Highly Linear and Compact MMW Phased Array Transmitters

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Critical Technology that will Enable Next Generation Satcom Phased Arrays

- Next generation phased array designs will be driven by desire for increased capacity
- Evolution to smaller beam widths and more simultaneous beams favors phased arrays
  - ~100 simultaneous beams from one aperture
  - Today’s typical communication links use complex modulation requiring greater than 26 to 30 dB C/N for BER of $10^{-6}$ to $10^{-9}$
- Critical phased array technologies will be:
- High efficiency and linearity SSPA’s
  - Maintain high C/I with many beams
  - $P_{1\text{dB}}$ is not a good measure of linearity for multi-carrier modulation
  - Two tone OIM$_3$ /OIP$_3$ is an approximation for multi-carrier schemes
  - Noise to Power Ratio (NPR) for intra channel signal distortion
  - Adjacent Channel Power Ratio (ACPR) for adjacent channel interference
- Compact multiple-beam beam formers
  - Earth coverage, ~1000 beams
  - Need to reduce die size and cost
Background

Noise Power Ratio Explained

Adjacent Channel Power Ratio Explained
Selected linearity tests were performed at different frequencies dependent on test equipment availability.

A sampling of measurements at frequencies from 20 GHz to 46 GHz are presented.

All 1 watt amplifiers have similar topologies:

- Show similar $P_{1\text{dB}}$, $P_{\text{sat}}$, and $\text{OIP}_3$ behavior.
- ACPR and NPR behavior should be similar.
- Behavior over temperature is similar.
NGST 0.15µm GaAs PHEMT

- Flight qualified profile (die thickness: 100 µm; 50 µm.)
- $F_T \sim 75$ to 80 GHz @ $V_{DS} = 5V$
- $I_{max} \geq 600$ mA/mm
- $V_{BD} > 9$ V @ 0.1 mA/mm, > 11V @ 1 mA/mm
- $G_m > 550$ to 600 mS/mm
- $OIP_3 \geq P_{1dB} + 9$dB or better @ 10dB OBO
  - $OIP_3 \geq P_{1dB} + 9$dB holds at 5dB OBO
- $P_{1dB} \sim 400$ to 500 mW/mm; $P_{sat} \sim 500$ to 650 mW/mm
20 GHz Driver Amplifier

- Freq: 20 GHz
- Gain: 20 dB
- $P_{1dB}$: 25 dBm (329 mW/mm, 30% PAE)
- $P_{sat}$: 26 dBm (414 mW/mm, > 42% PAE)
- OIP$_3$: 35 dBm ($IM_3 = -46dB_c$ @10dB OBO)
- AM/PM $\leq$ 5 degrees under drive
- NPR calculated $> 18dB_c$ @ 4.5 OBO
  - Using single tone AM/PM, $P_{in}/P_{out}$ and current vs. drive characteristics.
- PAE at NPR $> 18dB_c$ $\sim$ 21%
- Size: 2.5 mm$^2$

State-of-the-art NPR for multi beam operation
24-26 GHz Power Amplifier

- **Freq:** 24 to 26 GHz
- **Gain:** 18 dB
- **P_{1dB}**: 31 dBm (525 mW/mm, 22% PAE)
- **P_{sat}**: 32 dBm (660 mW/mm, 29% PAE)
- **OIP_{3}**: 40.5 dBm (IM_{3} = -45 dB_{c} @ 10 dB OBO)
- **Size:** 5.88 mm²

- Amplifier topology chosen for maximum linear performance. PAE was a secondary consideration.

At \( P_{out} = (P_{1dB} - 2 \text{ dB}) \),

\[ IM_{3} = -25 \text{ dB}_{c} ! \]
ACPR Test Bench

- Freq: 26 GHz
- WCDMA (25MHz BW) up converted to pass band.
- ACPR > –44dBc @ 5 MHz offset
- Raw test data (no corrections for test set)
- Performance is expected to repeat for power amplifiers up to 45 GHz processed in NGST’s 0.15um 4mil GaAs.

Excellent linearity (ACPR) @ $P_{out}=P_{1dB} – 9dB$
37-40 GHz Power Amplifier

- **Freq:** 37 to 40 GHz
- **Gain:** 15 dB
- **$P_{1dB}$:** 30 dBm (463 mW/mm, 18% PAE)
- **$P_{sat}$:** 31 dBm (583 mW/mm, 20% PAE)
- **OIP$_3$:** 41 dBm (IM$_3$ = -40 dBc @ 6dB OBO)
- **OIP$_3$** degrades 2 dB at 85 degrees C.
  - OIP$_3$ very well behaved over temperature.
- **Size:** 4.5 mm$^2$
- **Temperature performance** typical of all NGST linear power amplifiers.

$IM_3 = -36$ dBc @ 85 degrees C with 6dB OBO!
40-44 GHz Power Amplifier

- Freq: 40 to 44 GHz
- Gain: 12 dB
- $P_{1dB}$: 29 dBm (368 mW/mm, 14% PAE)
- $P_{sat}$: 30 dBm (463 mW/mm, 18% PAE)
- OIP$_3$: 39 dBm (IM$_3$ = -42 dBc @ 8 dB OBO)
- Size: 4.25 mm$^2$

$OIP_3 = P_{1dB} + 10 \text{dB with gain of only } 6 \text{dB per stage!}$
43-47 GHz Phased Array Transmit Amplifier

- Freq: 43 to 47 GHz
- Gain: 22 dB
- Biased for power:
  - $P_{1dB} = 24$ dBm (465 mW/mm), PAE > 22%
  - $P_{sat} = 24.7$ dBm (546 mW/mm), PAE > 24%
- Biased for efficiency:
  - $P_{1dB} = 23$ dBm (370 mW/mm), PAE > 30%
  - $P_{sat} = 23.8$ dBm (450 mW/mm), PAE > 35%
- Size: 3.17 mm$^2$

State-of-the-art $P_{1dB}$ and PAE from 0.15um, 4mil GaAs process
### Figure of Merit Comparison Table

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<th>Freq.</th>
<th>Stages</th>
<th>Chip Size</th>
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CONCLUSIONS

- Demonstrated state of the art $P_{1\text{dB}}$, $P_{\text{sat}}$, Power Density and $OIP_3$ in compact die size.

- Meets high linearity requirements of phased array / radar transmitters.
  
  - High gain per stage enables excellent linearity, PAE and compact die size through 46 GHz.
  
  - Designs use NGST’s flight qualified 0.15µm GaAs PHEMT technology.
  
  - NGST space qualified 0.15µm PHEMT with its proven track record of volume production and use in automated assembly will support high chip counts in large arrays.

- Next phase in design will reduce area by 50% while maintaining performance.