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A Review of Applications for High Power GaN HEMT Transistors and MMICs

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Summary

- Available High Power RF Markets for VEDs and GaN HEMTs
- Advantages of GaN HEMT Technology and Impact on High Power PA Engineering
- Reliability and Robustness
- Thermal Management
  - CW, Pulsed and Linear
- Examples of Commercially Available Devices
- Examples of Hardware Realizations
- Different Methods of Power Combining
- Conclusions

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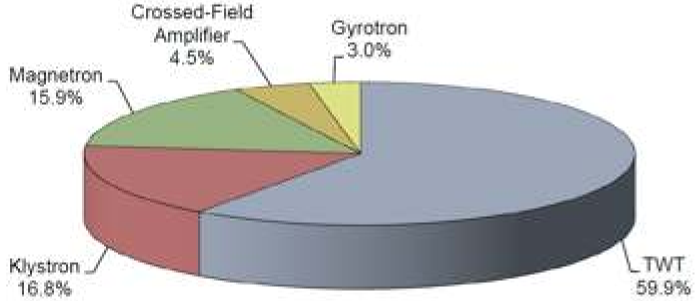
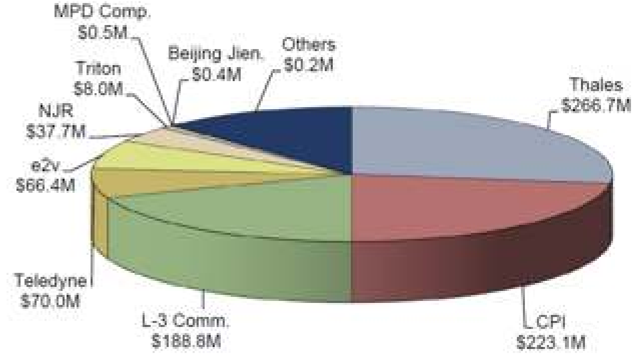
Available High Power RF Markets for VEDs and GaN HEMTs (1)

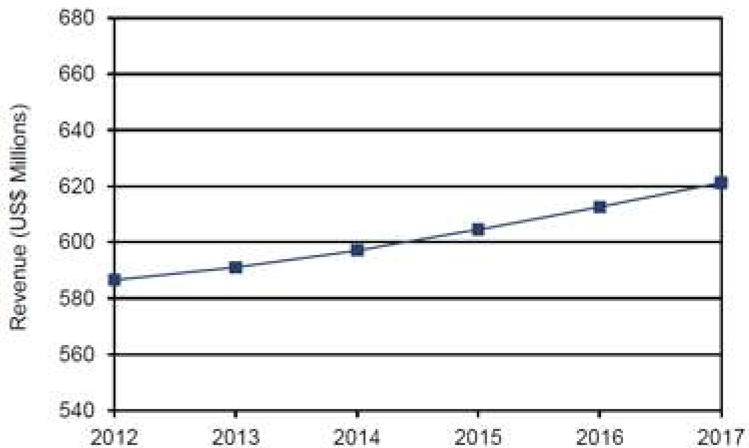
- Many microwave and mm-wave high power VEDs (vacuum electron devices) are designed for long lifetime programs that continue for decades
- Business forecast for VEDs is flat at a TAM of around $1B US per year up to 2017



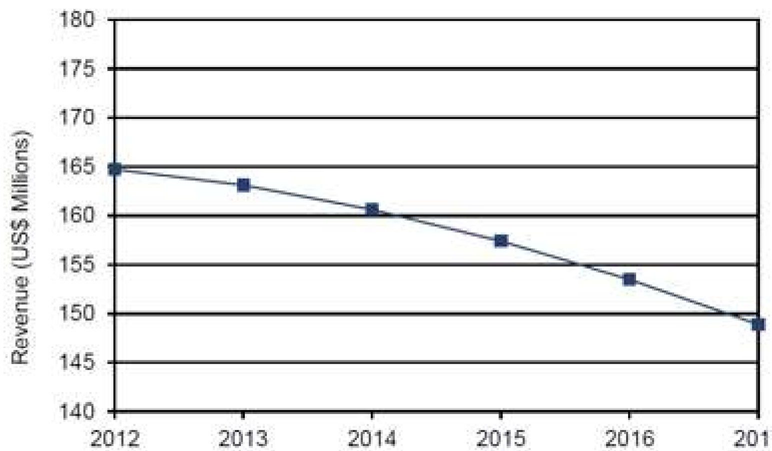
2012 Total VED Market Share by Type



2012 Total VED Market Share by Vendor



Total TWT Device Revenue by Year



Total Klystron Device Revenue by Year

Source: ABI Research October 2012

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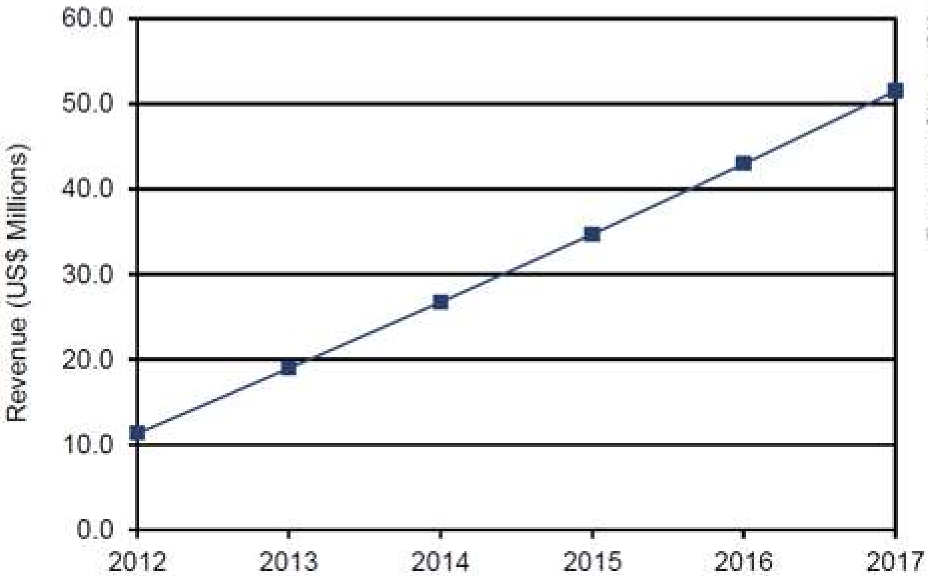
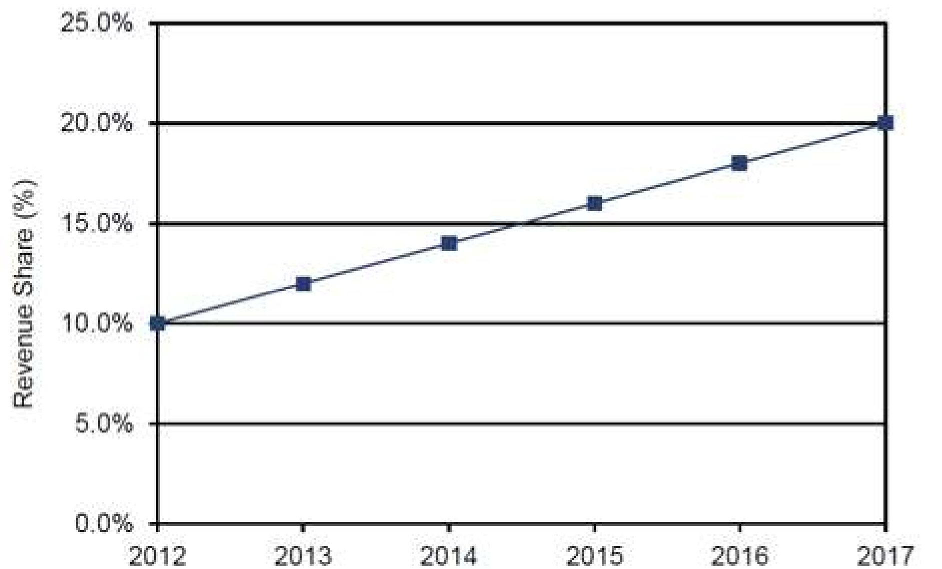
Available High Power RF Markets for VEDs and GaN HEMTs (2)

- GaN HEMT deployments to replace VEDs in many current equipments are limited by electromechanical and logistical reasons
- Opportunities for GaN HEMT deployments in new high power applications are very promising e.g. GaN HEMTs have been qualified for space applications

Total GaN Device TWT Application Replacement Revenue





Percentage of TWT Application Revenue Vulnerable to GaN Device Replacement

Source: ABI Research October 2012

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Advantages of GaN HEMT Technology and Impact on High Power PA Engineering

Summary of GaN HEMT Advantages

- As the state-of-the-art in solid state device technology advances, vacuum tube microwave devices used in high power electromagnetic systems as well as military radar systems are being replaced with solid state power amplifiers (SSPA's)
- Wide bandgap semiconductor materials like GaN HEMTs have potential to operate at power densities many times higher than Si-LDMOS, GaAs FET, and silicon carbide (SiC) devices
- High power density is an important factor for high power devices enabling smaller die sizes and more easily realized input and output matching networks
- GaN HEMTs have other advantages:
  - High breakdown voltages (200+ volts)
  - High saturated electron velocity
  - Good thermal conductivity
  - Low parasitic capacitances and low turn-on resistances
  - High cut off frequencies.

A Summary of TWTA and SSPA Advantages and Disadvantages

Function	TWTA		SSPA	
	Advantage	Disadvantage	Advantage	Disadvantage
Linearity and Intermodulation Distortion	No memory effects	Can have high harmonic content		Maybe memory effects
Available Output Power	Generally higher output power			
Efficiency of Operation i.e. AC Power Consumption	TWTA's are efficient in back-off state	High Voltage		Can be high currents
Size and Weight	Total TWTA package may be smaller		Basic RF modules are smaller than TWTA's	Heat sinks may make total size larger than TWTA's
Heat Dissipation	Heat dissipation over large area			Heat dissipation is a challenging problem
Reliability	Many years of reliable space operation	Tubes have limited life of 100,000 hours of operation	MTBF's proven to be greater than 1 million hours	Power supplies may be less reliable than RF transistors
Temperature Stability	Very stable over temperature			Solid state power amplifiers need temperature compensation

Reliability and Robustness

Different Amplifier Technologies for EMC Testing Applications

Amplifier	Linearity 1dB point	Harmonics at 1dB	Harmonics above 1dB*	Noise power density/ Spurious	Ability to handle VSWR*	Frequency coverage
Tube	Bad	Good	Worst	Bad	Best	Low freq. <250 MHz
TWTA	Worst	Worst	Worst	Worst	Worst	High freq. >1 GHz
Solid state Class A	Best	Best	Best	Good	Best	Full coverage
Solid state Class AB	Bad	Good	Good	Good	Good	Full coverage
Solid state Class B	Bad	Good	Bad	Best	Good to bad	Full coverage

* Results greatly depends on how the technology is implemented

Courtesy: G. Barth, Amplifier Research

Amplifiers and VSWR Withstand (1)

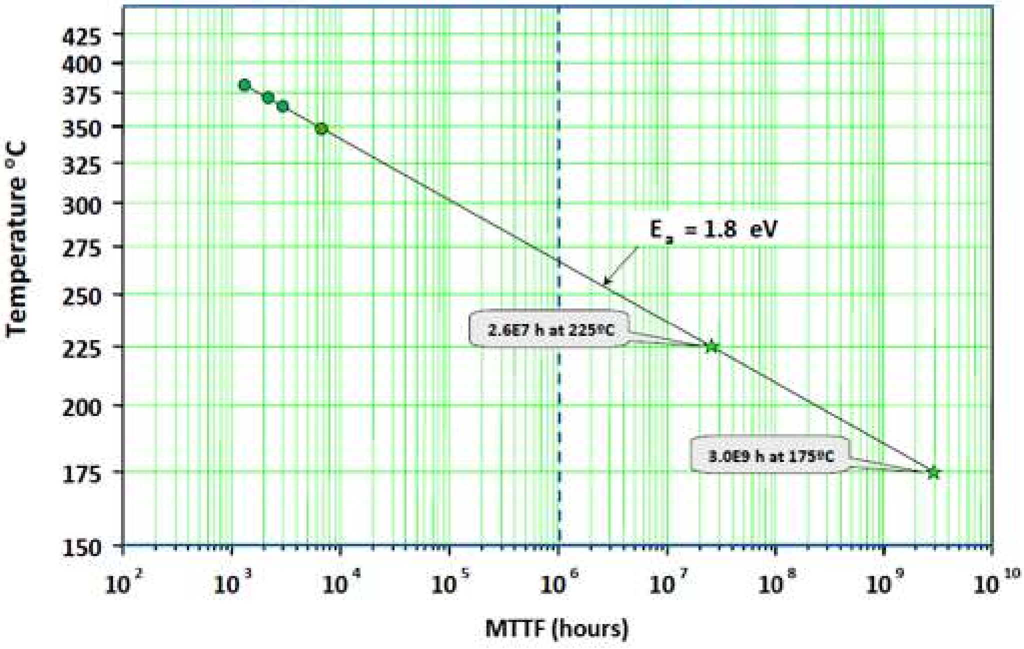
- TWTAs have a relatively low threshold to VSWR
    - The TWT will fail at high VSWR without protection or precautions.
    - 2:1 VSWR at rated power
        1. Fold back at 20% reflected power (best)
            - – pulsed amplifiers fold back at 50% reflected power
        2. Shutdown at 2:1 VSWR
        3. Rely on user to take responsibility to be proactive
- Low Power Solid State can have high threshold to VSWR
    - Dependent on technology used
        - Infinite VSWR handling, no protection needed

Amplifiers and VSWR Withstand (2)

- High Power Solid State PA's can have high threshold to VSWR
  - Dependent on the technology used
    - High VSWR handling, some protection required
    - GaN can usually handle up to 67% of rated power (10:1 VSWR) when used at full power
      - Folds back so that reverse power does not exceed reverse power limit
    - Latest LDMOSFETs claim to handle up to 94% of rated power
- Why can't higher power amplifiers handle infinite VSWR like lower power versions?
  - Combining
    - Components see up to twice the power (4x voltage and current)
    - Combiners also act as splitters and direct energy back to output stages
- GaN HEMTs because of high power density, high breakdown voltage and good thermal characteristics are ideal for broadband EMC testing PA's

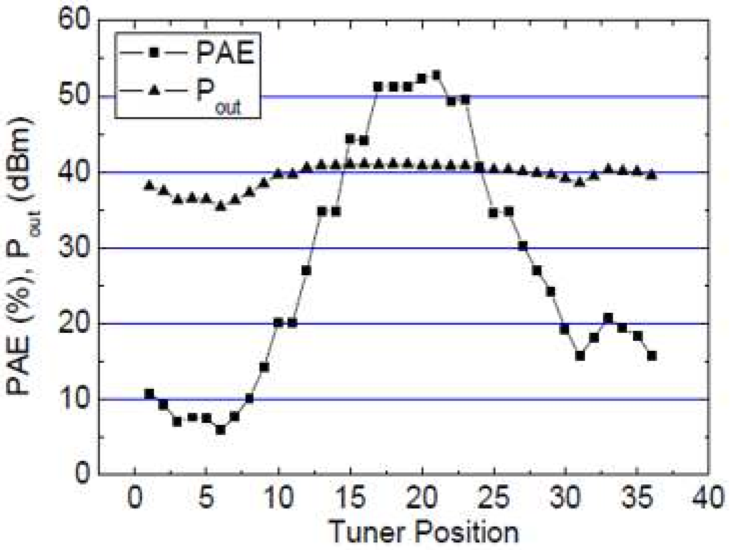
Reliability and VSWR Robustness of GaN HEMTs

Cree 28 volt qualified GaN HEMT process



MTTF at 225 deg C Channel Temperature is >20 million hours

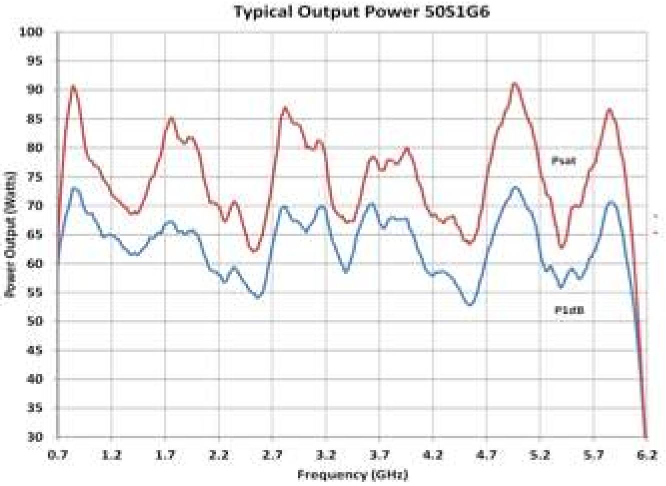
Robustness data from Fraunhofer Institute



Most GaN transistors are specified to withstand a 10:1 output mismatch at fully rated output power. Worst case in example above shows PAE of 7% and a maximum channel temperature of 278^{O}C but device does not fail

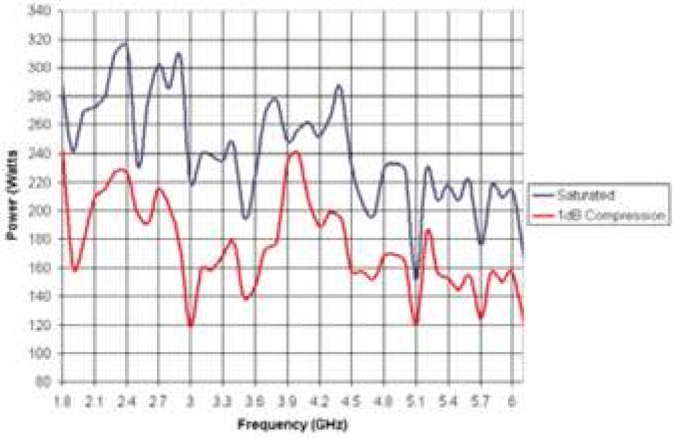
Broadband EMC Power Amplifier Examples

Amplifier Research



- **1 to 6 GHz GaN HEMT Power Amplifier**
  - >70 watts
  - 48 dB Gain
  - Mismatch tolerance of 100% without fold-back
  - 60 lb and 3400 cu. in.

Milmega



- **1.8 to 6 GHz GaN HEMT Power Amplifier**
  - 130 watts
  - 46 dB Gain
  - 100% tested into short and open
  - 103 lb and 3900 cu. in.

Thermal Management

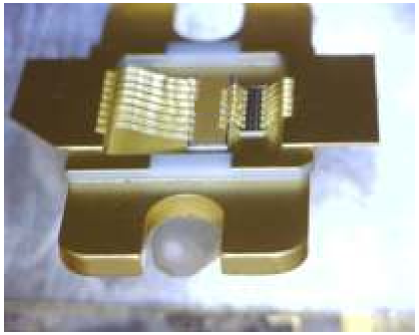
Thermal Management of GaN HEMT Transistors (1)

- GaN HEMTs (particularly at 50 volts) have very high RF power densities (typically 4 to 8 watts per mm of gate periphery) and high power dissipation per unit area
- Onus of heat dissipation is placed not only on die transistor design (dependent on mode of operation – e.g. CW versus pulsed or backed-off linear) BUT also on heat sink material and die attach

	CuW-10 10%Cu 90%W	CuMoCu 30%Cu 70%Mo	CMC Cu/Mo/Cu 1:1:1	CPC Cu/CuMo/Cu 1:4:1	Alumina
Thermal Conductivity, W/mK	197	190	260	220	35
Coefficient of Thermal Expansion, ppm/K	8	7.65	7.1	7.5 to 8.5	5.4

	Super CMC Cu/Mo multilayers	Aluminum Diamond/Silver Diamond
Thermal Conductivity, W/mK	370	>500/800
Coefficient of Thermal Expansion, ppm/K	6 to 10	7.5/<10

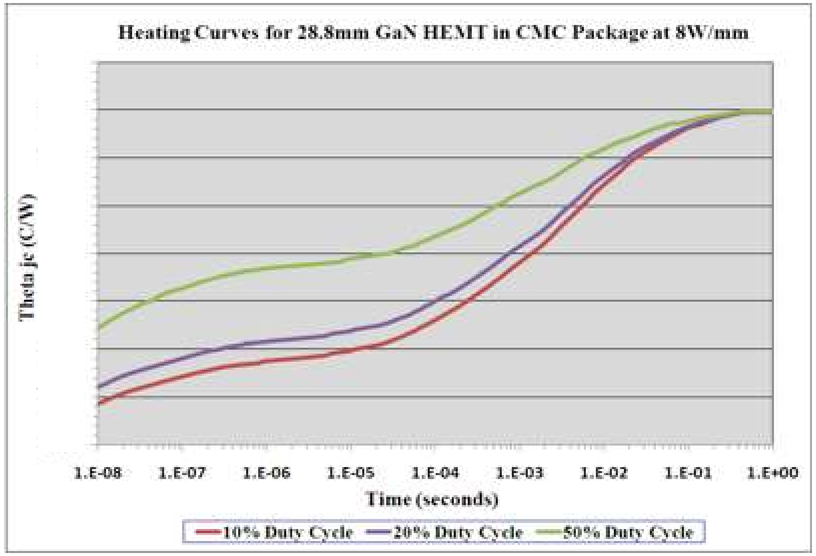
- Flange materials need
  - High thermal conductivity
  - Thermal expansion coefficient match to SiC and alumina ceramic ring frames
  - Stable properties such as
    - Bowing and flatness
    - Low surface roughness
    - Void free die attach

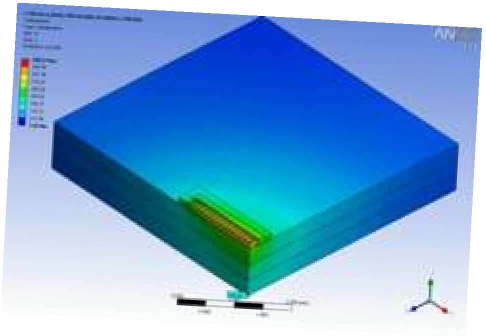


Thermal Management of GaN HEMT Transistors (2)

- For pulsed applications (large range of pulse widths and duty factors) the thermal resistance [redacted] is modeled as a function of time.
- Transient thermal analysis requires a knowledge of the properties of all the materials in the “stack” including die, solder, flange etc.

Material	Density (gm/cm^3)	Specific Heat (J/KgC)
GaN	6.1	490
SiC	3.1	681
Au	19.32	126
AuSn	14.5	150
Cu	8.3	385
Mo	10.3	250

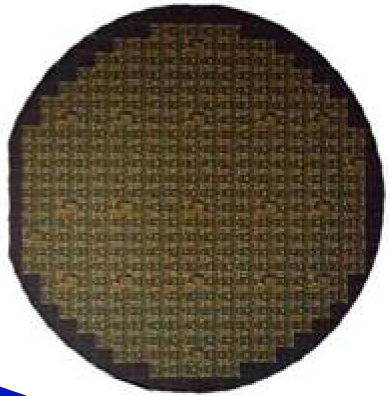


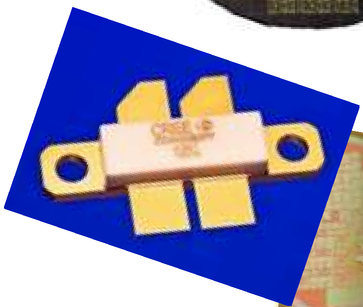


Examples of Commercially Available Devices

Some GaN HEMT Suppliers Worldwide

- ***COTS, MOTS and Foundry***
  - Cree
  - M/A-Com
  - Mitsubishi
  - RFMD
  - SEDI
  - Toshiba
  - Triquint
  - UMS
- ***Captive Foundry***
  - BAE Systems
  - Hughes Research Laboratories
  - Lockheed-Martin
  - Northrop-Grumman Aerospace Systems
  - Raytheon





Summary of High Power Transistors available from Cree – 28 volt products

Product Name	Frequency, GHz	Small Signal Gain, dB	Output Power, Watts	Drain Efficiency, %	Drain Voltage, Volts	Application
CGH40120F	Up to 2.5	15	120	70	28	General purpose
CGH40180PP	Up to 2.5	15	220	70	28	General purpose
CGH31240F	2.9 - 3.1	12	250	60	28	Radar
CGH35240F	3.1 - 3.5	11.5	240	57	28	Radar
CGH09120F	UHF - 2.5	21 @ 0.9	20 Pave	35 @ Pave	28	Telecom
CGH21120F	1.8 - 2.3	15	20 Pave	35 @ Pave	28	Telecom
CGH21240F	1.8 - 2.3	15	40 Pave	33 @ Pave	28	Telecom
CGH25120F	2.3 - 2.7	13	20 Pave	30 @Pave	28	Telecom

Lower power transistors are also available to provide complete PA line-ups