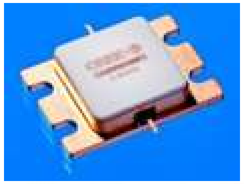
Summary of High Power Transistors available from Cree – 40/50 volt products

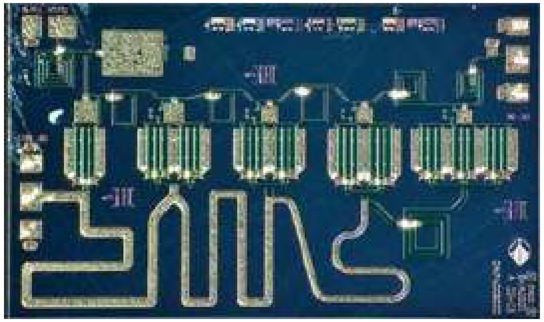
Product Name	Frequency, GHz	Small Signal Gain, dB	Output Power, Watts	Drain Efficiency, %	Drain Voltage, Volts	Application
CGHV09200F	0.68 – 0.96	23	240	65	50	Telecom
CGHV14250F	1.2 – 1.4	20	300	65	50	Radar (*)
CGHV14500F	1.2 – 1.4	20	500	52	50	Radar (*)
CGHV22100F	1.8 – 2.2	20	25 Pave	35 @ Pave	50	Telecom
CGHV22200F	1.8 – 2.2	18	50 Pave	35 @ Pave	50	Telecom
CGHV27100F	2.5 – 2.7	18	25 Pave	33 @ Pave	50	Telecom
CGHV27200F	2.5 – 2.7	16	40 Pave	29 @ Pave	50	Telecom
CGHV50200F	4.4 - 5	14	170	52	50	Satcom
CGHV96050F	8.4 - 9.6	10	80	55	40	Radar/Satcom
CGHV96100F	8.4 - 9.6	10	145	45	40	Radar/Satcom

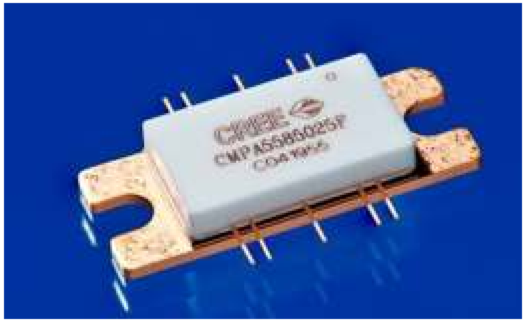
(*) Typically 300 [redacted]ec pulse width and 10% duty factor



Summary of High Power MMICs available from Cree

Product Name	Frequency, GHz	Small signal gain, dB	Output Power, Watts	Drain Efficiency, %	Drain Voltage, Volts	Application
CMPA2735075	2.7 – 3.5	27	75	56	28	Radar
CMPA2560025	2.5 – 6.0	24	25	33	28	General Purpose
CMPA5585025	5.5 – 8.5	30	40	43	28	Satcom/P2P
CMPA801B025	8.0 – 11.0	24	37	37	28	Satcom/Radar
CMPA1D1E060	13.75 – 14.5	21	60	40	40	Satcom





Examples of Note-Worthy High Power GaN HEMT Transistors

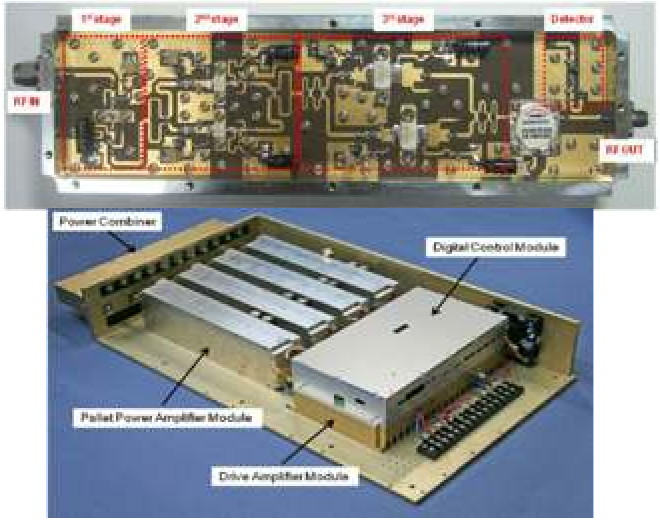
Manufacturer	Part #	Frequency, GHz	Power Gain, dB	Output Power, Watts	Drain Efficiency, %	Applications
Integra	IGN2729M500	2.7 – 2.9	12	570	60	Pulsed Radar
M/A-Com	MAGX-001214-250L00	1.2 – 1.4	17.7	250	58	Pulsed Radar
Mitsubishi	MGFK47G3745	13.75 – 14.5	9 (linear)	50	30	Satcom
RFMD	RF3928	2.8 – 3.4	10	280	54	Pulsed Radar/Air Traffic Control
RFMD	RF3928B	2.8 – 3.4	11.8	380	50	Pulsed Radar/Air Traffic Control
SEDI	SGN2933-600D-R	2.9 – 3.3	12.8	600	50	Pulsed Radar
Toshiba	TGI1314-50L	13.75 – 14.5	8 (linear)	50	30	Satcom
Triquint	TGF2023-20	14.0	5.1	50	40	General Purpose

As of January 2013

Examples of Hardware Realizations

Application Areas for High Power GaN HEMT Power Amplifiers

Military and Weather Pulsed Radars

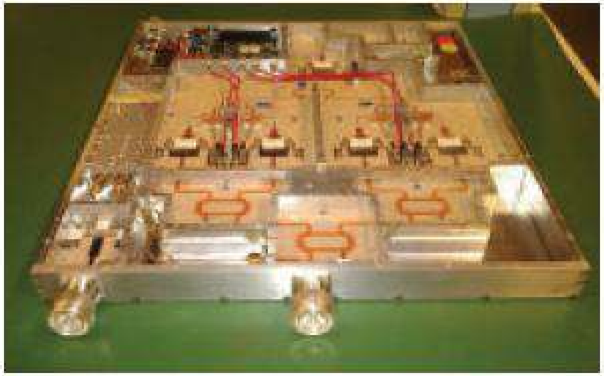


Courtesy: Department of Electronics Convergence Engineering, Kwangwoon University South Korea. Agency for Defense Development , South Korea

Space (Satellite and Radar)

A. Katz, B. Eggleston, and D. McGee, “A linear GaN UHF SSPA with record high efficiency,” in IEEE MTT-S Int. Microwave Symp. Dig., Boston, MA, June 7–12, 2009, pp. 769–772.

Satellite Communications



Courtesy: Teledyne Paradise Datacom

High Peak/Average Power Telecommunications (500 Watts at high efficiency)

Courtesy: RFHIC

ARMMS
RF & Microwave Society

Examples of Note-Worthy 50 ohm Matched GaN HEMT Power Pallets and Amplifiers

Company	Part #	Frequency, GHz	Power Gain, dB	Output Power, Watts	Drain Efficiency, %	Applications
RFHIC	RUP15050-12	0.5 – 2.5	55	50	30	Broadcast/ Comms
M/A-Com	MAPG-001214-450L00	1.2 – 1.4	17	450	50	Pulsed Radar
RFHIC	RRP291K0-10	2.7 – 3.1	60	1100	35	Pulsed Radar
CPI	VSS3607	2.7 – 2.9	>60	1300	33	Pulsed Radar
SEDI	SMC2933L6012R	2.9 – 3.3	13.6	800	52	Pulsed Radar
Comtech PST	BME2969-200	2.0 – 6.0	56	200	24	EW/Comms
Microsemi	AML811P5013	7.8 – 11.0	50	80	25	Satcom/Space

As of January 2013

Courtesy: M/A-Com

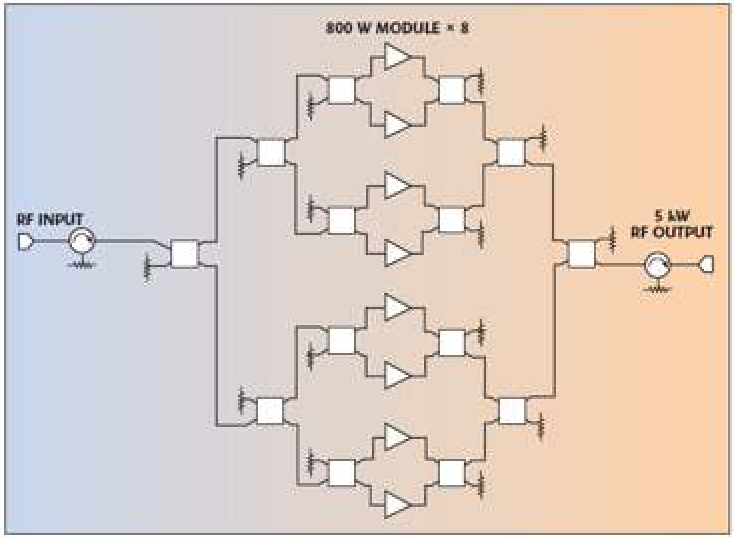
Courtesy: Microsemi

Courtesy: RFHIC

Courtesy: Comtech PST

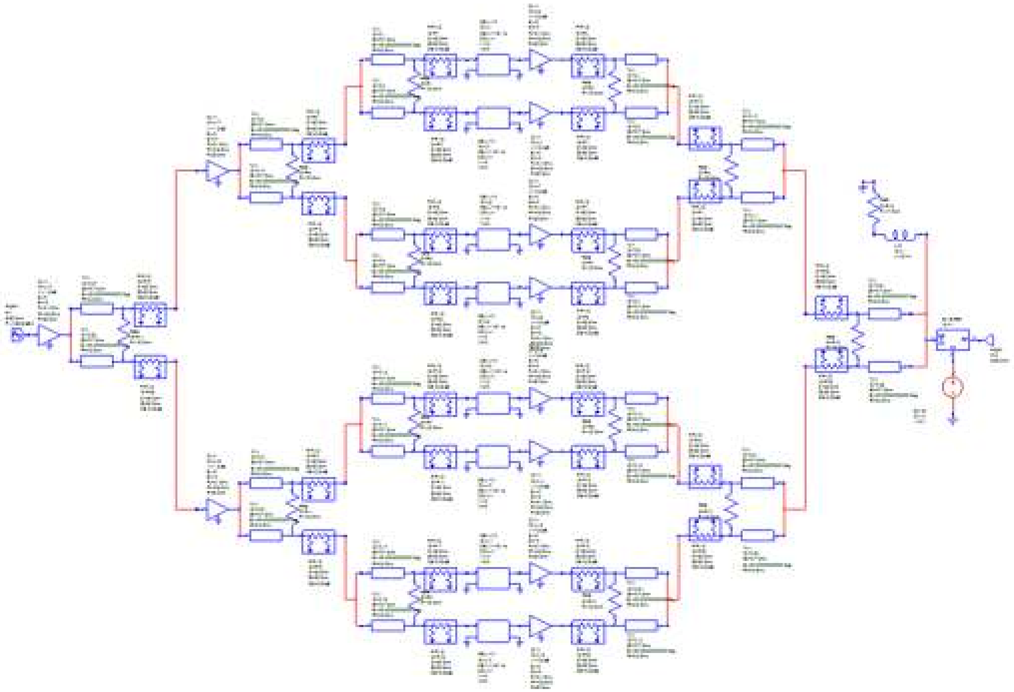
CREE

Examples of Microstrip Combined GaN HEMT Modules



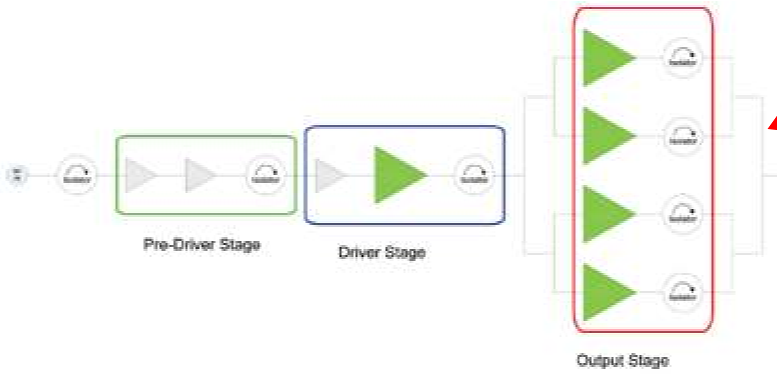
5kW S-Band SSPA Pallet
(8 GaN HEMT Modules)

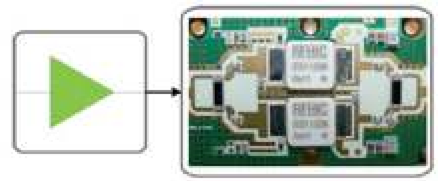
- High Transistor Efficiencies
- Effective Thermal Management
- Low Loss Power Combining
- Graceful Degradation



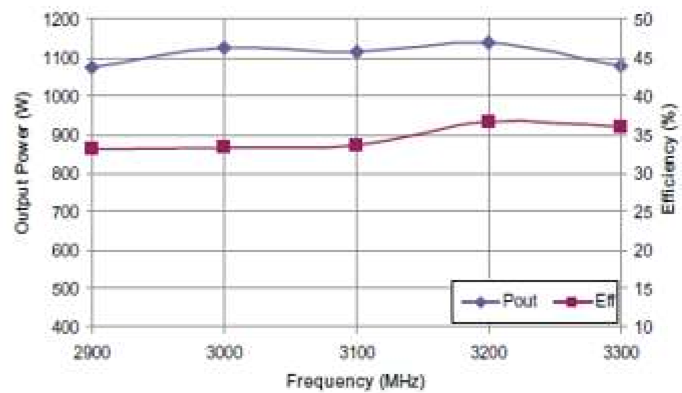
1kW X-Band SSPA Pallet
(10 GaN HEMT Modules + MMIC Driver)

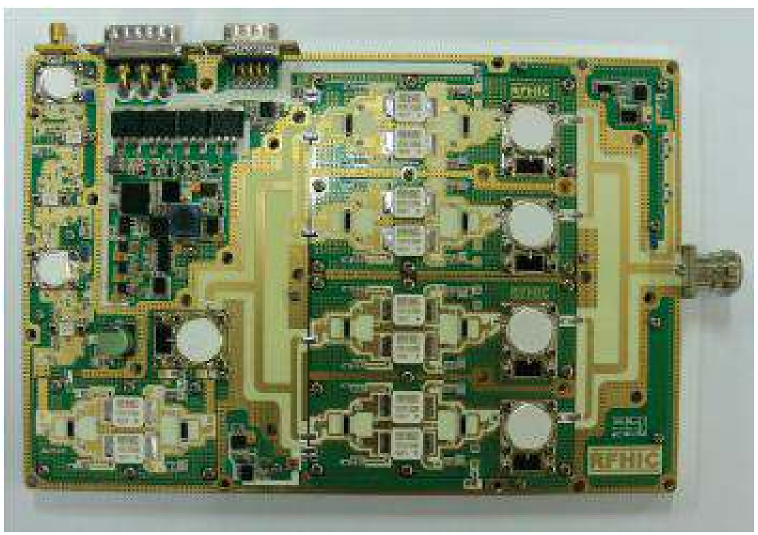
Radar – 1 kW, S-Band GaN HEMT Power Amplifier



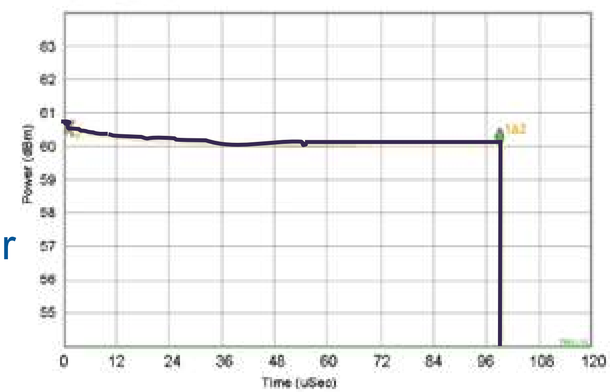


Use Cree GaN-0n-SiC HEMTs



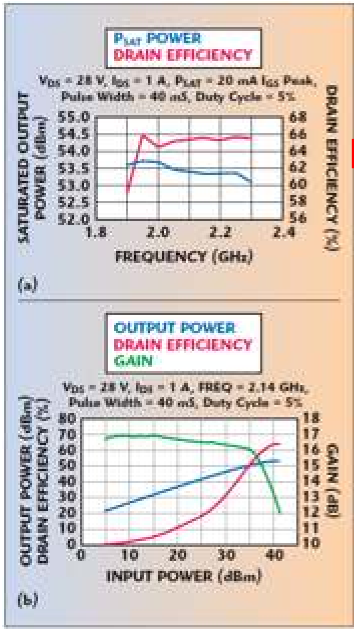


2.9 to 3.3 GHz
Pulsed Radar
100 [redacted]ec,
10% duty factor

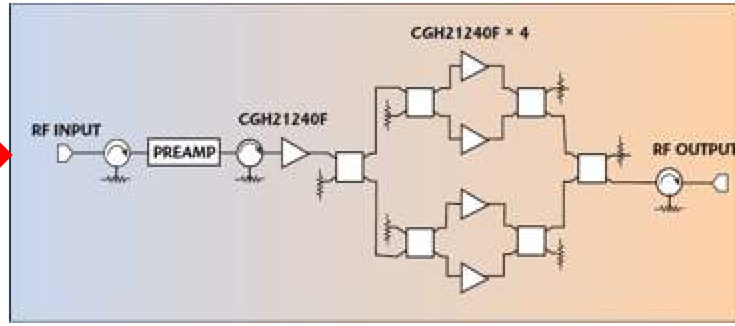


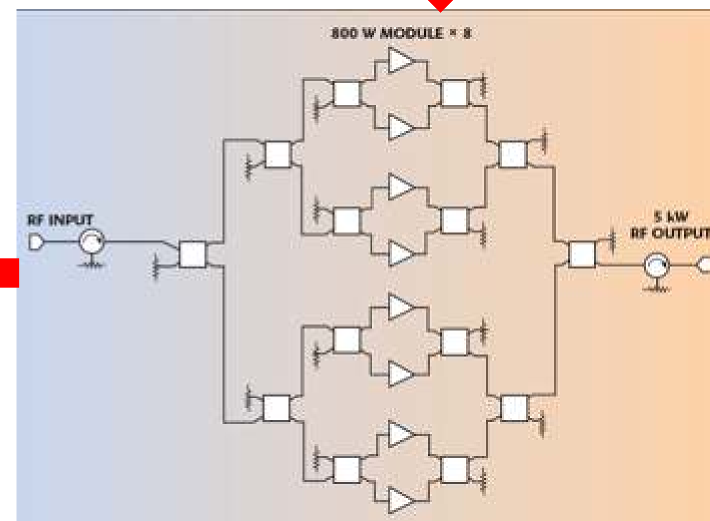
Reference: "1kW S-band Solid State Radar Amplifier" Ju-Y. Kwack, Ki-W. Kim, S. Cho, IEEE Wamicon 2011

Satcom – 10 kW, S-Band GaN HEMT Power Amplifier

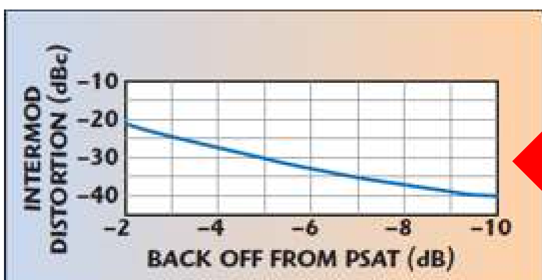


CGH21240F Performance at 28 volts





Graceful Degradation – Failure of element power reduces by 10 log (good/bad)^2 dB

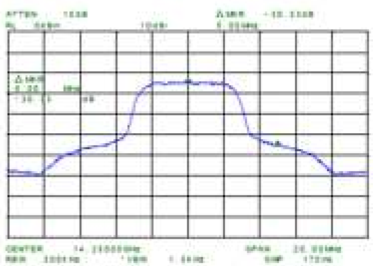


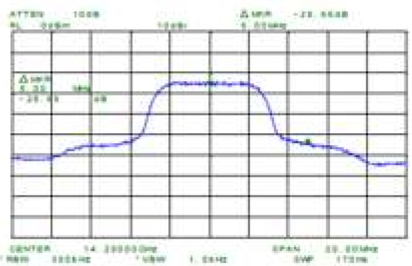
Reference: "SSPA Technology Achieves 10 kW CW at S-Band", S.D. Turner and T. Dekker, Microwave Journal, October 2012

Satcom – 400 W, Ku-Band GaN HEMT Power Amplifier Comparison with GaAs

No.	Operating Power	400W Ku-band GaN	400W Ku-band GaAs
1	55 dBm	-30.3 dBc	-28.6 dBc
2	54 dBm	-35.7 dBc	-29.3 dBc
3	53 dBm	-37.5 dBc	-34.3 dBc
4	52 dBm	-38.3 dBc	-37.6 dBc

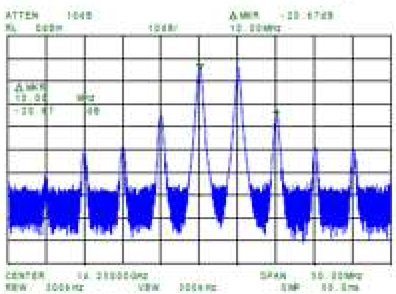
Spectrum Regrowth, GaN versus GaAs, 400W Ku-band SSPA

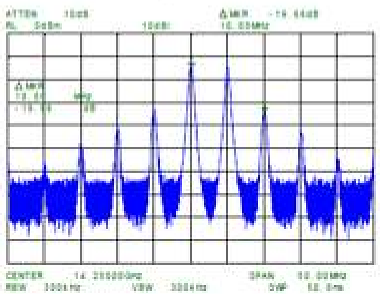

GaN SSPA, 55 dBm output


GaAs SSPA, 55 dBm Output

No	Operating Power	400W Ku-band GaN	400W Ku-band GaAs	750W Ku Non linearized TWT
1	54 dBm	- 20.67 dBc	- 19.86 dBc	- 18 dBc
2	53 dBm	-26.63 dBc	- 23.16 dBc	- 20 dBc
3	52 dBm	-31.63 dBc	- 27.50 dBc	- 22 dBc

Third Order Intermodulation products, GaN versus GaAs, versus TWTA


Intermodulation 400W Ku-band GaN, 54dBm


Intermodulation 400W Ku-band GaAs, 54 dBm

No	Operating Power	400W Ku-band GaN	400W Ku-band GaAs	750W Non linearized TWTA
1.	55 dBm	1.5° / dB	2.5° / dB	4.0° / dB
2.	54 dBm	1.0° / dB	2.0° / dB	3.5° / dB
3.	53 dBm	0.8° / dB	1.5° / dB	3.0° / dB
4.	52 dBm	0.5° / dB	1.0° / dB	2.5° / dB

AM/PM, GaN versus GaAs, versus TWTA

Parameter	400W Ku-band GaN	400W Ku-band GaAs	750W TWTA
Weight	30 Kg	80 Kg	37 Kg
Volume	29 dm^3	142 dm^3	74 dm^3
Energy Consumption	2,200 W	3,500 W	2,500 W

Weight , volume, and energy consumption GaN versus GaAs, versus TWTA

Acknowledgement: "A new generation of Gallium Nitride (GaN) based Solid State Power Amplifiers for Satellite Communication", C. Damian and D. Gelerman, Advantech Wireless Inc, 2012

Satellite Communications in Space – 100 Watt, S Band GaN HEMT Power Amplifier (1)

Travelling Wave Tube Amplifier (TWTA)

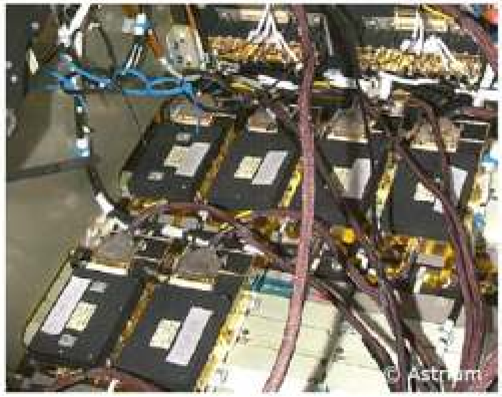
- Good for high saturated powers
- Physically long (C-band 381x78.7x73.6mm)
- Overall Mass is high (C-band 1990grm)

Solid State Power Amplifiers (SSPA).

- Good for medium / high powers
- Physically Compact (C-band 236x135x49mm)
- Low Mass (C-band 1200grm)

Small Size	→ Accommodation
Low Mass	→ More Transponders
High Efficiency	→Thermal management
High Linearity	→Traffic capacity

- Increasing customer need to exploit the available spectrum for space communications across all satcom frequencies from UHF to Ka-Band.
- Frequency bands are limited, and competition for them is increasing,
- Consequently a demand for ever higher level of payload frequency reuse, flexibility and performance
- Capacity demands require high linearity in conjunction with good efficiency

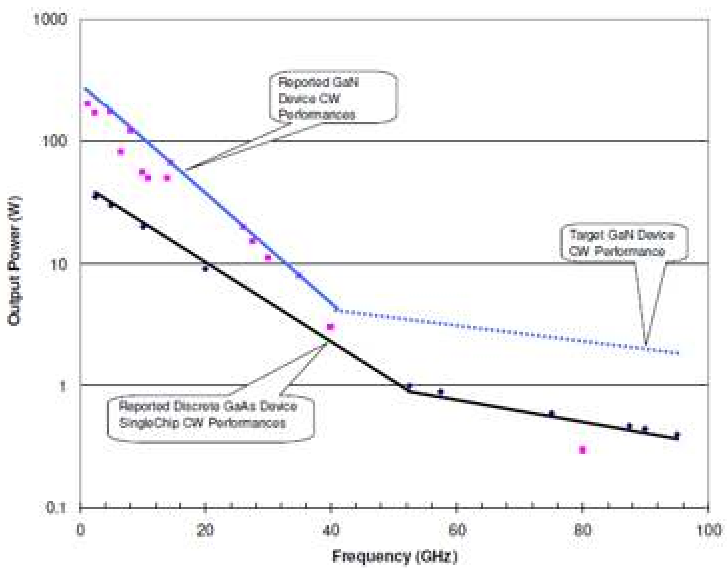


L-band SSPAs On Spacecraft

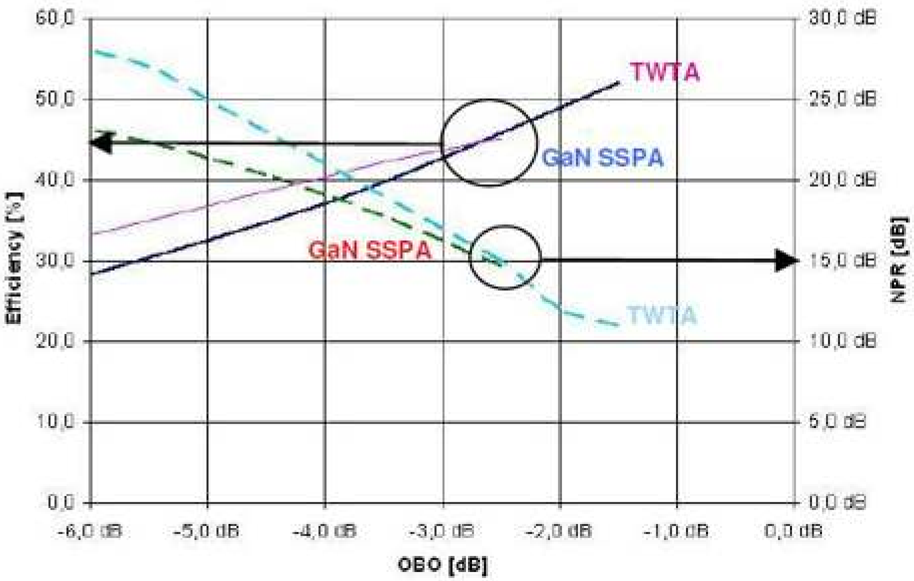
TWTA on Spacecraft

Courtesy: EADS Astrium Ltd.

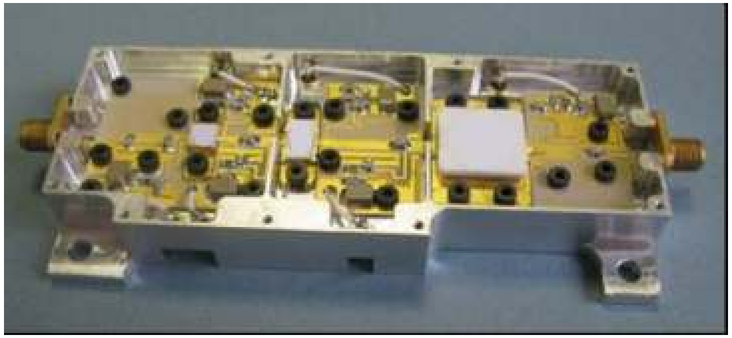
Satellite Communications in Space – 100 Watt, S Band GaN HEMT Power Amplifier (2)



Single chip power levels from GaN HEMT versus GaAs FET



Comparison of Class A/B GaN (un-linearized) and TWTA (linearized) amplifiers



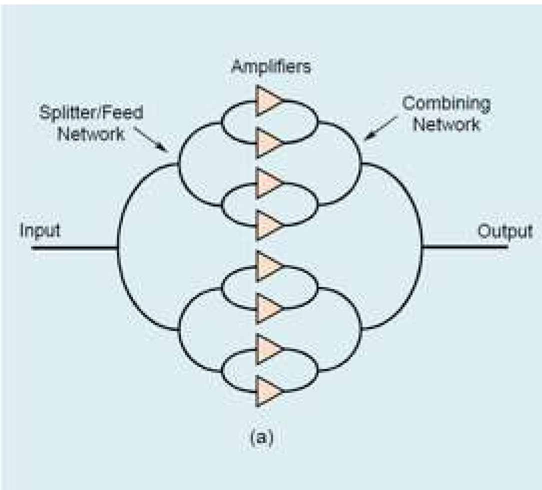
S-Band, 100 Watt GaN SSPA

GaN “drop-in” to GaAs. 3X the power at 40% efficiency

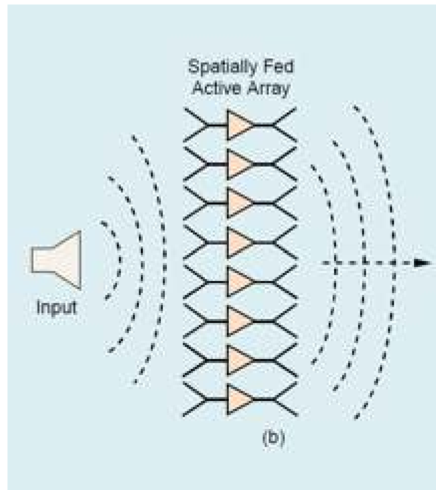
Courtesy: EADS Astrium Ltd.

Different Methods of Power Combining

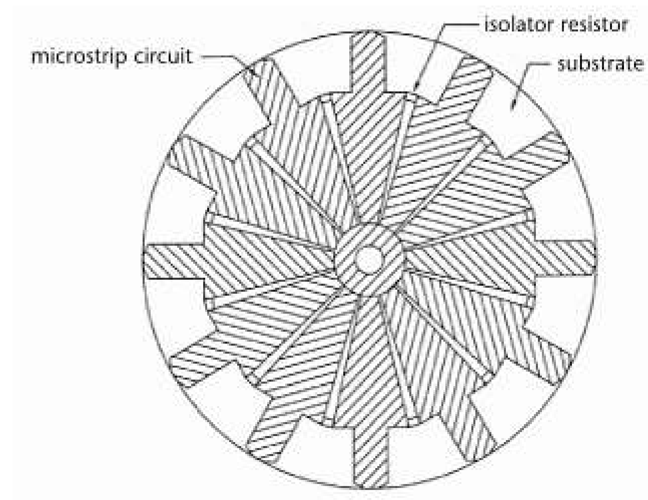
Conventional Power Combining vs. Spatial Combining and Radial Combining



Corporate Combiner



Spatial Combiner

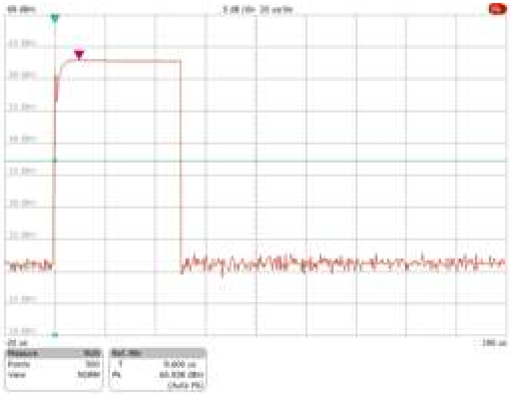


Radial Combiner

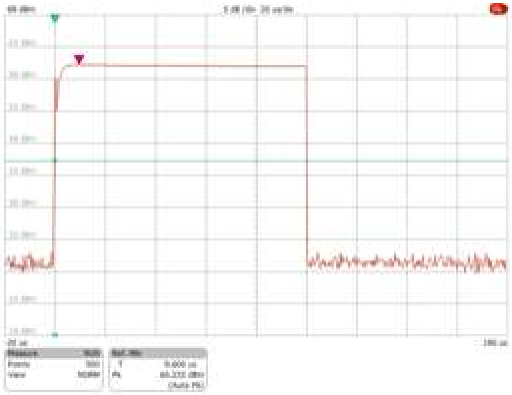
- Power Combining with multiple devices provides graceful degradation in the case of device failure
- Graceful Degradation – Failure of element power reduces by 10 log $(\text{good/bad})^2$ dB

X Band High Power Radial Combining Example

Examples of Radially Combined PA's using Cree GaN MMICs



9.345 GHz
100 [redacted]ec 10% DC
69 dB gain
1.23 kW
41% Efficient
2nd harmonic @ -36 dBc

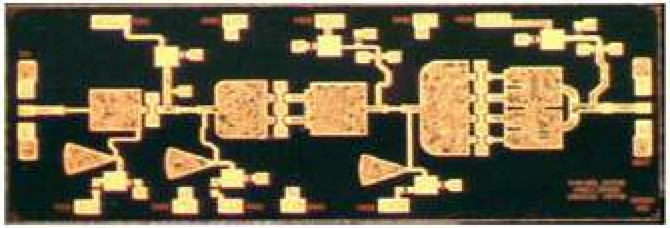


9.345 GHz
100 [redacted]ec 20% DC
69 dB gain
1.12 kW
41% Efficient
2nd harmonic @ -36 dBc

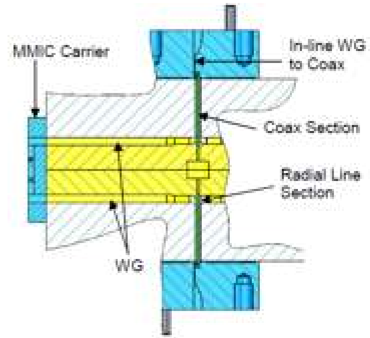
Complete Pulsed 1 kW X-Band Radar PA Demonstrator

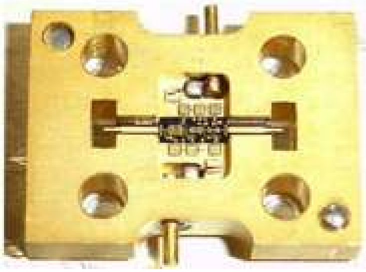
Courtesy: Keragis Microwave

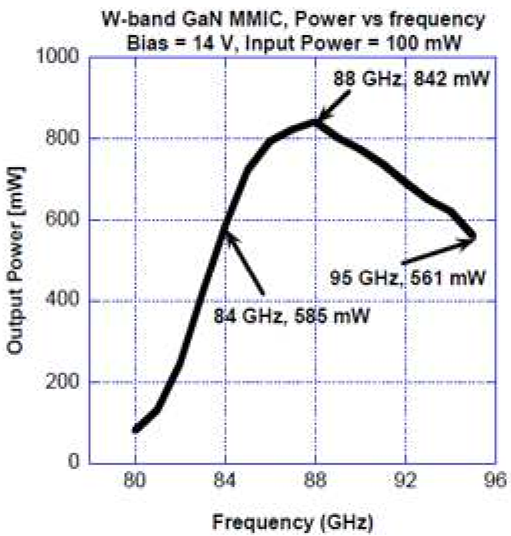
5 W, 95 GHz GaN MMIC Power Amplifier

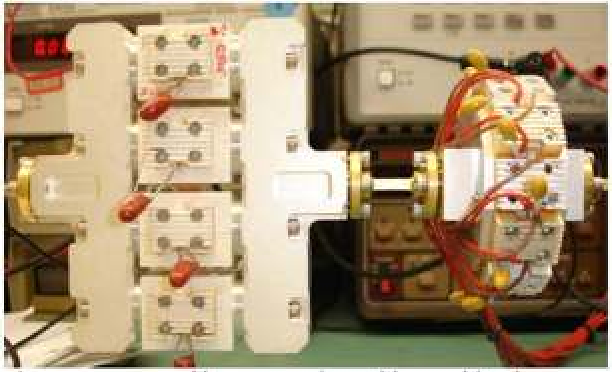


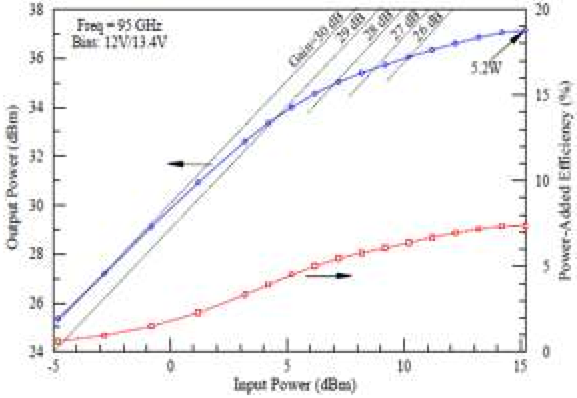
W-Band 0.15[redacted] GaN MMIC







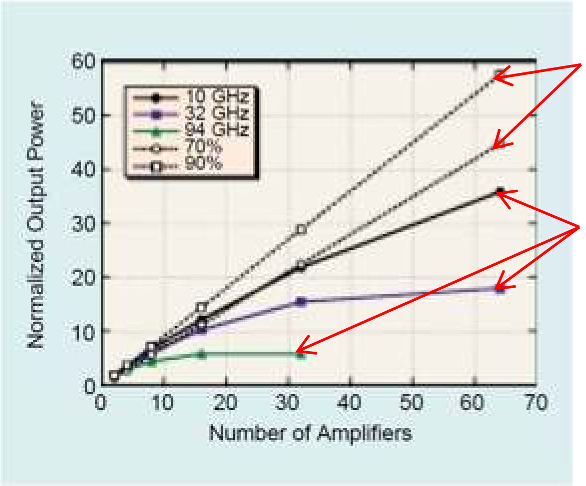




References: “W-Band GaN MMIC with 842 mW Output Power at 88 GHz”, M. Micovic, A. Kurdoghlian, K. Shinohara, S. Burnham, I. Milosavljevic M. Hu, A. Corrion, A. Fung, R. Lin, L. Samoska, P. Kangaslahti, B. Lambrigtsen, P. Goldsmith, W.S. Wong, A. Schmitz, P. Hashimoto, P. J. Willadsen and D. H. Chow; IEEE IMS 2010
“W-Band, 5W Solid-State Power Amplifier/Combiner”, James Schellenberg, Edward Watkins, Miroslav Micovic, Bumjin Kim, and Kyu Han; IEEE IMS 2010

High Power Spatial Combining of SSPA's

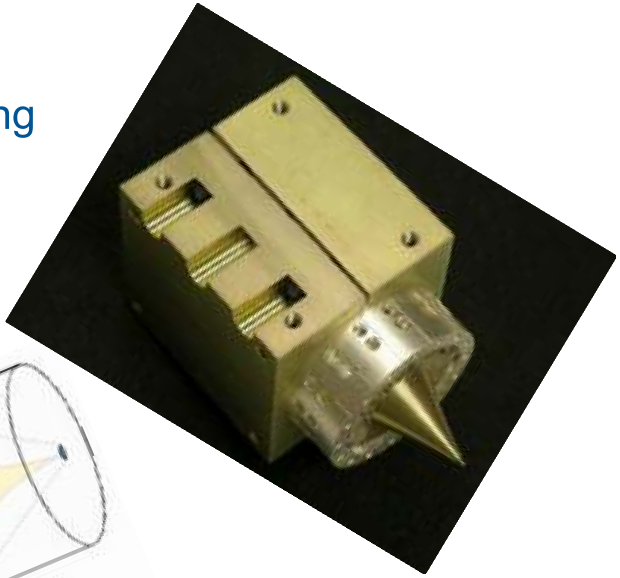
- **Principal of Operation**
  - Spatial Power Combining provides enhanced RF efficiency by coupling amplifiers to beams or modes in free space rather than via transmission lines in corporate combiners

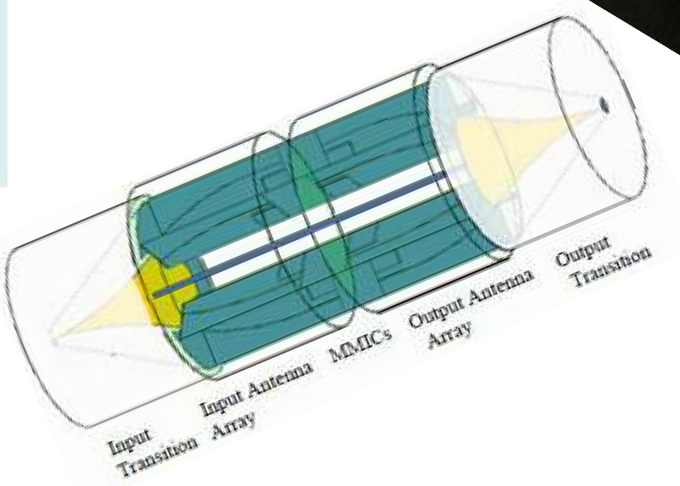


Range of Spatial Combining

Corporate Combining vs. frequency

Reference: Harvey et al,
IEEE Microwave Magazine, Dec. 2000





X-Band (8 to 12 GHz)
80 watts O/P Power
16 MMICs combined
40% efficiency
(CAP Wireless)

Conclusions

- Major market adoption of GaN HEMT Transistors and MMICs for both military and commercial applications
  - Significant number of device manufacturers worldwide
    - ✓ COTS, MOTS, Foundry and Captive Foundry
- Costs for GaN HEMT devices have decreased and continue to decrease significantly
- Advantages of SSPA's in terms of reliability, size, cost, manufacturability are outweighing tube-based solutions in many applications below 18 GHz
- Plethora of amplifier manufacturers employing GaN today
- Tubes (particularly TWTA's) will continue to hold certain market sectors particularly for very high power military applications

Acknowledgements

- Thanks for contributions to this presentation from the following companies:
  - Advantech
  - Aethercomm
  - Amplifier Research
  - CAP Wireless
  - Comtech PST
  - CPI
  - Keragis Microwave
  - Microsemi
  - Milmega
  - RFHIC
  - Teledyne Paradise Data
  - Quinstar