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Microwave and Millimeter Wave Power Amplifiers: Technology, Applications, Benchmarks, and Future Trends

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title slide

Why Are Power Transistors So Important?

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Power amplifiers typically *dominate* transmitter/system characteristics:

- **DC power consumption**
- **Power dissipation (heat) ➡ thermal load**
- **Reliability ➡ stressful operating conditions**
  - **High junction/channel temperature**
  - **High DC operating voltage (relative to other functions)**
  - **Large AC signals**
- **Cost**
  - **Power MMICs typically have largest chip area, highest chip count**
  - **Power MMICs typically are lowest yield, highest cost (\$/chip, \$/mm^2) of MMIC types due to large size, high periphery**

Current Generation Silicon LDMOS

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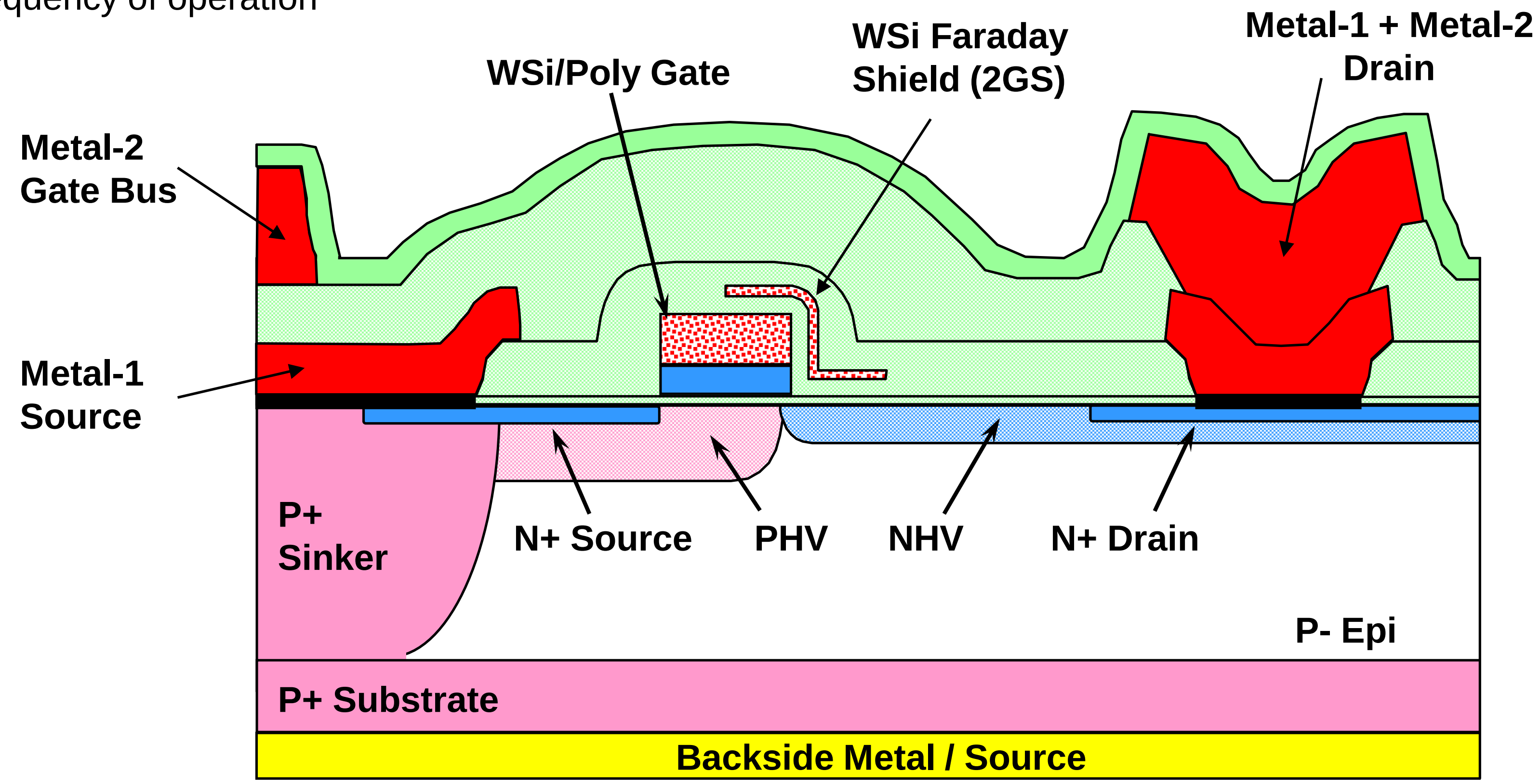
- Based on MOSFET technology
- Low cost, proven performance, reliability
- Low source inductance using p-type sinker
- Field plate for increased gain
- Multi-generation performance improvement continuously has increased frequency of operation



GaAs Pseudomorphic HEMT (PHEMT)

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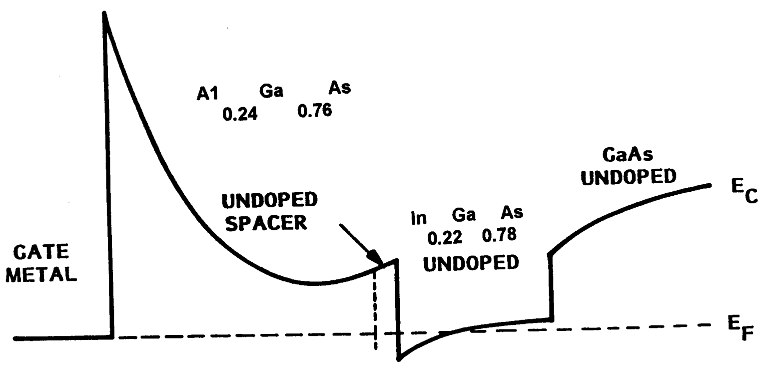
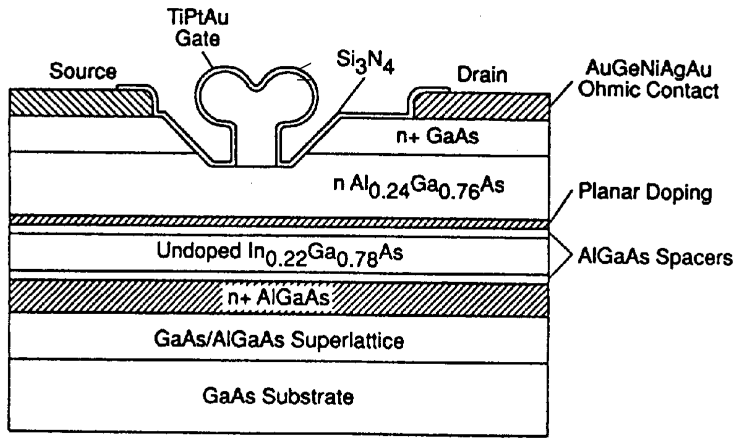
- First demonstrated for microwave power in 1986
- $In_x Ga_{1-x} As$ channel, with $0.15 \leq x \leq 0.30$
  - Enhanced electron transport
  - Increased conduction band discontinuity, allowing higher channel current
  - Quantum well channel provides improved carrier confinement
- Power devices typically use "double heterojunction" layer structure
- Material grown by MBE or MOCVD
- Used for power amplifiers from 0.9 to 80 GHz
- Enhancement mode (E-mode) PHEMT for cell-phone PAs -- single supply voltage



Conduction Band Profile



Typical Power PHEMT

InP HEMT

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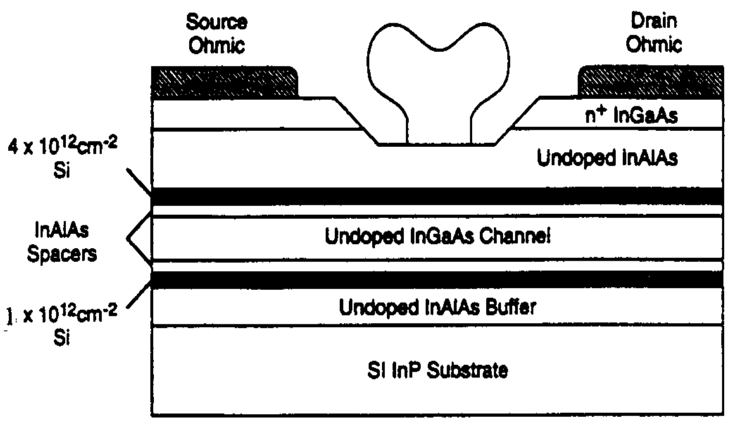
- Millimeter-wave operation first demonstrated in 1988 (low noise)
- Based on InGaAs/InAlAs material system on InP substrate
  - InGaAs channel with 53% In (lattice-matched), 80% In (pseudomorphic), 100% In (strained pseudomorphic)
  - Enhanced transport, large conduction band discontinuity
- High current (1A/mm), very high transconductance (3000 mS/mm) demonstrated
- Sub-Millimeter Wave frequency response fmax = 1500 GHz, ft = 610 GHz
- Low breakdown for single recess (low bandgap of InAlAs gate layer)
- Double-recess devices have been reported
- Metamorphic HEMT (MHEMT) – InP HEMT on GaAs Substrate
- Superior PAE and power gain demonstrated at 20-1000 GHz



GaN HEMT

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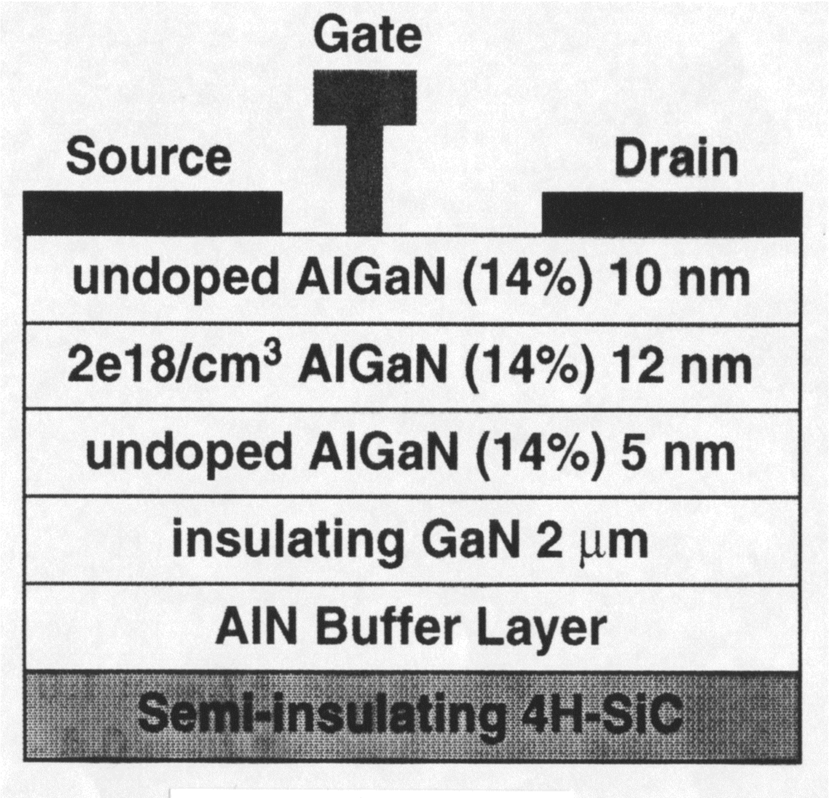
- Grown on SiC substrates
- Heterojunction with undoped channel
- Electron mobility $\mu = 1500\ cm^2/V\text{-}sec$
- High surface defect density (10^7-$10^8/cm^2$)
- First GaN HEMT MMIC reported in 2000
- Millimeter Wave frequency response
  f_{max} of 230 GHz, f_t of 97 GHz
- Very high power density demonstrated >10W/mm
- Thermally limited device



Best Reported Microwave Transistor Efficiencies

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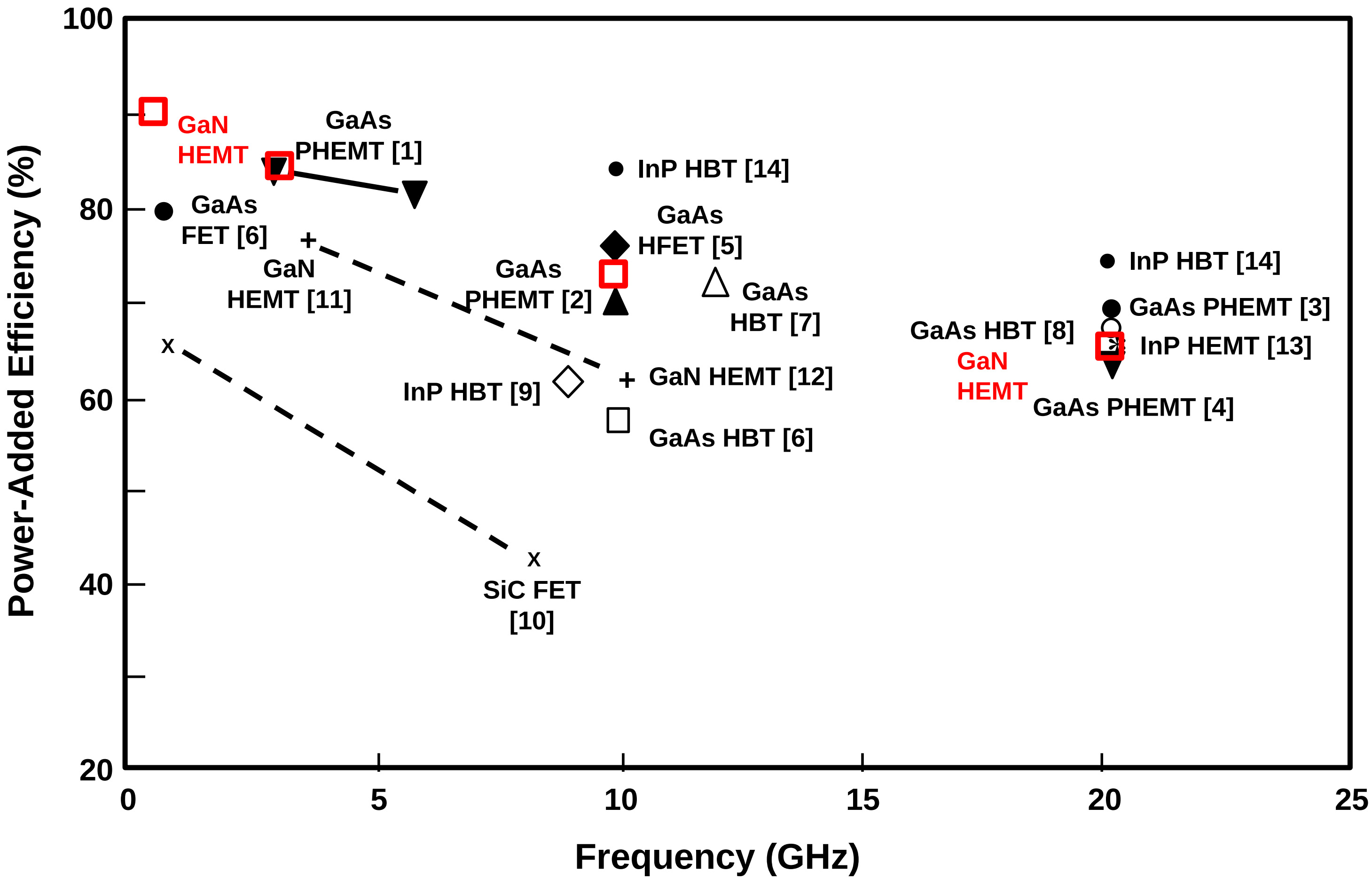

High Gain Enables High Efficiency Modes of Operation: Class AB2, Class B, Class C, Class F

Integration to Higher Power Levels

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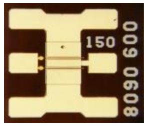
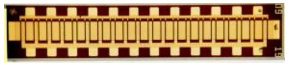
Intrinsic Device (single finger)

Small periphery (gate/emitter)
Short gate/emitter fingers
Low parasitics

Power Transistor "Cell"

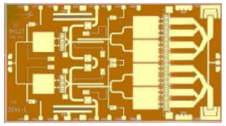


"Building block" for higher power
Longer fingers
Characterized for power amplifier design



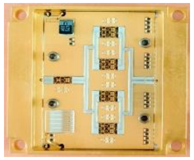
Discrete device: all matching off-chip

Hybrid Power Amplifier | Power MMIC



Full MMIC: all matching on-chip

Module



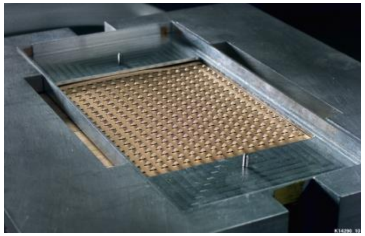
Power amplifier or T/R module
MIC power combining (typ. 2 to 8-way)

Waveguide/Radial Combiners
W/G: 2 to 32-way
Radial: to 128-way

Constrained Combining (Plumbing)

Spatial Combining (Phased Array/ Quasioptics)

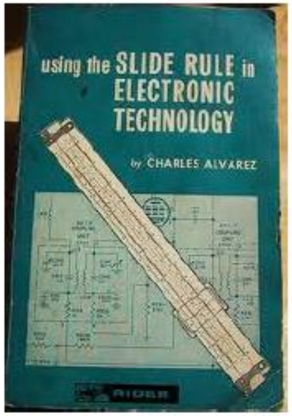
Each MMIC feeds separate radiating element
(typ. 100s-1000s of elements)



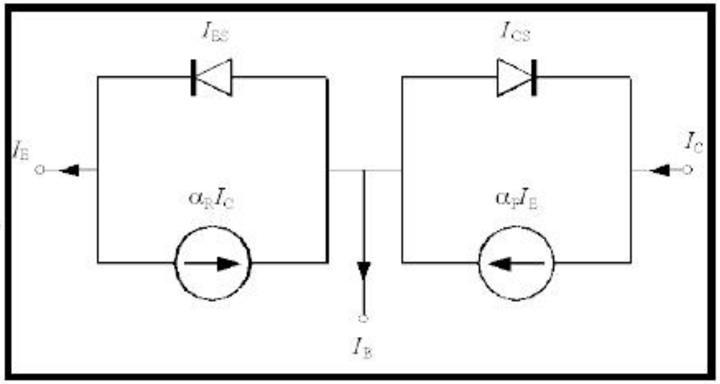
Pre-history of Circuit Design

- Characterization:
  Simple analytical models derived from DC I-V measurements

- Simulation:
  Hand calculation of model parameters

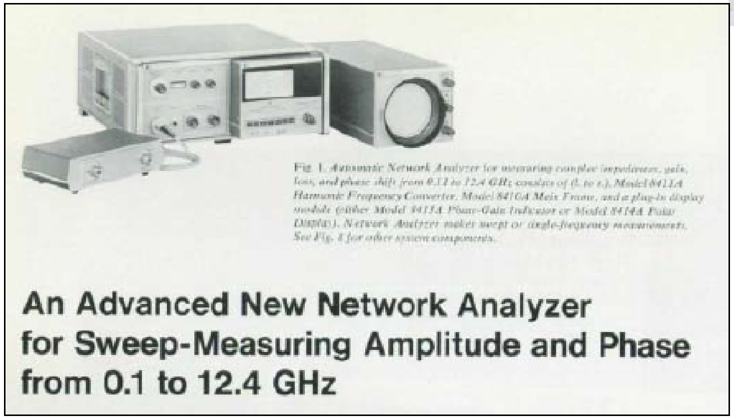


- Models:
  Ebers-Moll....



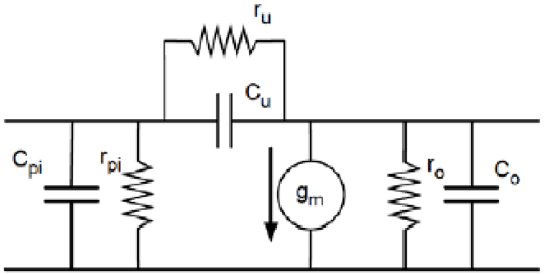
1970s Circuit Design

- **Characterization:**
  I-V & C-V measurement;
  S-parameters - HP8410



- Simulation:
  …increasing sophistication!

- Models:
  … “hybrid-π”



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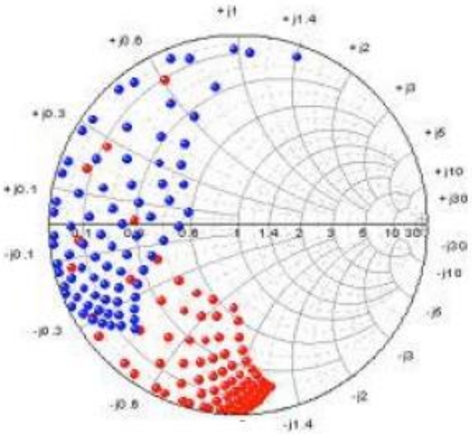
Raytheon
Space and Airborne Systems

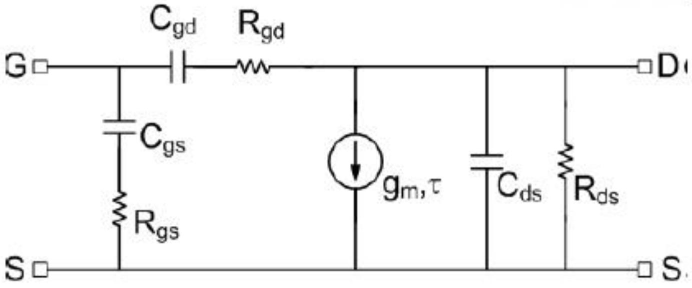
1980s Circuit Design

- Characterization:
  S-parameters over bias
  – HP8510

- Simulation Tools:
  Touchstone, *Compact*



- Models appear in the simulators:



Small-signal bias-dependent
equivalent-circuit FET model

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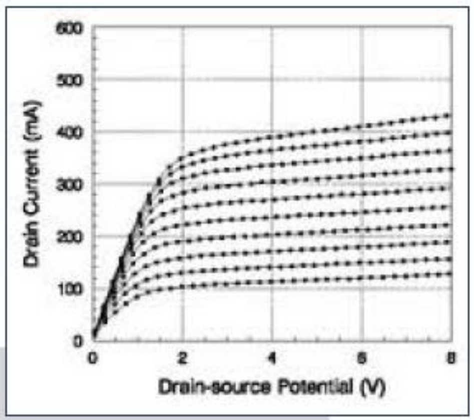
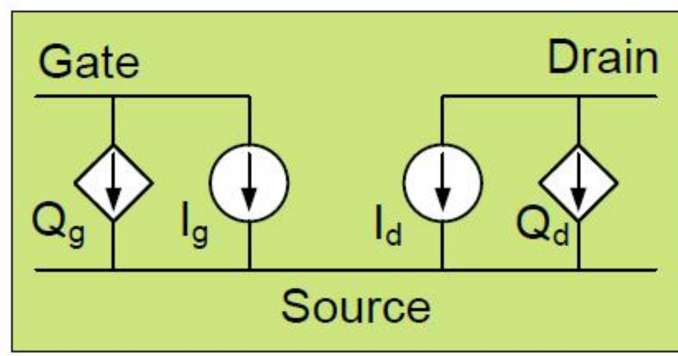
Space and Airborne Systems

1990s Circuit Design

- **Characterization:**
  Pulsed I-V and S-parameters



- **Simulation Tools:**
  Harmonic Balance enables large-signal simulation in HP '*MDS*', EEsof '*Libra*'
- **Models:**
  Large-signal models: 'Root' FET model

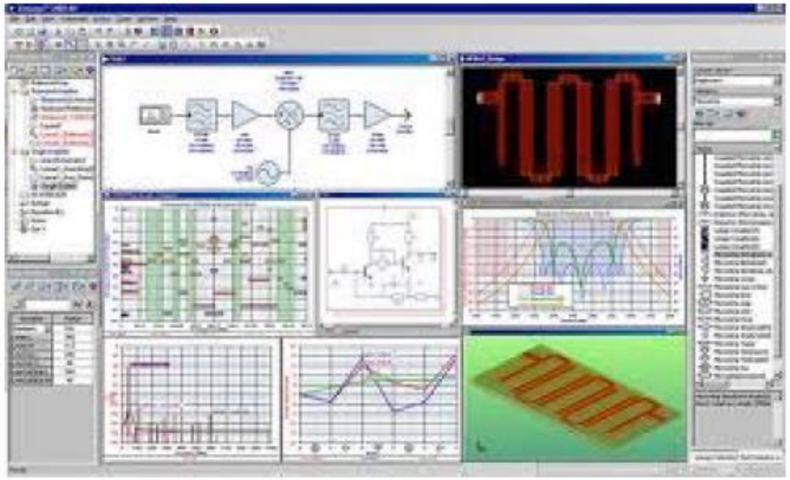


2000s to now Circuit Design

- Characterization:
  X-Parameters – PNAX

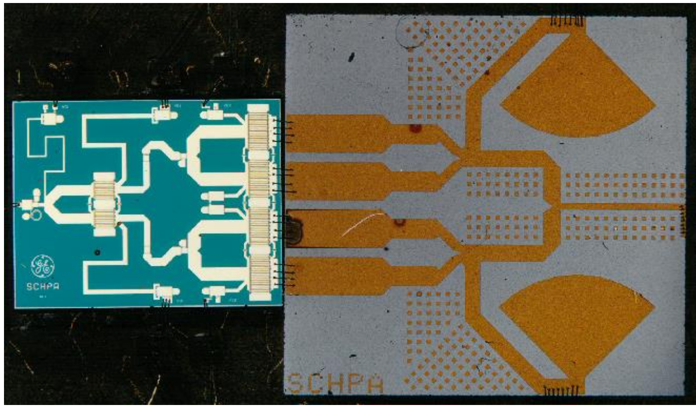
  Vector Signal Analysis

- Simulation Tools:
  HB, *Circuit Envelope*
  Agilent '*ADS*'
  AWR '*Microwave Office*'



1990 State of the Art Amplifier

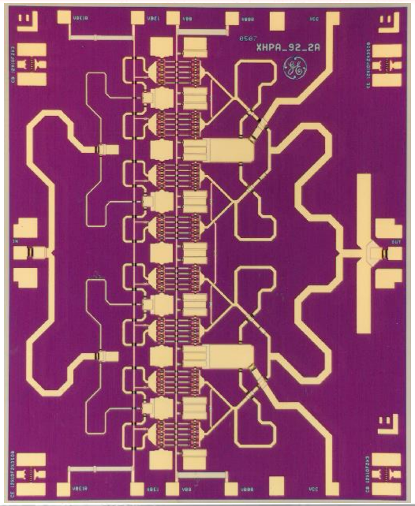
- Two stage MMIC Amplifier, 3 to 6 GHz, off-chip matching network
  - Output Power 11 W ± 1dB
  - Large signal gain of 10 to 13dB
  - PAE in the range of ~10 to 17%
  - 43% to 57% dc / visual yield
  - Extensive discussion on thermal performance
- Output stage design methodology
  - Comprehensive device characterization including both measurements and linear/nonlinear modeling
    - Measured small-signal ***S*** parameters, equivalent circuit models fitted to the data
    - *I / V* measurements augmented with optimum load/contour data obtained via load pull, are used to derive a consistent linear/nonlinear model
  - Network synthesis techniques consisting of transforming the 50Ω load to the required optimum large-signal load impedance
    - Cripps technique, a value of R_{opt} derived from I_{dss} and the V_{ds}, and the small-signal model parameters C_{ds} and L_d, determines an approxim*ation* to the optimum class A load.
    - An enhanced version of the Cripps technique takes into account the effect of the full-channel current I_{max} and the nonunilateral nature of the device by large-signal conductance substitution of the load line into the complete small-signal model
    - The use of the load-pull measurements with variable tuners, automated to search for optimum conditions

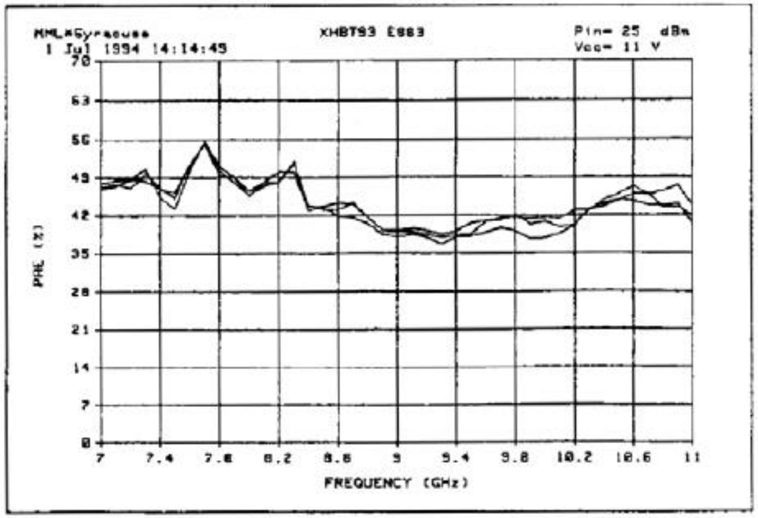


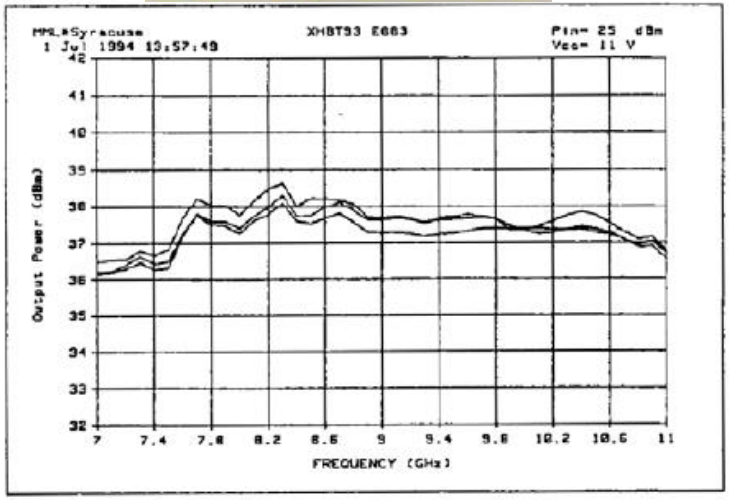
Komiak, J.J.; , "Design and performance of an octave band 11 watt power amplifier MMIC," *Microwave Theory and Techniques, IEEE Transactions on* , vol.38, no.12, pp.2001-2006, Dec 1990

1995 State of the Art Amplifier

- A fully monolithic HBT power amplifier
  - 2400 µm consisting of 8 - 300 µm unit cells in a cascode configuration
  - Power-added efficiencies of 56% max / 38% min, 44.4% average across 7 to 11 GHz band
  - Output power levels of up to 7.3 Watts with a gain of 11 to 14.1 dB
    - Under long pulse (500 usec) and high duty cycle (25 %) conditions.



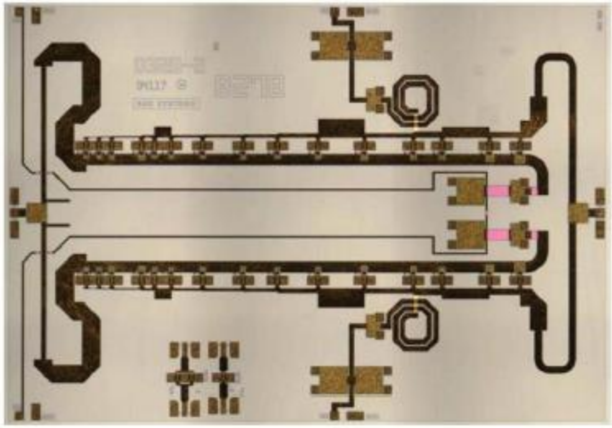




Komiak, J.J.; Yang, L.W.; , "5 watt high efficiency wideband 7 to 11 GHz HBT MMIC power amplifier," *Microwave and Millimeter-Wave Monolithic Circuits Symposium, 1995. Digest of Papers., IEEE 1995* , vol., no., pp.17-20, 15-16 May 1995

2011 State of the Art Amplifier

- Decade Bandwidth 2 to 20 GHz GaN HEMT Power Amplifier MMICs in DFP and No FP Technology
- With Dual Field Plate [DFP] Technology
  - P_{3dB} of 26.3 Watts max, 15.4 Watts average, 7.1 Watts min.
  - PAE of 38.3 % max, 19.8 % average, 5.9 % min.
  - Power gain of 11.2 dB max, 8.6 dB average, 5.0 dB
- No Field Plate [FP] Technology
  - P_{3dB} of 21.6 Watts max, 16.0 Watts average, 9.9 Watts min.
  - PAE of 35.7 % max, 25.9 % average, 15.3 % min.
  - Power Gain of 11.1 dB max, 9.7 dB average, 8.0 dB min.



With Dual Field Plate [DFP] Technology

Freq (GHz)	Power (Watts)	Gain (dB)	PAE (%)
2	13.46	6.42	27.66
3	14.29	7.24	20.63
4	20.51	9.14	31.63
5	26.30	10.90	38.29
6	22.34	11.20	31.52
7	18.20	9.29	22.46
8	15.17	8.56	17.22
9	17.02	8.59	20.14
10	22.75	9.36	24.39
11	17.62	8.66	20.19
12	13.68	7.90	14.45
13	12.76	7.61	13.17
14	14.96	8.75	17.97
15	13.90	10.55	20.07
16	13.00	9.07	16.06
17	8.36	5.77	7.50
18	7.13	5.02	5.91
19	11.43	7.21	12.43
20	9.14	9.98	14.15

No Field Plate [FP] Technology

Freq (GHz)	Power (Watts)	Gain (dB)	PAE (%)
2	13.18	8.05	34.72
3	12.47	8.77	25.13
4	16.60	10.14	30.45
5	18.79	10.73	32.72
6	20.61	11.08	35.69
7	18.54	10.81	32.66
8	17.30	10.58	28.68
9	17.46	10.42	26.18
10	19.27	10.37	25.37
11	21.63	10.48	26.43
12	17.50	9.20	23.14
13	14.45	9.06	23.36
14	15.14	9.69	24.00
15	16.98	10.49	25.57
16	16.86	10.27	24.46
17	14.39	9.31	20.27
18	9.91	7.95	15.28
19	12.42	8.05	18.14
20	11.09	8.11	18.88

Komiak, J.J.; Kanin Chu; Chao, P.C.; , "Decade bandwidth 2 to 20 GHz GaN HEMT power amplifier MMICs in DFP and No FP technology," Microwave Symposium Digest (MTT), 2011 IEEE MTT-S International , vol., no., pp.1-4, 5-10 June 2011

Power Amplifier Advance Architectures

- Stage Bypassing and Gate Switching
- Kahn Envelope Elimination and Restoration Technique
  - Combines a highly efficient, but nonlinear RF Power Amplifier with a highly efficient envelope amplifier to implement a high-efficiency linear RF Amplifier
- Envelope Tracking
  - The supply voltage is varied dynamically to conserve power, but with sufficient excess ("headroom") to allow the RF PA to operate near saturation at high efficiency.
- Outphasing
  - Produces an amplitude-modulated signals that combine the outputs of two amplifier driven with signals of different time-varying phases. The resulting output is the instantaneous vector sum of the two amplifier outputs to follow the desired signal amplitude. In a modern implementation, a DSP and synthesizer produce the inverse-sine modulations of the driving signals.
- Doherty Technique
  - This architecture combines two amplifiers of equal capacity through quarter-wavelength lines or networks. The "carrier" (main) amplifier is biased in class B, while the "peaking" (auxiliary) amplifier is biased in class C. Only the carrier PA is active when the lower signal amplitudes. Both amplifiers contribute output power when the input signal amplitude is approaching levels to saturate the main amplifier.

Raab, F.H.; Asbeck, P.; Cripps, S.; Kenington, P.B.; Popovic, Z.B.; Pothecary, N.; Sevic, J.F.; Sokal, N.O.; , "Power amplifiers and transmitters for RF and microwave," *Microwave Theory and Techniques, IEEE Transactions on* , vol.50, no.3, pp.814-826, Mar 2002

150 Watt 110-450 MHz Si LDMOS Power Amplifier

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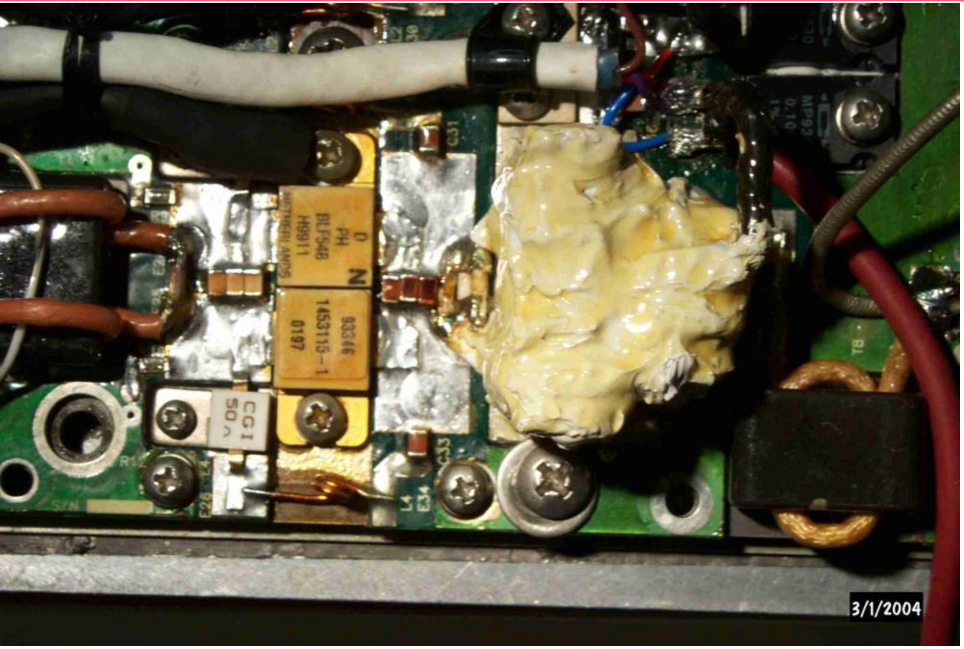
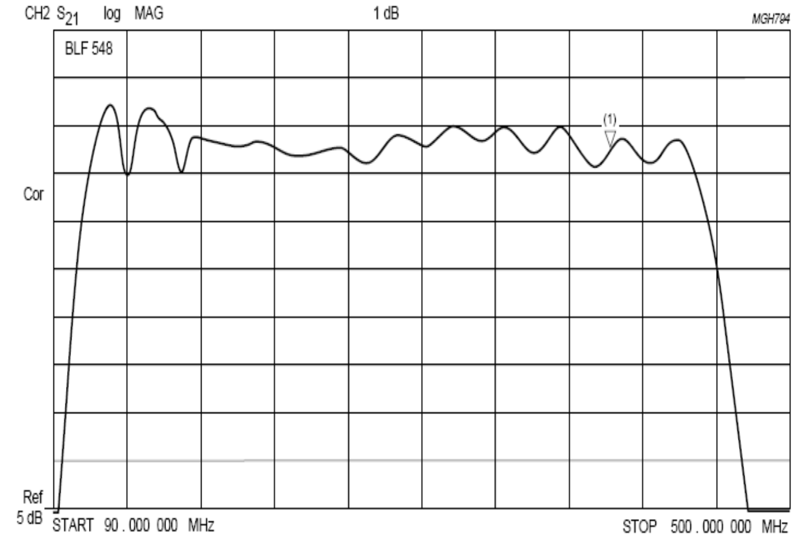
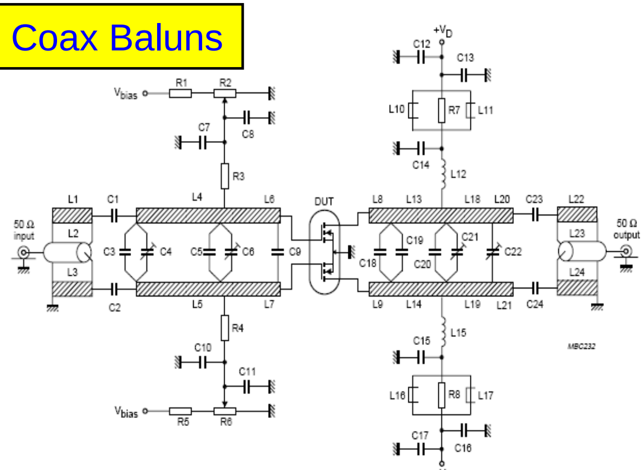




(1) 400 MHz; 12.526 dB.

Push-Pull with Ferrite Loaded Coax Baluns

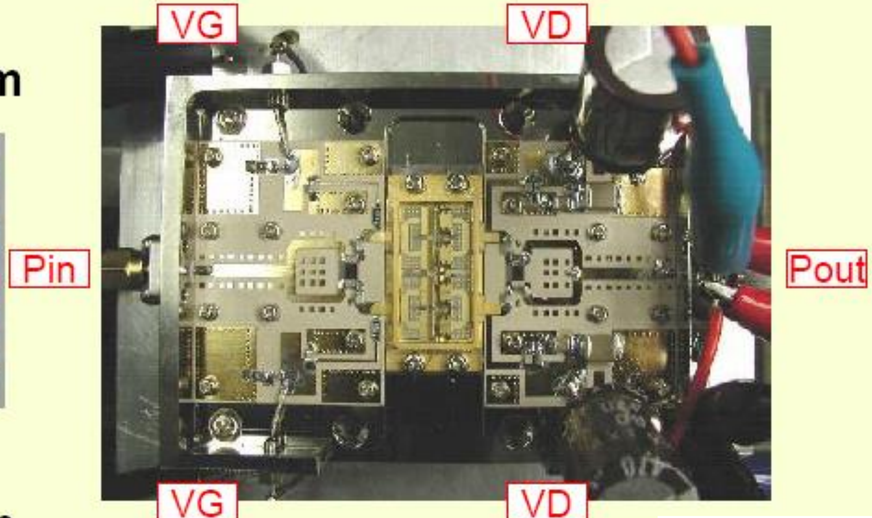


Power Gain at 150 Watts ~ 12.5 dB

S-Band GaN HEMT High Power Amplifier

GaN Chip : 4 x 36mm

Package size :
36.4 mm x 17.4 mm



Evaluation Board

Frequency = 2.9 GHz

Pout ~ 800 Watts

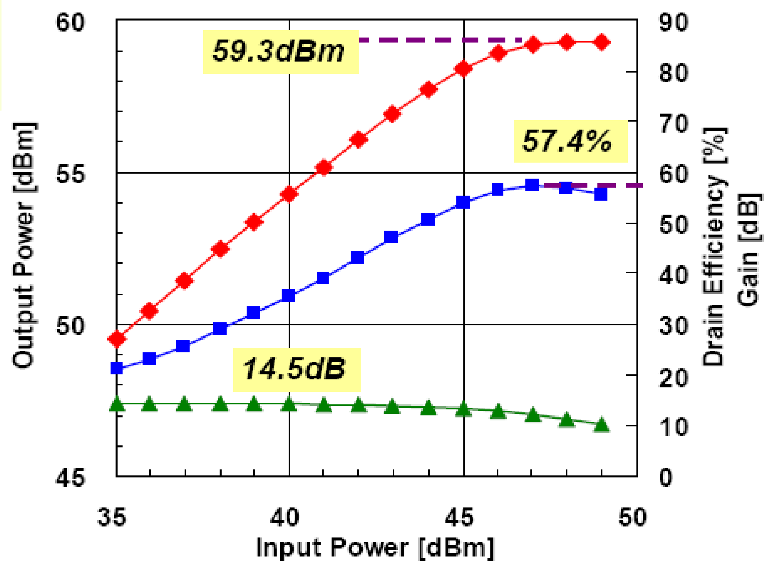
Bandwidth > 2.9 to 3.3 GHz

Vds = 65 V

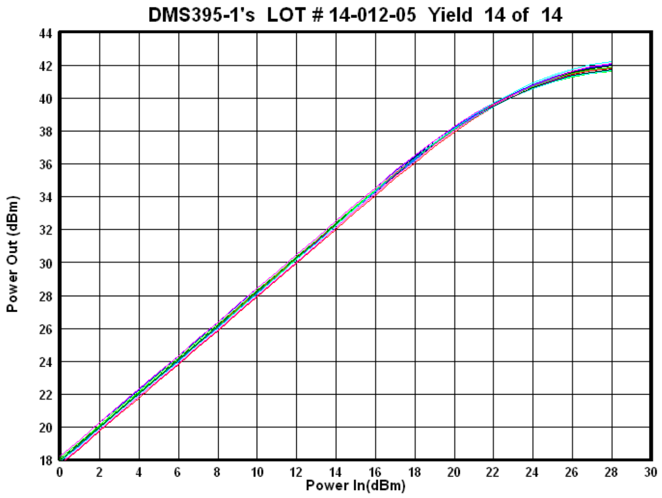
Idsq = 2 A

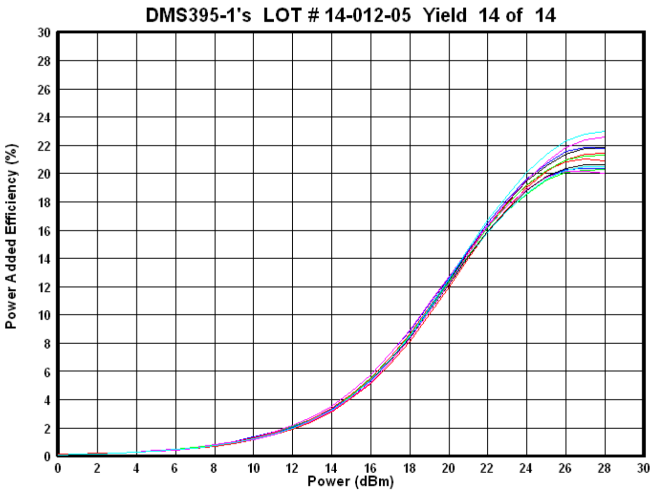
PW = 200 usec

Duty Cycle = 10 %

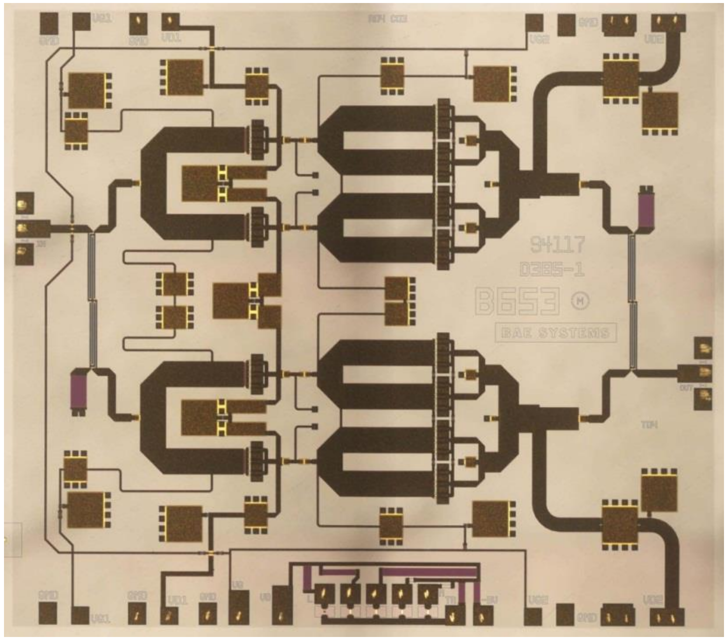


Ka-Band 0.2 μm NFP GaN HEMT MMIC HPA





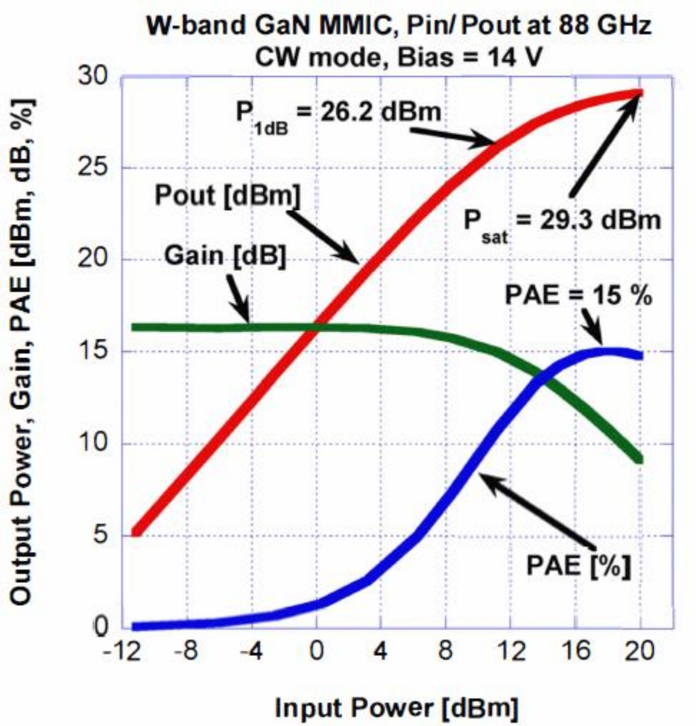
- **Process**: 0.2 um NFP GaN HEMT
- **Frequency Range: 34 to 36 GHz**
  - 14.8 - 15.8 Watts Pout
  - 21% PAE
- **Design Details**
  - Quadrature Balanced
  - Fast gate switching FRAP bias network
  - Vds = 20 to 34 Volts
  - 5.4 mm periphery, Idsq = 200 mA/mm
- **Chip Size**: 4.568 mm x 4.025 mm x 55 um

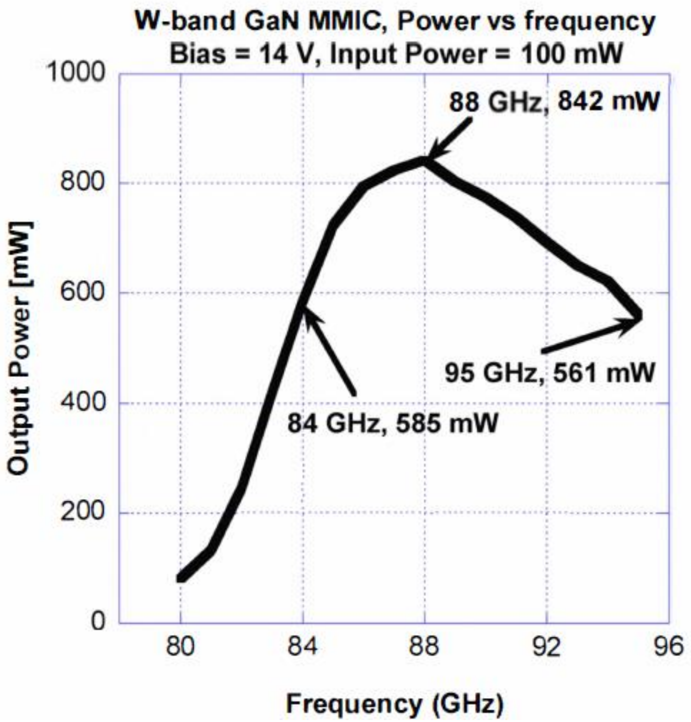


Highest MMIC CW Power Reported at Ka-Band

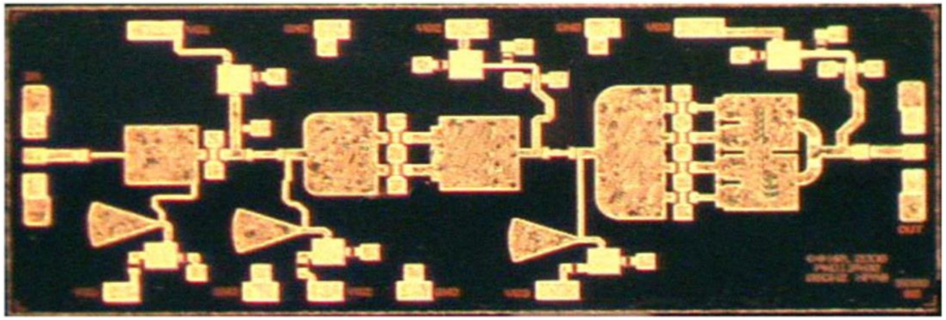
W-Band 0.15 μm GaN HEMT MMIC HPA

HRL LABORATORIES



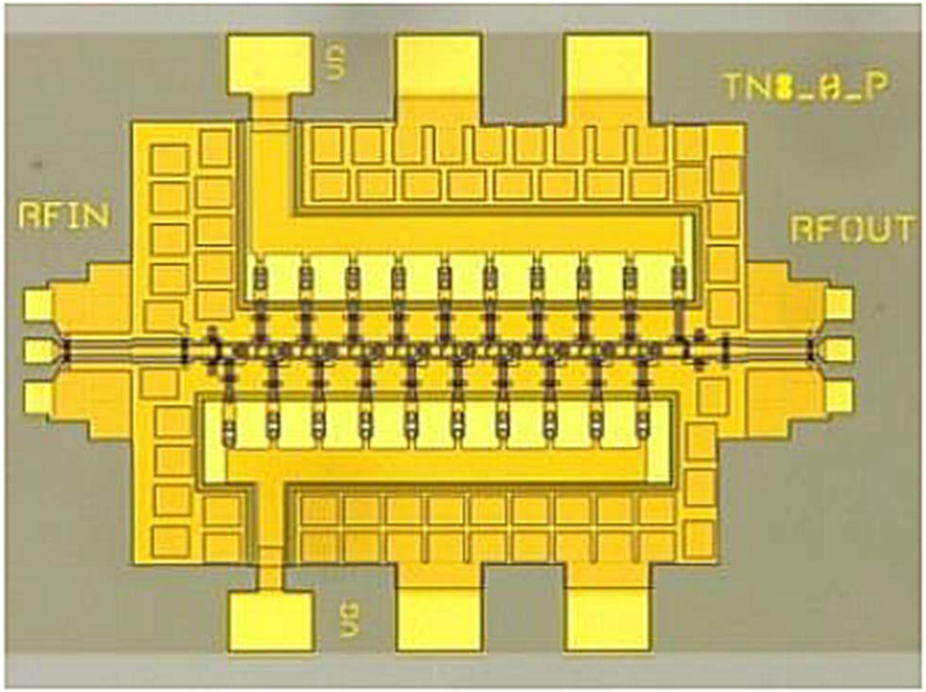


- **Process:** **0.15 μm GaN HEMT**
- **Frequency Range: 84 to 95 GHz**
  0.5 to 0.8 W @ 10-15 % PAE (2010)
  1.5 to 1.8 W @ 17.8 % PAE (2012 8-way)

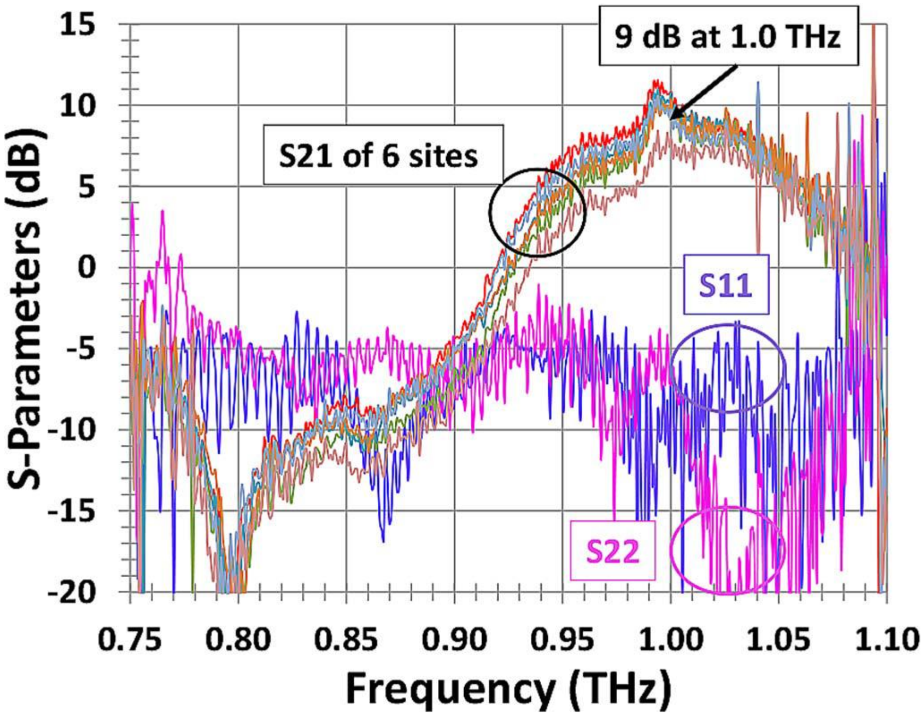


0.15 mm – 0.3 mm – 0.6 mm

1 THz InP HEMT MMIC



Ten stage InP HEMT MMIC



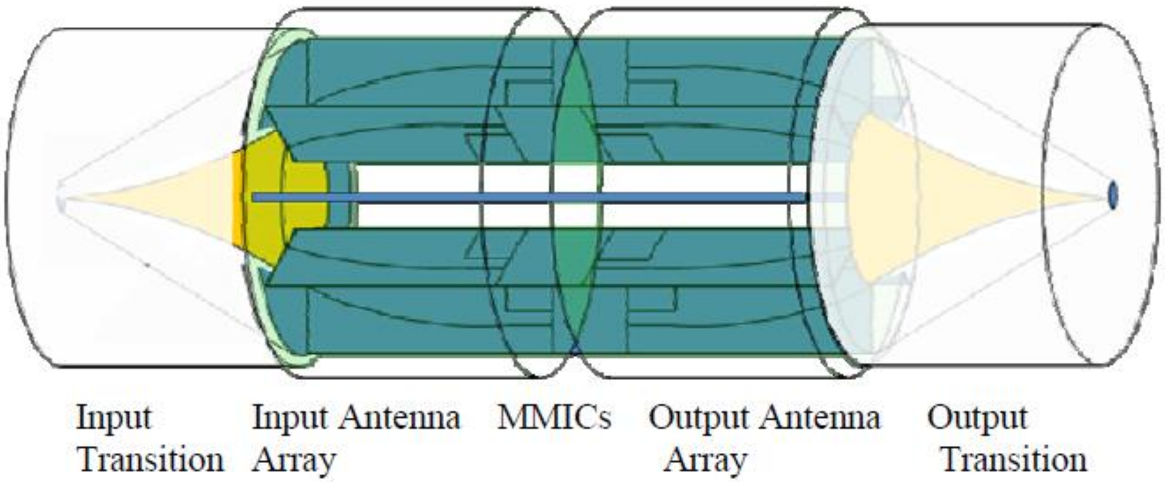
S-Parameters

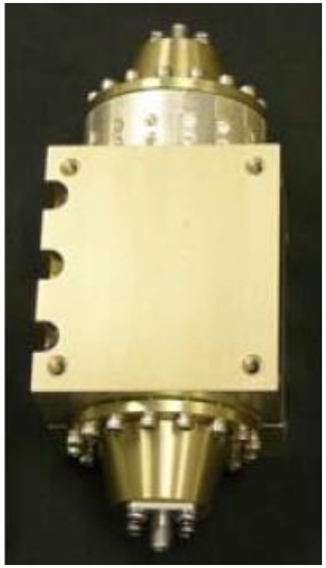
- **Process: 25 nm InP HEMT**
- **Application: THz**
- **Frequency Range: 0.95 to 1.05 THz**
  Pout 0.25 mW (estimated)
- **Chip Size:**
  550 um x 350 um x 18 um (WR-1.0 version)

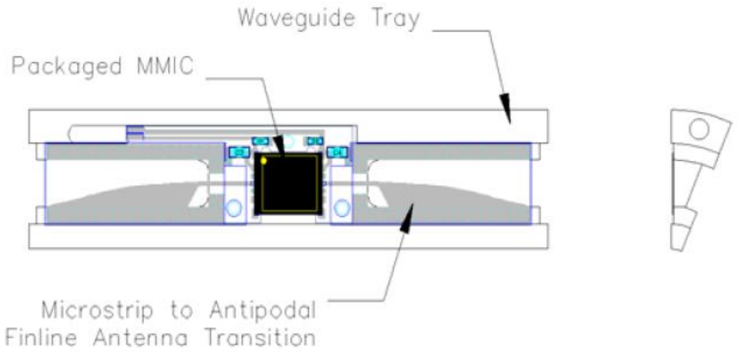
- **8 um transistor cell**
- **2 fingers x 4 um**
- **CPW MMIC**

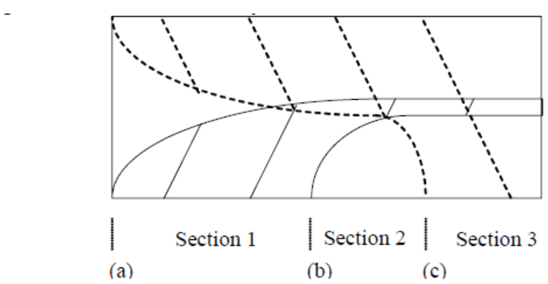
Coaxial Waveguide Spatial Power Combiner

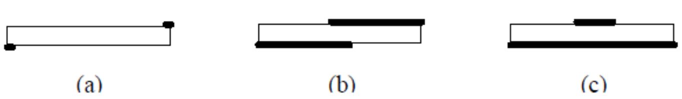
TriQuint CAP Wireless, Inc.





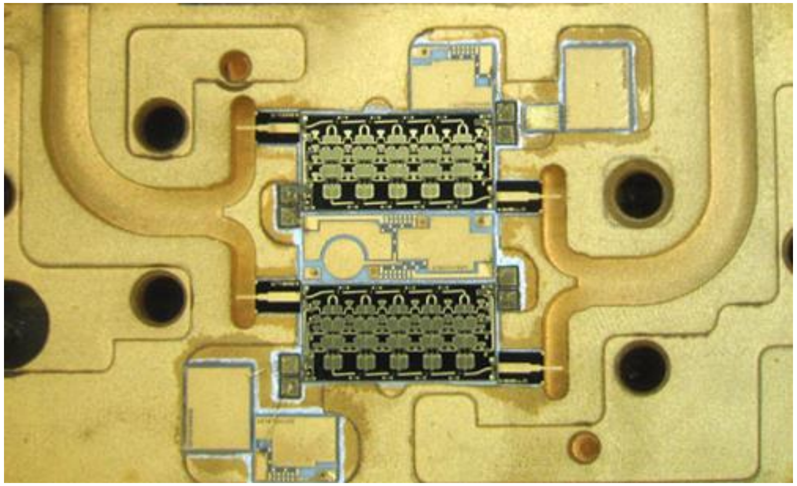




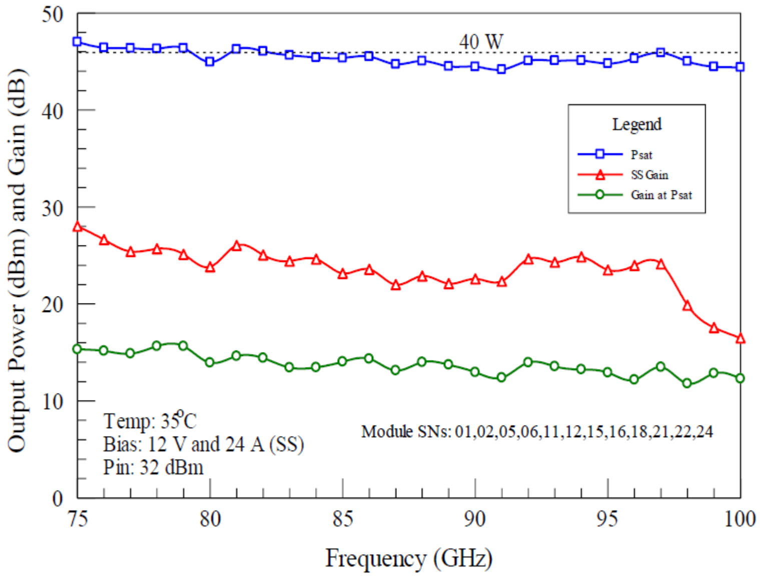


W-Band SSPA

QUINSTAR TECHNOLOGY, INC.



Two-chip module binary WG septum combiner, transitions, bias networks. Module dimensions are 2.05 x 0.57 x 0.19 inches.

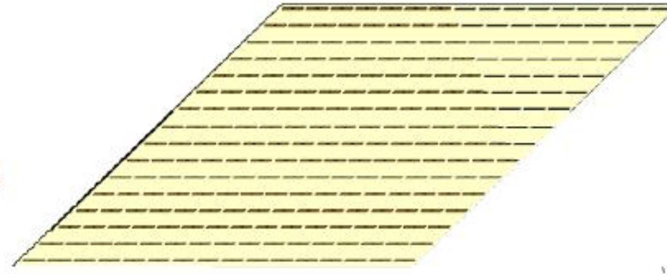


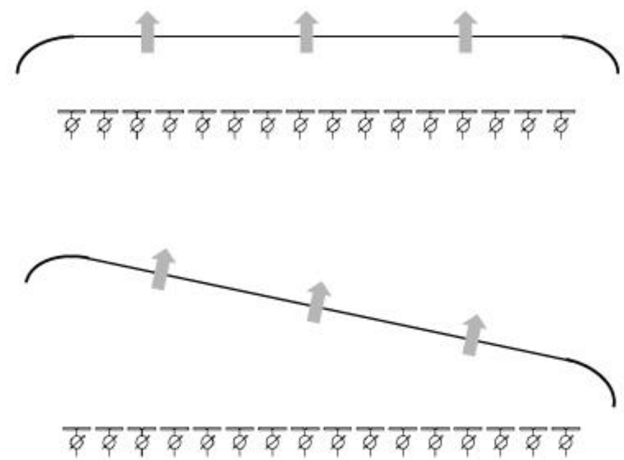
SSPA with the air-cooling fins attached. Mass of this unit is 0.47 kg and its dimensions are 2.4 inches dia x 2.5 inches.

J. Schellenberg, et al., “37 W, 75-100 GHz GaN Power Amplifier,” IMS 2016 Sym. Dig., May 2016.

Phased Array

An array of antennas in which the relative phases of the respective signals feeding the antennas are varied in such a way that the effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions.

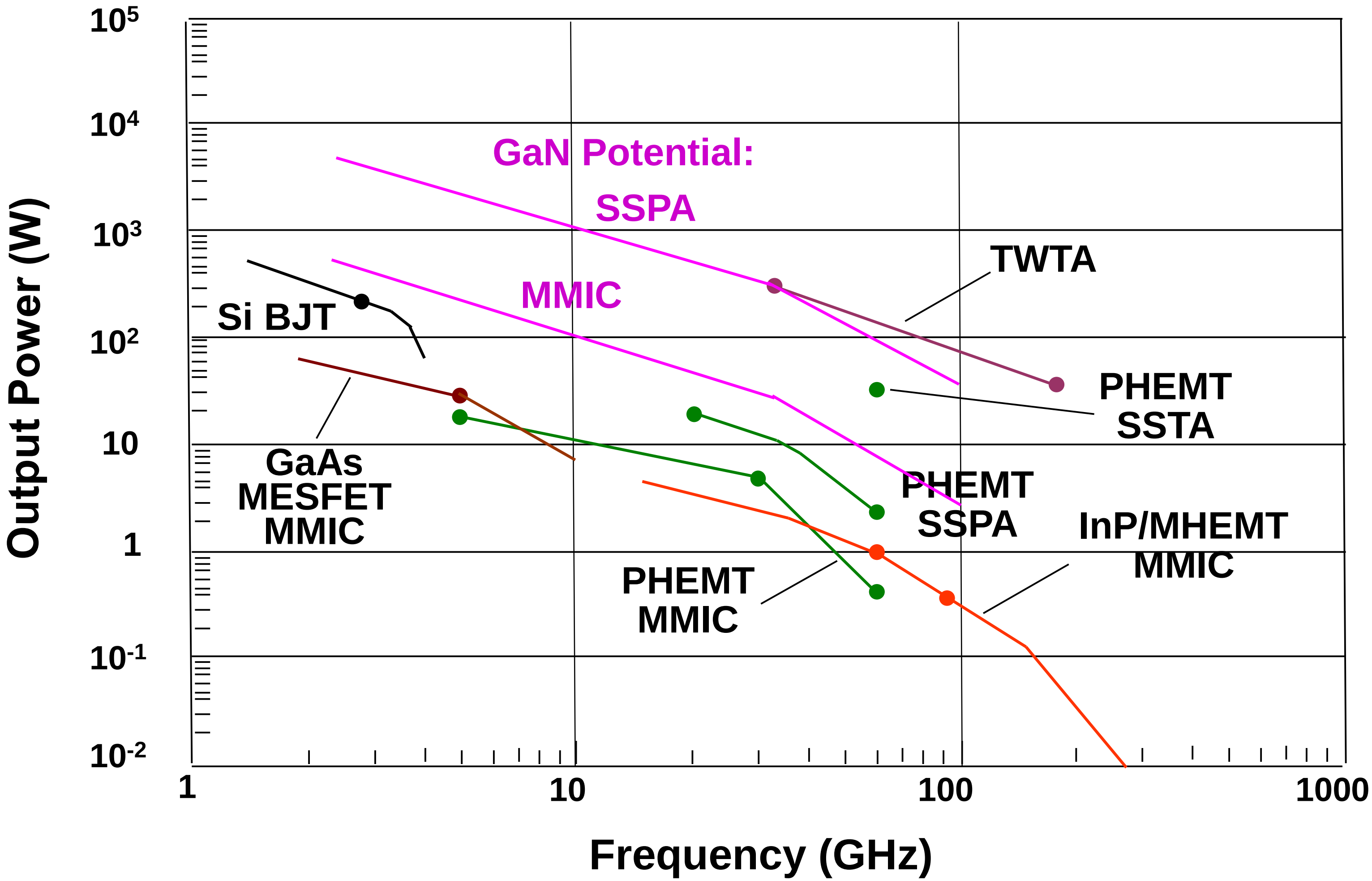




EIRP = $G_e \times P_e \times N^2$

High Power Solid State Transmit Technologies (not including Phased Arrays)

BAE SYSTEMS



GaN potential -- 10X increase in MMIC and SSPA power, 1-100 GHz

Future Trends

BAE SYSTEMS

- Circuit Technique Development & Implementation
  - Multi-tone with controlled distortion
  - STAR: Simultaneous Transmit and Receive
- Sub-Millimeter Wave Applications
- Thermal
  - Near Junction Thermal Transport (NJTT) – GaN on Diamond
  - Thermal Ground Plane (TGP) -- alloy heat spreader
  - IntraChip/InterChip Enhanced Cooling (ICECOOL) -- convective or evaporative microfluidic cooling built directly into devices or packaging
  - Microtechnologies for Air Cooled Exchangers (MACE) – enhanced heatsinks
  - Active Cooling Module (ACM) – miniature refrigeration systems based on thermoelectric or vapor-compression technologies
- Semiconductor Devices
  - Evolutionary
  - Diamond
  - Graphene, Carbon Nanotube
  - Boron Nitride
  - ? ? ?