC3}$</th>
<th>$I_{BB1}$</th>
<th>$I_{BB2}$</th>
<th>$I_{BB3}$</th>
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</thead>
<tbody>
<tr>
<td>121mA</td>
<td>52mA</td>
<td>31.8mA</td>
<td>4.1mA</td>
<td>1.7mA</td>
<td>0.95mA</td>
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Measured (solid) vs simulated (dotted) S-parameters
Measurement results

- $P_{\text{sat}} = 20.5 \text{dB}_m$, and $\text{PAE} = 20.8\%$
- $P_{\text{sat}} = 18.9 - 20.5 \text{dB}_m$ over 125-150GHz

![Graph showing measured and simulated $P_{\text{out}}$, PAE, and gain vs input power at 140GHz.](image)

<table>
<thead>
<tr>
<th>$V_{\text{CC1}}$</th>
<th>$V_{\text{CC2}}$</th>
<th>$V_{\text{CC3}}$</th>
<th>$V_{\text{BB1}}$</th>
<th>$V_{\text{BB2}}$</th>
<th>$V_{\text{BB3}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5V</td>
<td>2.5V</td>
<td>1.5V</td>
<td>1.95V</td>
<td>1.4V</td>
<td>1.1V</td>
</tr>
<tr>
<td>$I_{\text{CC1}}$</td>
<td>$I_{\text{CC2}}$</td>
<td>$I_{\text{CC3}}$</td>
<td>$I_{\text{BB1}}$</td>
<td>$I_{\text{BB2}}$</td>
<td>$I_{\text{BB3}}$</td>
</tr>
<tr>
<td>130mA</td>
<td>56mA</td>
<td>34mA</td>
<td>5mA</td>
<td>2mA</td>
<td>1mA</td>
</tr>
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</table>

![Graph showing measured and simulated saturated $P_{\text{out}}$, PAE, and gain vs frequency.](image)
State-of-the-art results

- Highest PAE for comparable $P_{\text{sat}}$ and gain

<table>
<thead>
<tr>
<th>Ref</th>
<th>Technology</th>
<th>Freq (GHz)</th>
<th>$P_{\text{sat}}$ (dBm)</th>
<th>$B W_{\text{3dB GHz}}$</th>
<th>Gain at $P_{\text{sat}}$ (dB)</th>
<th>Peak PAE %</th>
<th>Size (mm$^2$)</th>
<th>$P_{\text{DC}}$ (W)</th>
<th>$P_{\text{sat}}$/Area mW/mm$^2$</th>
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<tbody>
<tr>
<td>[2]</td>
<td>40 nm CMOS</td>
<td>140</td>
<td>14.8</td>
<td>17</td>
<td>13**</td>
<td>8.9</td>
<td>0.34</td>
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<td>88.8</td>
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<tr>
<td>[4]</td>
<td>130-nm SiGe HBT</td>
<td>155-180</td>
<td>18.0</td>
<td>25</td>
<td>23.5**</td>
<td>4.0</td>
<td>0.85</td>
<td>1.57*</td>
<td>74.2</td>
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<td>[5]</td>
<td>130-nm SiGe HBT</td>
<td>112-142</td>
<td>17+</td>
<td>16</td>
<td>29**</td>
<td>13+</td>
<td>1.06</td>
<td>0.39*</td>
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<td>[6]</td>
<td>130-nm SiGe HBT</td>
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<td>14</td>
<td>49</td>
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<td>[7]</td>
<td>250-nm InP HBT</td>
<td>110-150</td>
<td>23.2-24.0</td>
<td>32.7</td>
<td>14-16</td>
<td>5.8-7.0</td>
<td>1.89</td>
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<td>[8]</td>
<td>250-nm InP HBT</td>
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<td>21-21.8</td>
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<td>15-17.5</td>
<td>8.2-10.5</td>
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<td>This work</td>
<td>250-nm InP HBT</td>
<td>125-150</td>
<td><strong>18.9-20.5</strong></td>
<td>43</td>
<td>12.3-15.9</td>
<td><strong>14.3-20.8</strong></td>
<td>0.69</td>
<td>0.52</td>
<td>162</td>
</tr>
</tbody>
</table>
Summary

• Demonstration of record PAE at D-band
• Teledyne 250nm InP HBT has high $f_{\text{max}}$ and $\text{BV}_{\text{CEO}}$
• Capacitively linearized common base
  – Higher $\text{OP}_{1\text{dB}}$, and PAE
  – Easier to bias and stabilize
• Compact and low loss transmission line network
• Driver scaling and bias optimization
Acknowledgement

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References