Highly Linear and Compact MMW Phased Array Transmitters

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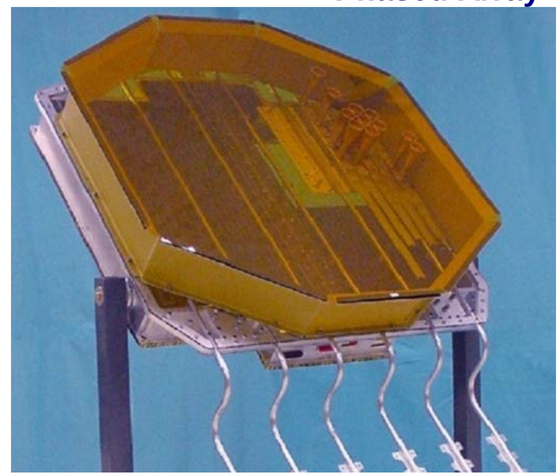
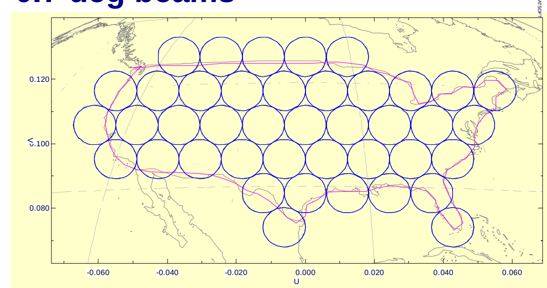
Critical Technology that will Enable Next Generation Satcom Phased Arrays

- 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_{1dB} 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

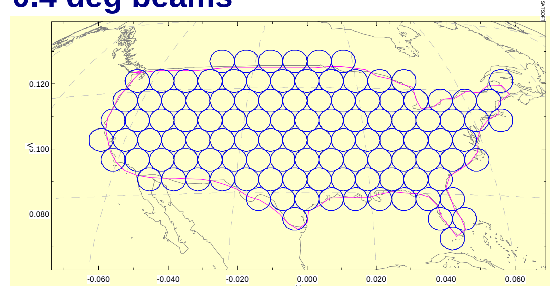
Phased Array



0.7 deg beams

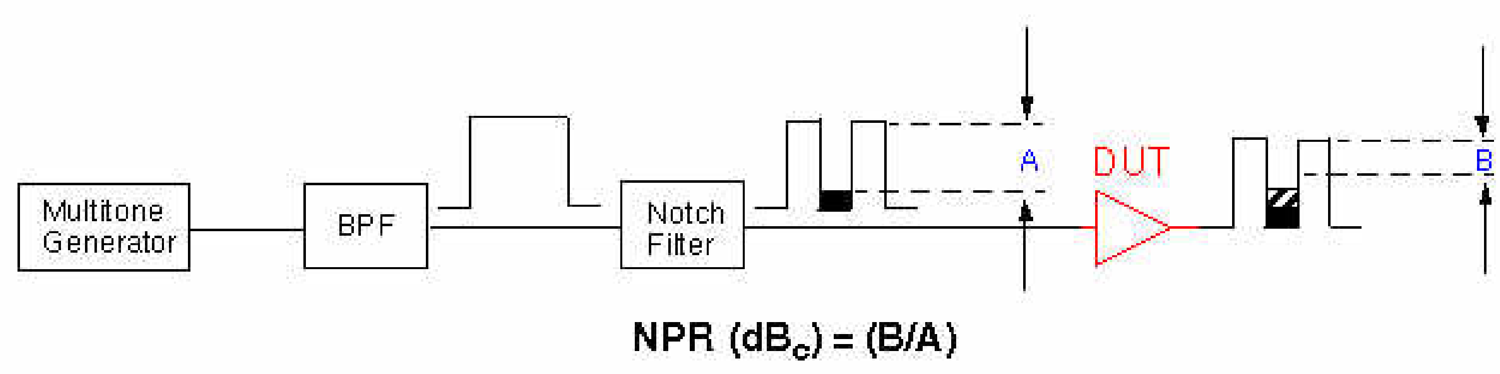


0.4 deg beams

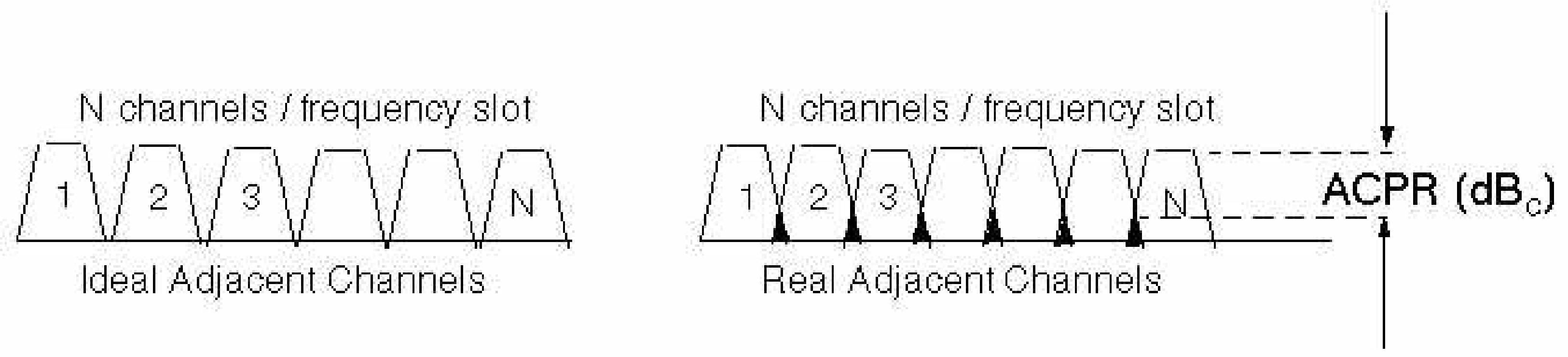


Background

Noise Power Ratio Explained



Adjacent Channel Power Ratio Explained



Outline

- 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_{1dB}, P_{sat} and OIP_3 behavior.
  - ACPR and NPR behavior should be similar.
  - Behavior over temperature is similar.

NGST 0.15µm GaAs PHEMT

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- Flight qualified profile (die thickness: 100 µm; 50 µm.)
- F_T ~ 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
- $OIP_3 \geq P_{1dB}$+ 9dB or better @ 10dB OBO
  - $OIP_3 \geq P_{1dB}$+ 9dB holds at 5dB OBO
- P_{1dB} ~ 400 to 500 mW/mm; P_{sat} ~ 500 to 650 mW/mm

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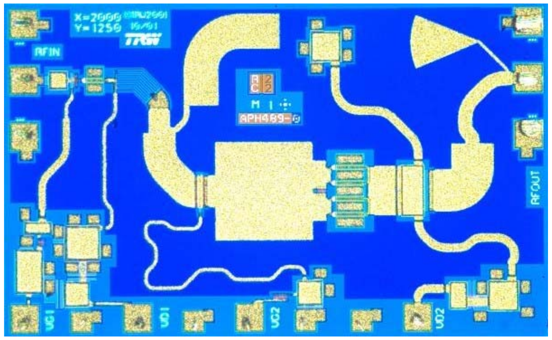
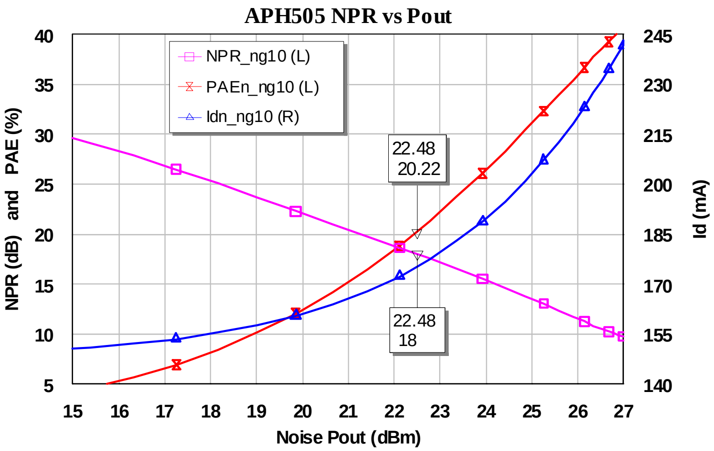
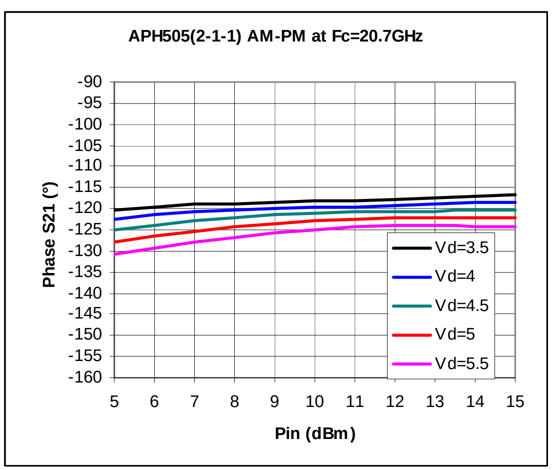
20 GHz Driver Amplifier







- 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 ~ 21%
- Size: 2.5 mm^2

State-of-the-art NPR for multi beam operation

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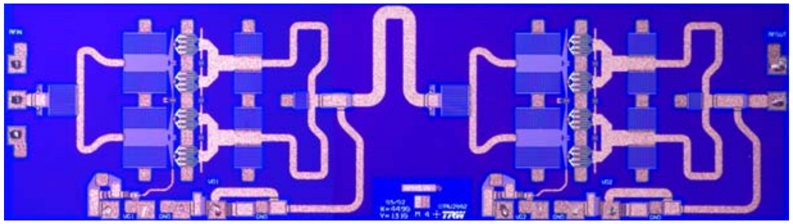
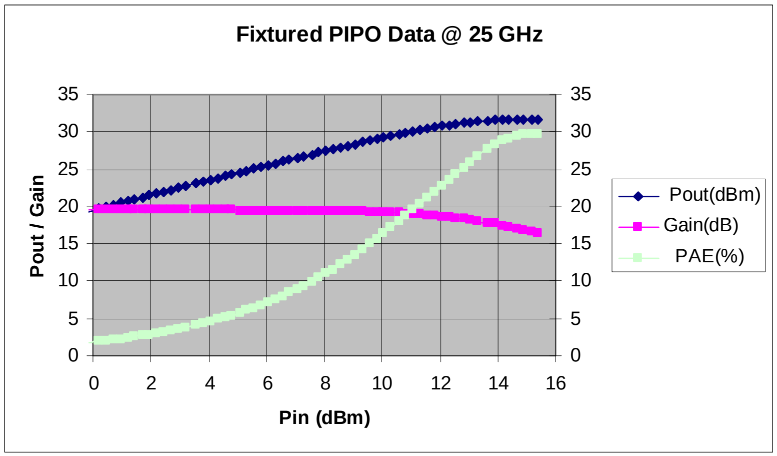
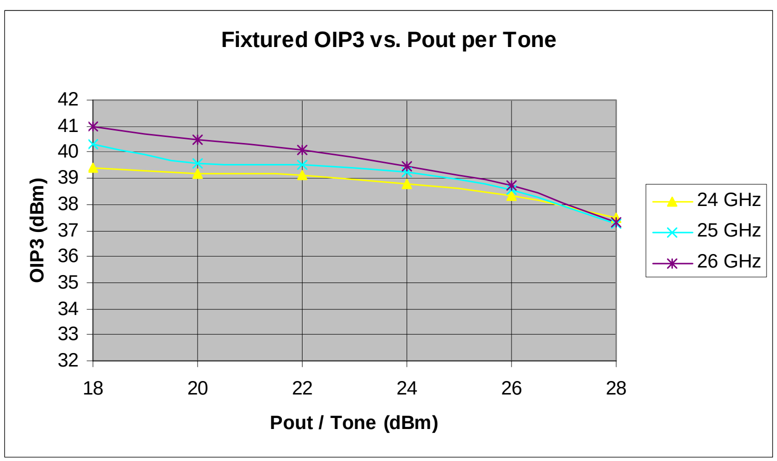
24-26 GHz Power Amplifier





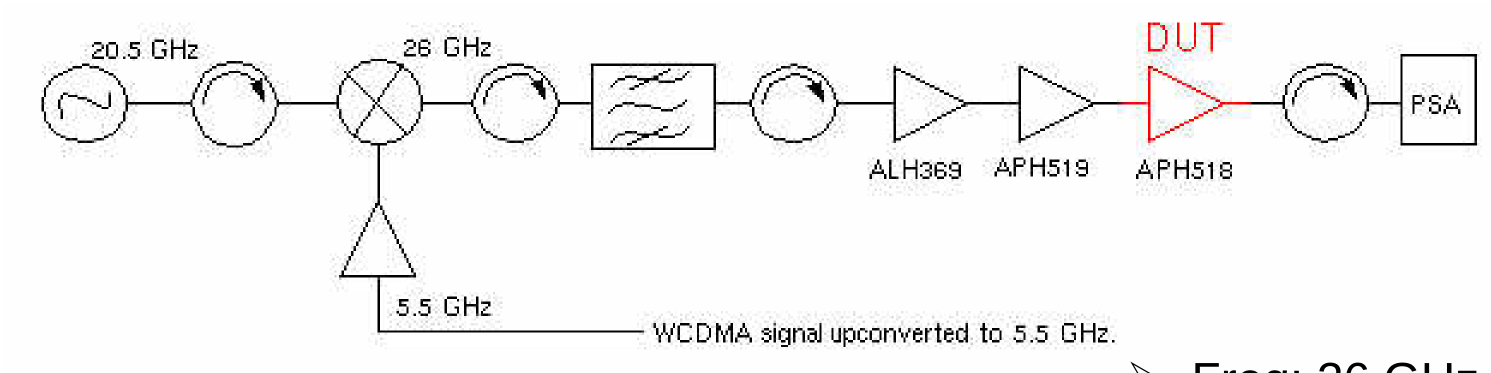


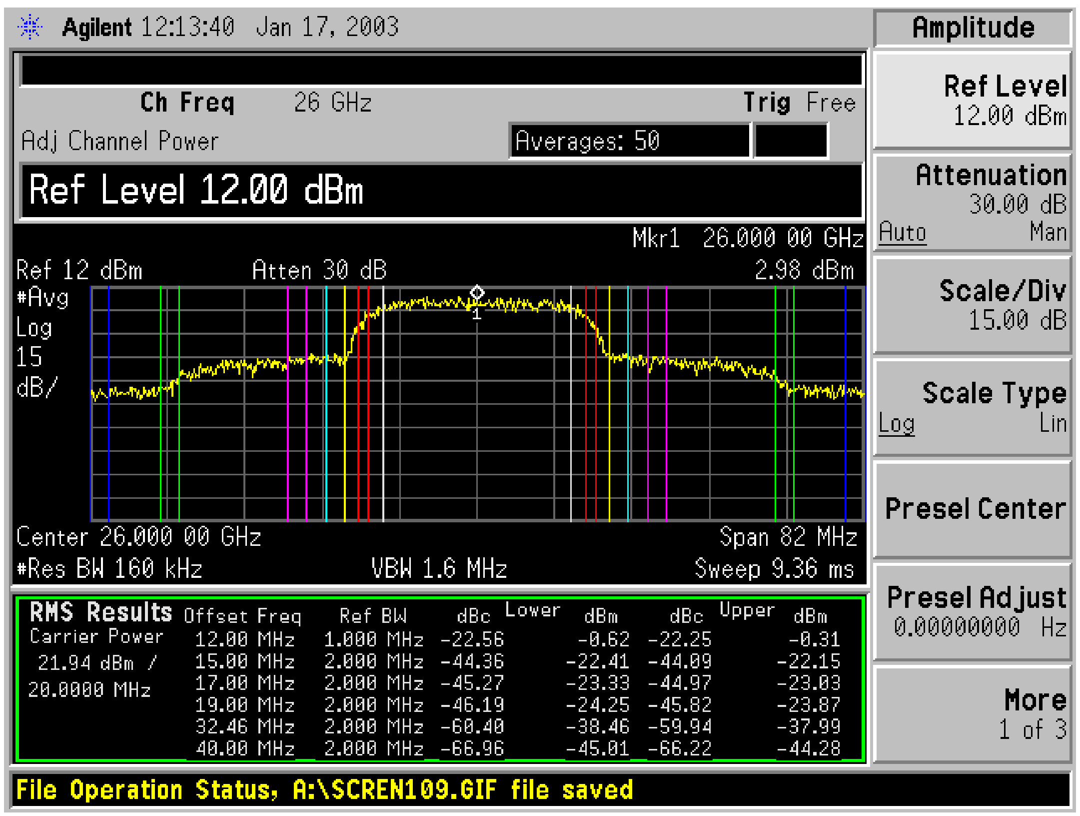
- Freq: 24 to 26 GHz
- Gain: 18 dB
- P_{1dB}: 31 dBm (525 mW/mm, 22% PAE)
- P_{sat}: 32 dBm (660 mW/mm, 29% PAE)
- OIP_3: 40.5 dBm (IM_3 = -45dB_c @ 10dB OBO)
- Size: 5.88 mm^2
- Amplifier topology chosen for maximum linear performance. PAE was a secondary consideration.

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

IM_3= -25 dB_c !

ACPR Test Bench

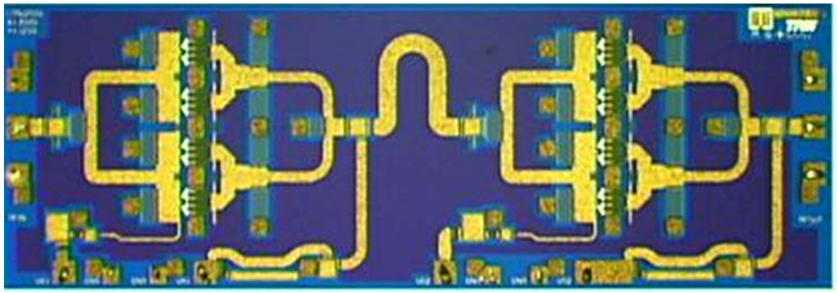


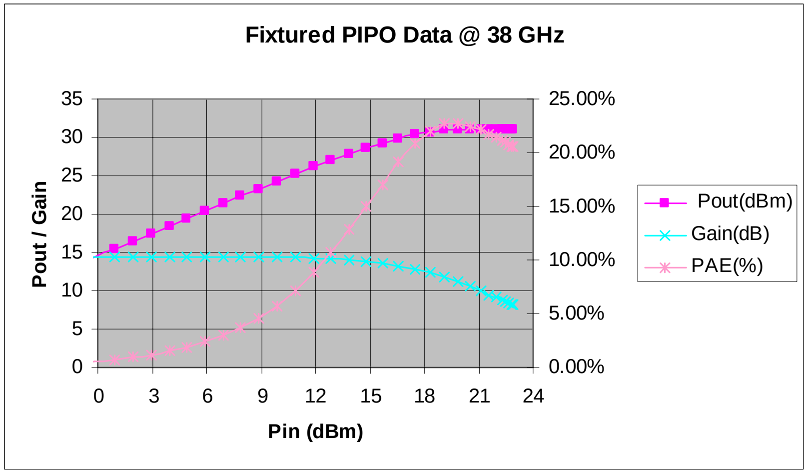


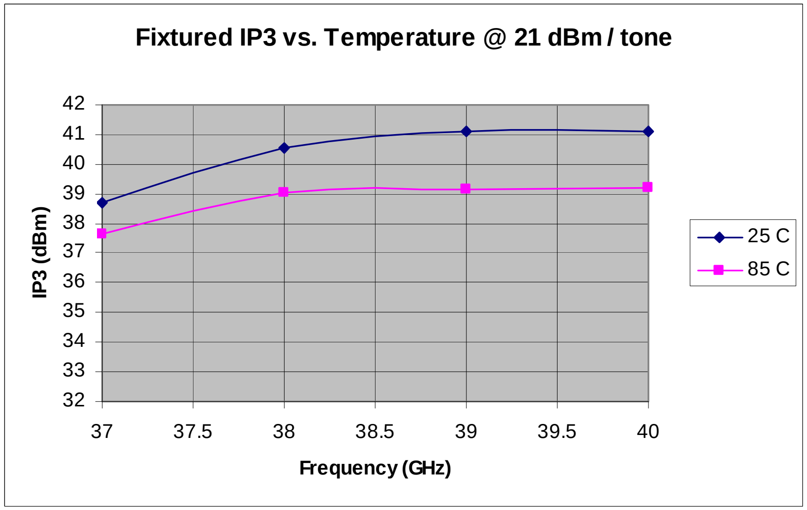
- Freq: 26 GHz
- WCDMA (25MHz BW) up converted to pass band.
- ACPR > –44dBc @ 5 MHz offset
- Raw test data (no corrections for test set)
- Performance is expected to repeat for power amplifiers up to 45 GHz processed in NGST's 0.15um 4mil GaAs .

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 = -40dB_c @ 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 dB_c @ 85 degrees C with 6dB OBO !

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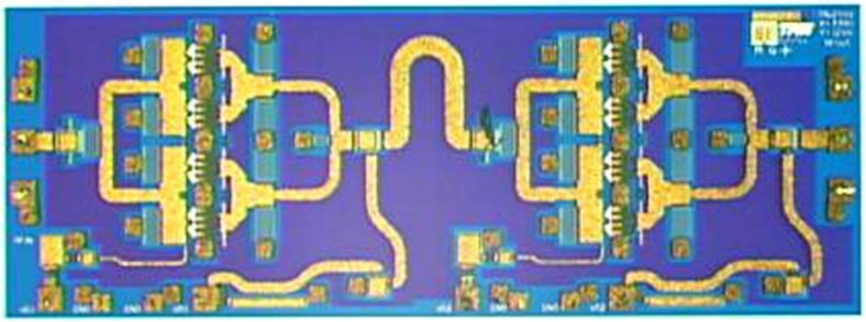
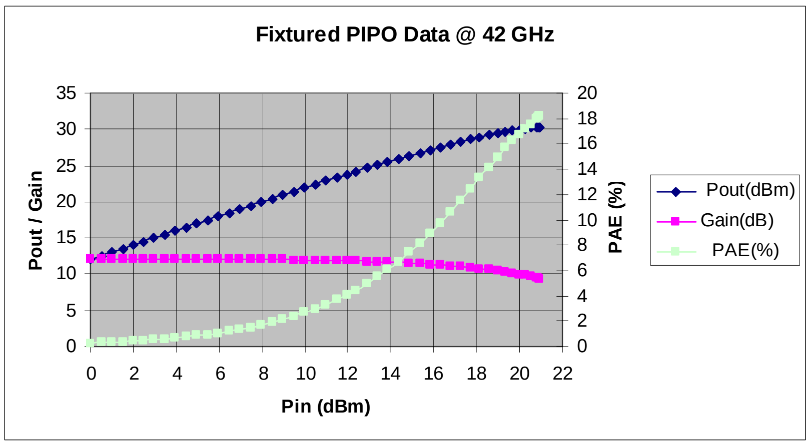
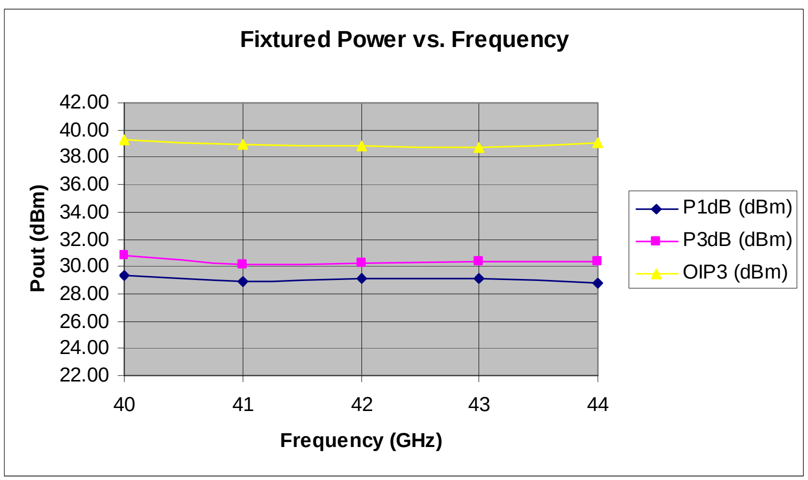
40-44 GHz Power Amplifier



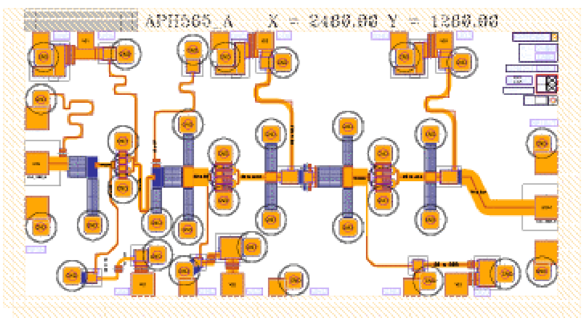


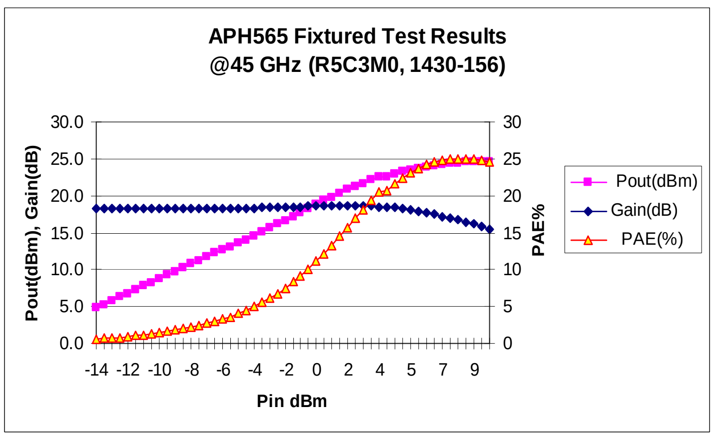


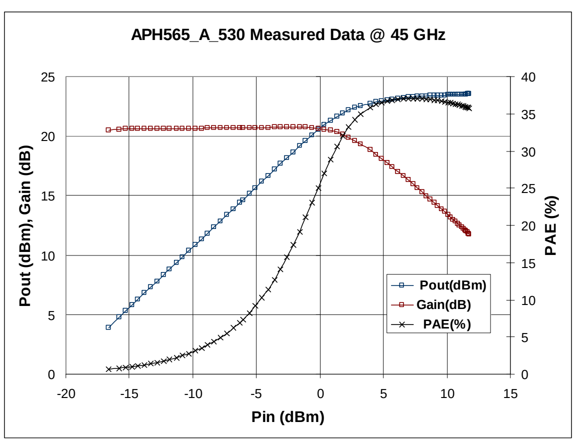
- Freq: 40 to 44 GHz
- Gain: 12 dB
- P_{1dB}: 29 dBm (368 mW/mm, 14% PAE)
- P_{sat}: 30 dBm (463 mW/mm, 18% PAE)
- OIP_3: 39 dBm (IM_3 = -42dB_c @ 8dB OBO)
- Size: 4.25 mm^2

$OIP_3 = P_{1dB}$ + 10dB with gain of only 6dB per stage!

43-47 GHz Phased Array Transmit Amplifier







Biased for Power

Biased for PAE

- 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

Foundry	Year	Freq. (GHz)	Stages	Chip Size mm^2	Output mm	S.S. Gain dB	P1dB dBm	PAE %	Psat dBm	Psat density mW/mm	OIP3 dBm	OIP3:P1dB	P1dB density mW/mm	OIP3 density W/mm
NGST	2003	19-21	2	2.5	0.8	18.5	24.0	30.0	25.9	**486**	35	**11**	**314**	**3.98**
Transcom	2002	14-17	4	4.1	3.6	30	30.8	24.5	31.3	375			333	
Triquint	2000	18-26	2	3.9	2.4	15	31.0	25.0	32	660	38.5	7.5	525	2.95
NGST	2003	24-27	2	5.9	2.4	19.5	30.9	24.0	31.6	**602**	40.5	**9.6**	**513**	**4.70**
NGST	2002	21-26	2	5.9	2.4	19.5	30.9	24.0	31	**525**	40.5	**9.6**	**513**	**4.70**
NGST	2003	30	1	1.9	2.4	10	31.0	25.7	32	**660**	40.5	**10**	**525**	**3.30**
UMS	2002	29	2	2.3	2.4	18.5	29.5		30.1	426.4			375	
Triquint	2002	30	4	12.9		22.5	34.5						219	
Triquint	2000	28-31	2	3.7	2.4	16	29.5	20.0	30.2	436.3	37	7.5	525	2.08
BAE	1999	29-33	2	14.9	10.8	18	34.8	20.0	36.5	413.6			280	
NGST	2003	37-40	2	4.5	2.16	15	30.0	18.0	31	**583**	41	**11**	**463**	**5.73**
NGST	2003	40-44	2	4.3	2.16	15	29.0	12.0	30.5	**519**	39	**10**	**368**	**3.64**
NGST	2003	43-47	3	3.2	0.54	22	24.0	35.0	24.8	**559**			**465**	

CONCLUSIONS

- Demonstrated state of the art P_{1dB}, P_{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 0.15um 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.