A 190-210GHz Power Amplifier with 17.7-18.5dBm Output Power and 6.9-8.5% PAE

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Outline

• Motivation for mm-wave frequencies and prior work.
• Application for the amplifier.
• Amplifier design
  – Power and driver cells
  – Low-loss compact combiner
• Measurement results
• Summary and conclusion
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 $P_R \alpha \frac{\lambda^2}{R^2} e^{-\alpha R}$.
Prior Work at G-band

- At 200GHz, CMOS shows 9.4dBm with only 1.03% PAE [2].
- SiGe shows 13.5dBm with ~2% drain efficiency [3]
- GaN demonstrates higher power with <2.4% peak PAE [4], [5].
- InP presented the highest power and efficiency [6]-[18].

Key points
- Designs are not optimized for the highest PAE at OP$_{1dB}$. PAE at OP$_{1dB} < 3\%$
- Power measurement accuracy at the linear region is challenging.
This Work (190-210GHz)

- Optimize for the highest efficiency at $OP_{1dB}$.
- $OP_{1dB} \sim 17.4\,\text{dBm}$, PAE: 6.4% at $OP_{1dB}$, Gain $\sim 23\,\text{dB}$.
- Accurate power measurement at the linear region.
- This amplifier is integrated to a 200GHz transmitter (not published).
250nm InP HBT Process (Teledyne [6])

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

Cross section of TSC250 IC
Power Amplifier Design

- Four stages amplifier.
- Combine four power cells.
- Driver scaling sustains good PAE.

- Power combining techniques
  - Parallel combining: 4:1 transmission line combiner.
  - Series combiner: stacked unit cell.

Amplifier micrograph

Amplifier block diagram

48-μm HBT periphery

24-μm HBT periphery

24-μm HBT periphery

PA cell

Driver

In

OUT

4:1 combiner

1:2 split

1:2 split

Stage 1

Stage 2

Stage 3

Stage 4

96-μm HBT periphery
Power Cell Design

- CB architecture with finite base impedance.
  - **Superior PAE at OP\textsubscript{1dB},** compared to CE or grounded CB, due to the feedback linearization [14].
- Base capacitances
  - Maximum value: limited by the self resonance frequency.
  - Minimum value: limited by the acceptable gain.
- Shunt transmission lines tunes the transistor parasitics.
- Each cell requires \( \sim 29\Omega \) load impedance.
- Matching considerations
  - Staggered tuning for better bandwidth.
  - Input impedances are close to the loadline of the driver to ensure proper saturation.
Combinder Design

- Transmission line combiners have low loss and very compact [14], [15], [17].
- Low loss 4:1 transmission line combiner.
- Combiner transforms 50Ω to the required loadline impedance for each cell (~29Ω) using a single \( \lambda /4 \) transmission line.
- Each two cells are combined by a TL with negligible electrical length.
- The required impedance for the two combined cells is 29/2Ω.
- The quarter line’s impedance is chosen to transform 100Ω to 29/2Ω.
Driver Cell Design

- Design is similar to the power cell.
- Architecture uses CB with finite base capacitance.
- Conservative driver scaling ensures hard compression characteristics at the expense of PAE degradation.
Measurement Results: $s$-parameters

- Good agreement at low bias
- Some deviations are observed at higher bias -> maybe heating effect.

S-parameters at $P_{DC}=444\text{mW}$

S-parameters at $P_{DC}=858\text{mW}$
Power Measurement: literature

• Conventional measurement: attenuator after a frequency multiplier chain.
• Power sweep: change the attenuator settings.
• Cons
  – The actual input power is unknown -> less accurate results.
  – In many cases, the attenuator is manually changed -> lift the probes and turn off the PA, not convenient.

Conventional power setup
Proposed Approach: setup

- The VDI’s output power is sampled by a coupler and monitored by the spectrum analyzer.
- The spectrum analyzer readings represent the power by adding the appropriate correction factor in the calibration phase.
- Sweep input power: control the signal generator.

![Proposed power setup diagram]

- **Harmonic Mixer**
- **Waveguide**
- **Spectrum Analyzer N9030B**
- **Signal Generator N5183B**
- **PM4**
- **20dB coupler**
- **23.75-26.25GHz**
- **190-210GHz**
- **~20dB Attenuation**
- **x8**

23.75-26.25GHz
190-210GHz
~20dB
Calibration phase

- Record the power difference (dB) between the power meter and spectrum analyzer readings.
- This difference is the correction factor that should be added to the spectrum analyzer readings to represent the actual input power.

![Diagram](image-url)

- Spectrum Analyzer N9030B
- Harmonic Mixer
  - Attenuation ~20dB
- Waveguide
- Signal Generator N5183B
  - Frequency 23.75-26.25GHz
- PM4
  - Coupler 20dB
  - Frequency 190-210GHz
Measurement Phase

- Sweep the signal generator power.
- Record the spectrum analyzer readings + the appropriate correction factors. This represents the amplifier input power after calibrating the probe losses by through measurements.
- Report the power meter reading.
- The power meter readings represent the amplifier output power after calibrating probe loss.
Pros of this measurement approach

• Accurate gain measurement even at very low input power.

• Power is swept by the signal generator
  -> Extremely convenient since all the measurements are done without lifting the probes or turn off the PA bias.
**Power Measurement Results**

- Many points are recorded at different frequencies.

<table>
<thead>
<tr>
<th>Freq, GHz</th>
<th>( \text{OP}_{1\text{dB}}, \text{dBm} )</th>
<th>( \text{PAE, } % \text{ at } \text{OP}_{1\text{dB}} )</th>
<th>( P_{\text{sat}}, \text{dBm} )</th>
<th>( \text{PAE, } % \text{ at } P_{\text{sat}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>194</td>
<td>17.4</td>
<td>6.4</td>
<td>18.5</td>
<td>8.5</td>
</tr>
<tr>
<td>202</td>
<td>16.6</td>
<td>5.3</td>
<td>18.3</td>
<td>7.9</td>
</tr>
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</table>

- Discrepancy between simulations and measurement maybe due to the probe conditions.
Power Measurement Results

- More points are taken at different frequencies.
- $P_{\text{sat}} = 17.7\text{-}18.5\text{dB}_m$, with $\text{PAE}=6.9\text{-}8.5\%$ over 190-210GHz
- $\text{OP}_{1\text{dB}} = 16\text{-}17.4\text{dB}_m$ with $\text{PAE}=4.7\text{-}6.4\%$ over 125-150GHz

Measured $P_{\text{out}}$ with the associated PAE and gain vs. frequency reported at the peak PAE.
State-of-the-art results

<table>
<thead>
<tr>
<th>Ref</th>
<th>[7]</th>
<th>[8]</th>
<th>[9]</th>
<th>[10]</th>
<th>This work</th>
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</thead>
<tbody>
<tr>
<td>Freq, GHz</td>
<td>204</td>
<td>190</td>
<td>180-260</td>
<td>190.8-244</td>
<td>190-210</td>
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<td>$P_{\text{sat}}$, dBm</td>
<td>18.0</td>
<td>11</td>
<td>17.5-21.5</td>
<td>16.2-18.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>17.7-18.5</td>
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<tr>
<td>Gain at $P_{\text{sat}}$ (dB)</td>
<td>16.5</td>
<td>19.2</td>
<td>13-17.5</td>
<td>19-22&lt;sup&gt;a&lt;/sup&gt;</td>
<td>13.4-16.8</td>
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<td>PAE at $P_{\text{sat}}$%</td>
<td>4.8</td>
<td>9.6</td>
<td>5.1</td>
<td>3.3-6.1</td>
<td>6.9-8.5%</td>
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<td>OP&lt;sub&gt;1dB&lt;/sub&gt;, dBm</td>
<td>15.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3</td>
<td>17.5</td>
<td>16.1-17.16&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>PAE at OP&lt;sub&gt;1dB&lt;/sub&gt;%</td>
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<td>2</td>
<td>2.1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.3-3.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.7-6.4</td>
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<td>Gain at OP&lt;sub&gt;1dB&lt;/sub&gt;</td>
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<td>27&lt;sup&gt;a&lt;/sup&gt;</td>
<td>23.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>23.8-35.0&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>$P_{\text{DC}}$ (mW)</td>
<td>1180</td>
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<td>2620</td>
<td>1270</td>
<td>814</td>
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<td>$P_{\text{sat}}$/Area mW/mm&lt;sup&gt;2&lt;/sup&gt;</td>
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<td>28.2</td>
<td>77.9</td>
<td>50.6</td>
<td>62.1</td>
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<tr>
<td>OP&lt;sub&gt;1dB&lt;/sub&gt; /Area mW/mm&lt;sup&gt;2&lt;/sup&gt;</td>
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<td>28</td>
<td>31.2</td>
<td>33.8</td>
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<tr>
<td>Technology</td>
<td>130nm InP</td>
<td>250-nm InP HBT</td>
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</table>

- This work shows a record PAE at OP<sub>1dB</sub>
Summary

• Demonstration of record PAE at G-band
• Communication transmitter requires careful attention to the performance at OP$_{1\text{dB}}$
• Key features for highest efficiency at OP$_{1\text{dB}}$
  – Proper cell topology: Capacitively linearized common base
  – Higher OP$_{1\text{dB}}$, and PAE
  – Driver scaling sustains good PAE
• Compact and low loss transmission line network
Acknowledgement

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• The authors thank Teledyne Scientific & Imaging for the IC fabrication.
Thank You
References

DC Bias Lines and Power Supply Oscillations

- Only two independent DC supplies -> reduce the bias complexity.
- One supply biases all stages’ collectors and the second biases the stages’ bases.
- There are many feedback loops -> potential stability problems.
- We noticed a potential oscillation problem at low frequencies (~GHz and lower) in earlier designs.
- The low frequency oscillations are not adequately modeled and does not show up in simulations.
- **In this design, we added many bypass capacitors with series resistors** to avoid out of band oscillations.
- There is no indication for oscillations.
Measurement accuracy

- The dynamic range of the power sweep is defined as follows:
  - The minimum input power: limited by the spectrum analyzer noise level.
  - Spectrum analyzer with reasonable noise levels shows smooth gain curves at low input power -> get accurate results to accurately report OP_{1dB}.
  - The maximum power: limited by the harmonic mixer saturation limit.
Measurement accuracy

• Probe losses are calibrated by through measurement.

• Old probes show non-50Ω impedance which degrades the output power.

• So, the probes may contribute to higher losses than the one measured in the through measurement.

• We did the measurement with an old probe pair, and we believe that the results could be improved by a newer one.