GaN PAs for Microwave EME

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Gallium Nitride (GaN) FETs show great promise for use in solid state power amplifiers (SSPAs) for microwave EME applications. This paper will discuss what GaN technology has to offer and why it is of interest to amateurs. It will attempt to review what kind of devices are available and the performance they are capable of achieving. Some examples of home made SSPAs using GaN devices will be described, including basic information on how they were designed and the results obtained, both on the bench and on the air.

GaN Technology – What does it Offer?

GaN has received a lot of professional attention in recent years since it offers many potential advantages over GaAs, and is leading to the replacement of TWTs (and magnetrons) in many applications. A number of companies in the US, Japan and more recently Europe are now offering GaN discrete (unmatched) devices for general sale and these can be purchased by individuals in a large part of the world. Some MMICs are also available, but these are quite expensive and in most cases not available outside their country of origin.

Like GaAs, GaN is also a III/V semiconductor and is a good material for building microwave power devices. Compared to GaAs, it offers much higher 'power density' which means that for a given physical size of device up to four times the power output can be obtained, and many tens of watts can be obtained from a single die. GaN is also capable of higher efficiency than the majority of GaAs devices available to us amateurs. A GaN PA will typically have >50% efficiency compared to 25% or less for GaAs.

Another advantage is that GaN devices usually operate with considerably higher voltage, and along with their higher efficiency this means that the DC current drawn for a specific power level may be up to 8 times lower, cutting down I^2R losses in the DC cables and again resulting in more output power.

Unlike many GaAs devices, GaN FETs operate well in Class AB, with relatively low zero-signal drain current. The drain current may increase by a factor of 5 to 20 under RF drive, but little heat is generated during 'key up' periods so this helps to keep the average dissipation low compared to a Class A amplifier. Coupled with the higher efficiency, this means that for a given output power the amount of heat dissipated will be considerably lower than for a GaAs PA, allowing smaller heatsinks and lower mass per watt of RF power (0.6 g/W has been achieved for one of the amplifiers described below).

All of this means that GaN PAs are ideal candidates for mounting at or near the feedpoint, giving a further performance advantage by cutting feedline losses to a minimum.

From a design point of view, GaN devices are generally easier to match to 50 Ω than GaAs. The higher operating voltage means that output impedances are higher and the smaller size of device (for a given power) reduces the input capacitance.

The vast majority of GaN devices are depletion mode FETs. Like most GaAs devices therefore, they require a positive drain voltage and a guaranteed negative gate bias. GaN devices will die almost instantly if drain voltage is applied without gate bias. Sometimes you can get away with this with GaAs devices, but not with GaN. Power supply sequencing is therefore very important! Generally GaN devices do not draw much gate current until they are driven really hard, so the negative voltage generators that we are familiar with can also be used with GaN.

Available GaN Devices

GaN devices are available in bare die form and in packages. This paper will focus on packaged devices, since these can be readily used by amateurs. However, the parasitic reactances associated with packaged devices do restrict the maximum frequency on which they can be used.

There are two basic types of GaN devices available. Devices intended for cellular base stations with power levels of hundreds of watts exist, which could be used for 1.3 and 2.3 GHz, but these are very expensive and don't offer much performance advantage to amateurs compared to the silicon LDMOS devices in surplus PAs. The other family of devices are single transistors with output powers of up to 70 W at 3.4 GHz and 40 W at 5.7 GHz, and these were of most interest to me.

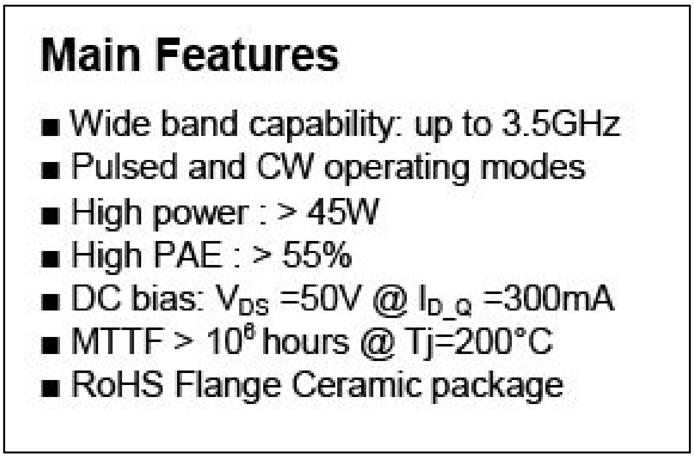
The number of suppliers of GaN devices is increasing all the time. At the time of writing, about 8 companies are offering GaN devices. Three suppliers were contacted and kindly agreed to supply devices for this work – Cree and TriQuint Semiconductor from the US and UMS from Europe.

Studying the Data Sheets

A good place to start looking at GaN devices is to study datasheets. These can be found on the manufacturers' websites, and if a full data sheet is presented it generally means that devices are available.

All manufacturers state the frequency of operation, output power, small signal and power gain, efficiency, DC operating conditions, whether the device is suitable for pulse or CW, absolute maximum ratings, source and load impedances for power operation, S-parameters, gain and stability information, applications circuits and package drawings. The package drawings need to be studied VERY carefully, since there is no standardisation of connections! The FET source is always the package ground tab or flange, but the chamfered lead can be either gate or drain according to the manufacturer's preference. Getting these reversed would be an expensive mistake!

There is usually a table of 'Main Features', from which the basic device information can be obtained, such as that shown in Figure 1 [1]:



Main Features

- Wide band capability: up to 3.5GHz
- Pulsed and CW operating modes
- High power : > 45W
- High PAE : > 55%
- DC bias: V_{DS} =50V @ I_{D_Q} =300mA
- MTTF > 10^6 hours @ Tj=200°C
- RoHS Flange Ceramic package

Figure 1: Main features of UMS CHK040A-SOA device

From this, we learn that the device is suitable for use up to 3.5 GHz, so it is good for our 9 cm band. It can be used for both pulse and CW, so is OK for amateur modes (pulse-only devices generally are not suitable). Expected output power would be a minimum of 45W in a properly designed circuit, with a high Power Added Efficiency[1] of 55% minimum. The device is intended for use with a drain voltage of 50 V and a quiescent drain current (ie with no RF drive) of 300 mA. The mean time to failure is > 1 million hours with a device junction temperature of 200°C; and the device is supplied in a lead-free flanged ceramic package.

Most of this information is self-explanatory and tells us how the device should be biased and what performance can be expected. Other performance tables show the small signal gain (15 dB in this case) and the power gain when the device is driven into near-saturation where the efficiency is at its highest (power gain falls to 12 dB). The near-saturated power gain is important to know, since it allows the required drive power to be estimated.

Other relevant information that can be gleaned from the datasheet includes the expected gate bias voltage (only a typical value, which will vary from device to device) and the thermal resistance R_{TH}. Knowledge of R_{TH} is important, as it allows the device junction temperature T_J to be estimated, based on the dissipated power P_{DISS} and the temperature of the device flange (T_B) using the formulae:

$$P_{DISS} = [(\text{DC input power}) + (\text{RF drive power}) - (\text{RF output power})]$$

$$T_J = T_B + (P_{DISS} * R_{TH})$$

A value for T_J is quoted (200°C for this device) which is usually chosen to ensure a given lifetime (eg 1 million hours). Some manufacturers also provide a graph showing how the lifetime is affected by the junction temperature. Often an absolute maximum value for T_J (220°C in this example) and a maximum for T_B are given. It is wise to follow the manufacturer's recommendations for all absolute maximum values – including T_J and T_B – to avoid blowing up the device. Often there is a disclaimer that states that not all maximum conditions can be applied together!

Information will also be provided in the datasheet that allows an amplifier to be designed with the device. There is usually a table of source and load impedance data, such as that shown below in Figure 2.

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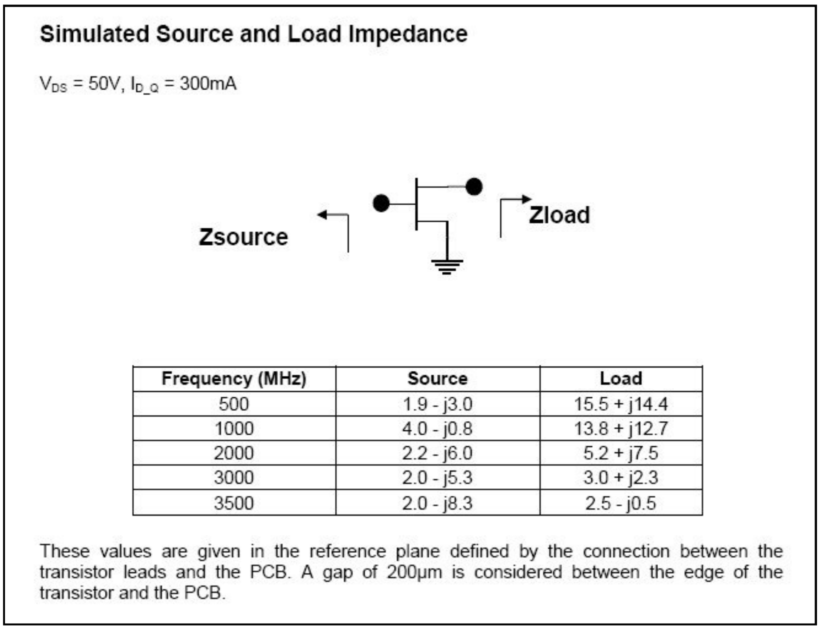
[1] . Power Added Efficiency = (RF output power – RF input power) / (DC input power)



Simulated Source and Load Impedance

V_{DS} = 50V, I_{D_Q} = 300mA

Frequency (MHz)	Source	Load
500	1.9 - j3.0	15.5 + j14.4
1000	4.0 - j0.8	13.8 + j12.7
2000	2.2 - j6.0	5.2 + j7.5
3000	2.0 - j5.3	3.0 + j2.3
3500	2.0 - j8.3	2.5 - j0.5

These values are given in the reference plane defined by the connection between the transistor leads and the PCB. A gap of 200µm is considered between the edge of the transistor and the PCB.

Figure 2: Source and load impedance data for CHK040A-SOA

The source impedance data can generally be ignored; what is of interest is the load data. This shows the impedance that needs to be presented *to* the drain of the device for it to work at the desired frequency. To obtain data at other frequencies (eg 3.4 GHz) it is necessary to interpolate. A linear approximation is usually accurate enough for practical purposes, since at the end of the day most amplifiers will need some tuning!

There will also be either a table of S-parameters or a link on the manufacturer's website to download them. These are used in the design process to design the input matching circuit, check stability and predict the (small-signal) gain response.

Finally, the datasheet will probably show some kind of demonstration amplifier. There may be a temptation to try to copy these, but generally what is shown is physically larger than needed, since demonstration amplifiers are usually designed to cover a broader bandwidth than we need. Usually some performance data are given for the demonstration amplifier, which can be taken as a good target for expected performance, but sometimes it is possible to do better over a narrow bandwidth.

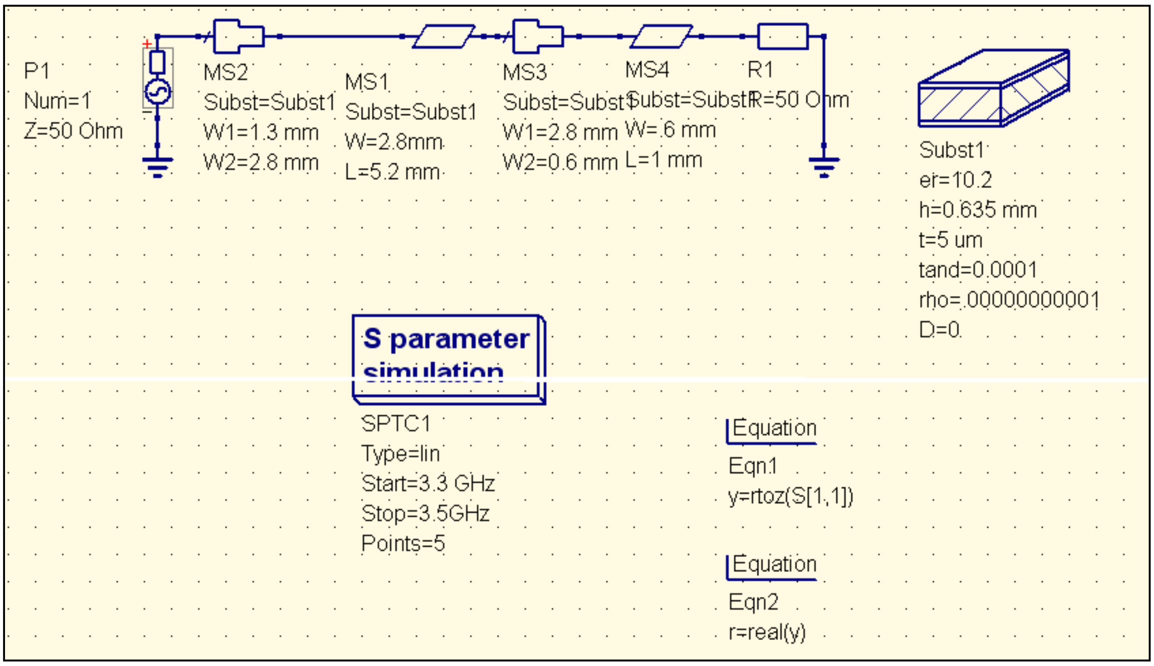
Designing a GaN PA at Home

As noted above, there is enough information in the datasheet to design a workable amplifier. If care is taken and the manufacturer's data are good, it has proved possible to design amplifiers that need little or no tuning for optimum performance. The following few paragraphs outline the method that I have used successfully without the need for expensive design software, non-linear models etc.

The first stage in the amplifier design is to design an output matching network that presents the correct load impedance, as specified in the datasheet. Often, a single microstrip element of the correct width and length is all that is needed. A good start is to design the element as a quarter-wave transformer of the required impedance to match the real part of the load impedance to 50 Ω. A microwave circuit design program can then be used to predict the impedance exactly and if the program is capable of optimization, it can also be used to adjust the width and length of the microstrip to get the required impedance. If the program allows, include discontinuity models for any changes in line width, as these can affect the impedance presented to the device. If the program is not able to optimize, cut-and-try methods can still be used to get the correct result. Of course more sophisticated methods can also be used, eg Smith Charts or network synthesis methods.

A suitable microwave design program that can be used for this kind of work is *QUCS* [2]. I have so far only used it to analyse circuits, and Figure 3 shows the results for the output network I designed for the TriQuint T1G6001528-Q3 device [3]. The datasheet gives a required output load of 8.85 – j7.85 Ω at 3.4 GHz.

The microstrip line length of 5.2 mm and width of 2.8 mm (MS1 in Figure 3) were designed initially using other software.



P1
Num=1
Z=50 Ohm

MS2
Subst=Subst1
W1=1.3 mm
W2=2.8 mm

MS1
Subst=Subst1
W=2.8mm
L=5.2 mm

MS3
Subst=Subst1
W1=2.8 mm
W2=0.6 mm

MS4
Subst=Subst1
W=.6 mm
L=1 mm

R1
R=50 Ohm

Subst1
er=10.2
h=0.635 mm
t=5 um
tand=0.0001
rho=.00000000001
D=0

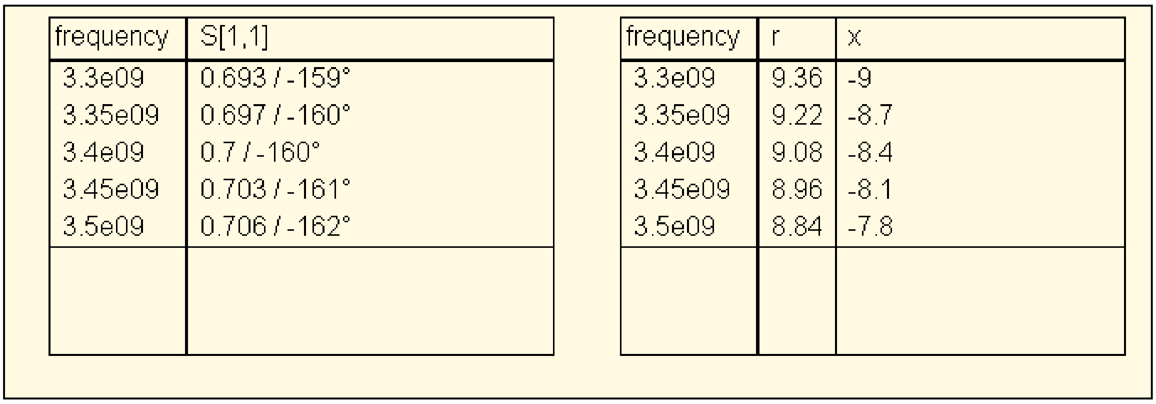
S parameter simulation
SPTC1
Type=lin
Start=3.3 GHz
Stop=3.5GHz
Points=5

Equation
Eqn1
y=rtoz(S[1,1])

Equation
Eqn2
r=real(y)

Figure 3: *QUCS simulation for T1G6001528-Q3 output match at 3.4 GHz*

The results of the *QUCS* simulation are shown in Figure 4.



frequency	S[1,1]
3.3e09	0.693 / -159°
3.35e09	0.697 / -160°
3.4e09	0.7 / -160°
3.45e09	0.703 / -161°
3.5e09	0.706 / -162°

frequency	r	x
3.3e09	9.36	-9
3.35e09	9.22	-8.7
3.4e09	9.08	-8.4
3.45e09	8.96	-8.1
3.5e09	8.84	-7.8

Figure 4: *QUCS simulation results for T1G6001528-Q3 output match*

The results of the *QUCS* simulation agreed quite well with the original simulation. Depending on the complexity of the networks, and especially if wide microstrip lines are used, the results from the simulator may not be sufficiently accurate. It is possible to use another software package called *Sonnet*, a free version of which (*Sonnet Lite*) is available to anyone [4]. This is a very accurate way of simulating microwave circuits with many different applications for amateur radio, and I have used *Sonnet Lite* for designing different kinds of microstrip circuits including branched arm couplers, filters and matching networks. It analyses the electromagnetic fields and currents of structures from first principles using Maxwell's Equations, and has proved to be highly accurate. Figure 5 shows the layout of the same network in *Sonnet* format, and the results are given in Figure 6.

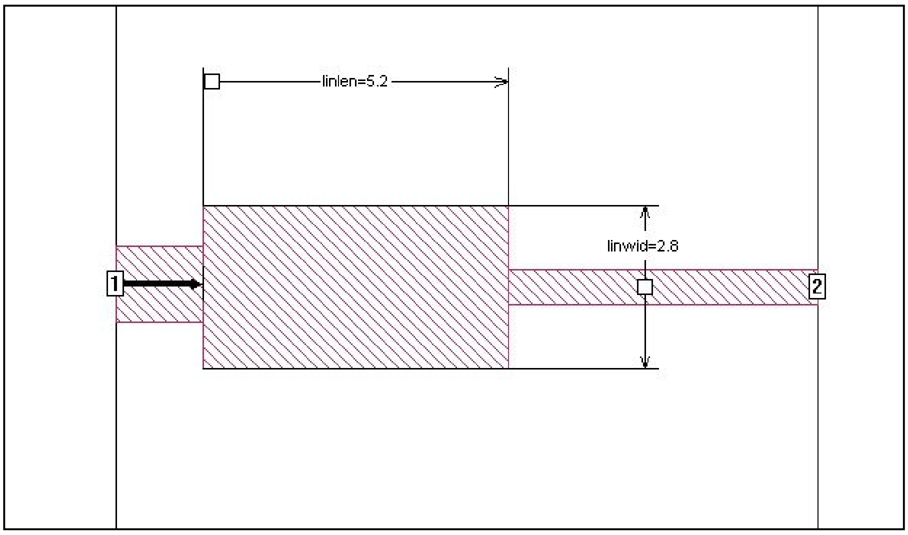


Figure 5: Sonnet *layout of output network*

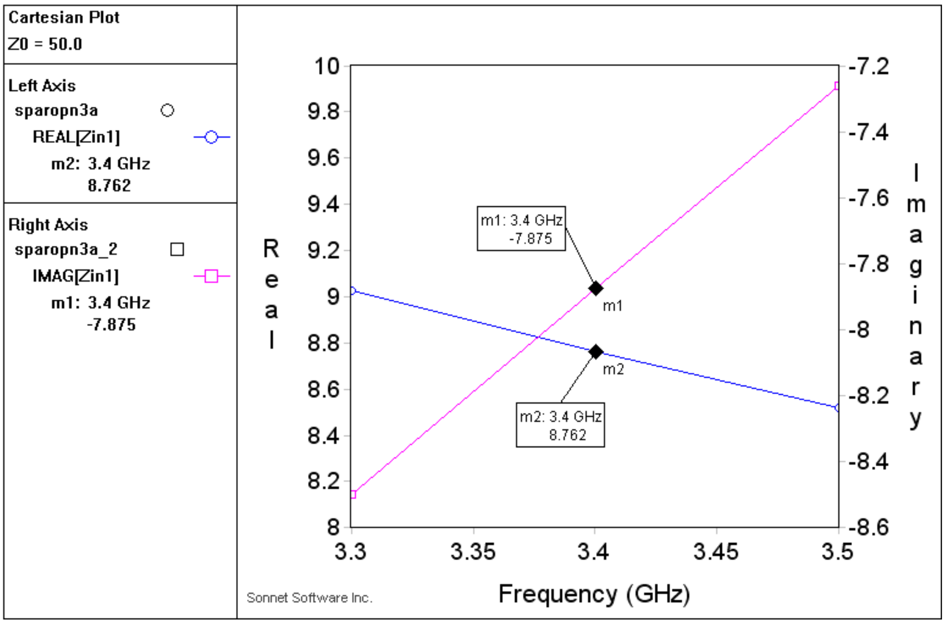


Figure 6: Sonnet *prediction of output load impedance*

The input circuit was designed using a similar method to the output circuit, using the device S-parameters and including the output matching circuit as described above connected to the device drain. The input microstrip was designed to achieve a low input VSWR, which also provides the maximum gain.

Figure 7 shows a photograph of the amplifier built to this design. The device was mounted on a 39 x 32 mm aluminium plate, 6 mm thick, which provides good heat transfer to the heatsink.

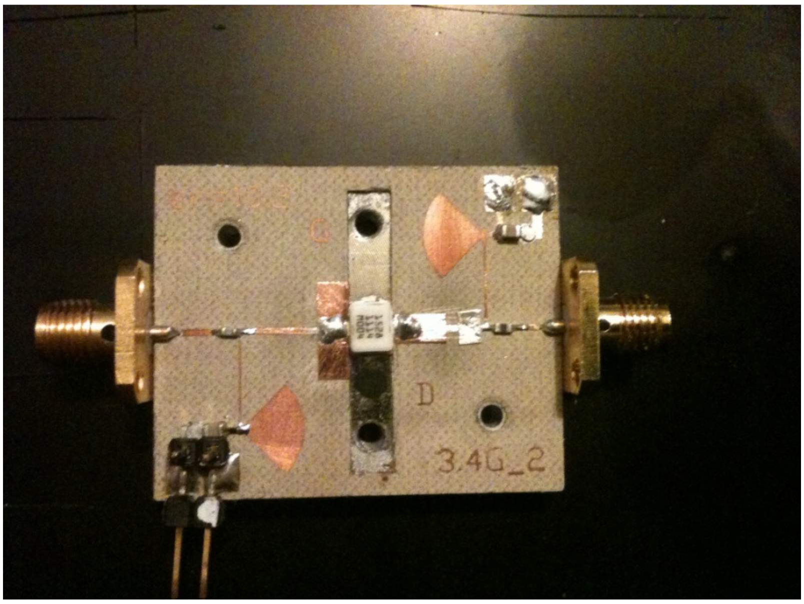


Figure 7: 25 W GaN SSPA for 3.4 GHz using TriQuint T1G6001528-Q3 device

The measured performance of this amplifier is given below. The performance of the device in the datasheet is shown in brackets, for comparison.

Test frequency	3400 MHz
Small signal gain	14.75 dB (13.9 dB)
Power output	25.5 W (21 W)
Power gain	12.7 dB (12.3 dB)
PAE	58% (56.7%)
Drain voltage	30 V
Drain current (RF off)	250 mA
Drain current (RF on)	1450 mA

More Examples of GaN Power Amplifiers

Following on from the good results obtained with the TriQuint T1G6001528-Q3 device on 9 cm, a number of other amplifiers have been developed as shown in Figures 8 to 11 below.

The black dots on some of the devices are matt black paint, to allow temperatures to be measured using a handheld infra-red thermometer.

52 W on 3.4 GHz

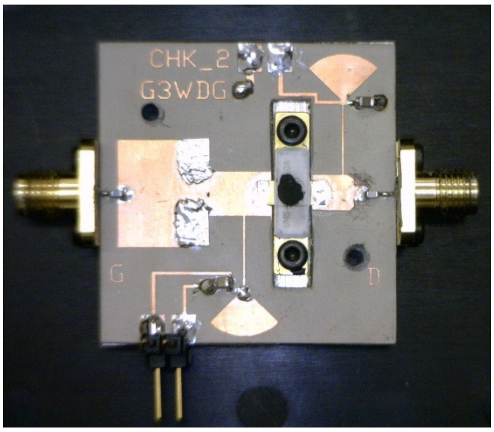


Figure 8: 3.4 GHz PA using UMS CHK040A-SOA

Test frequency	3400 MHz
Small signal gain	16.1 dB (15-17 dB)
Power output	52 W (40-50 W)
Power gain	13.4 dB (12 dB)
PAE	54% (50-55%)
Drain voltage	50 V
Drain current (RF off)	300 mA
Drain current (RF on)	1946 mA

70 W on 3.4 GHz

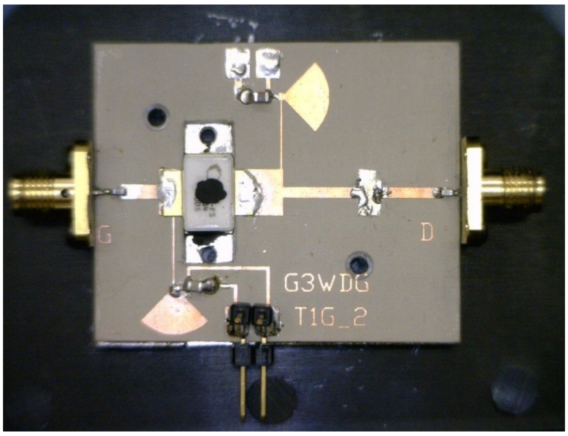


Figure 9: 3.4 GHz PA using TriQuint T1G4005528-FS

Test frequency	3400 MHz
Small signal gain	16.5 dB (15.1 dB)
Power output	68 W (66 W)
Power gain	14 dB (12 dB)
PAE	54% (49%)
Drain voltage	28.5 V
Drain current (RF off)	200 mA
Drain current (RF on)	4225 mA

21 W on 5.7 GHz

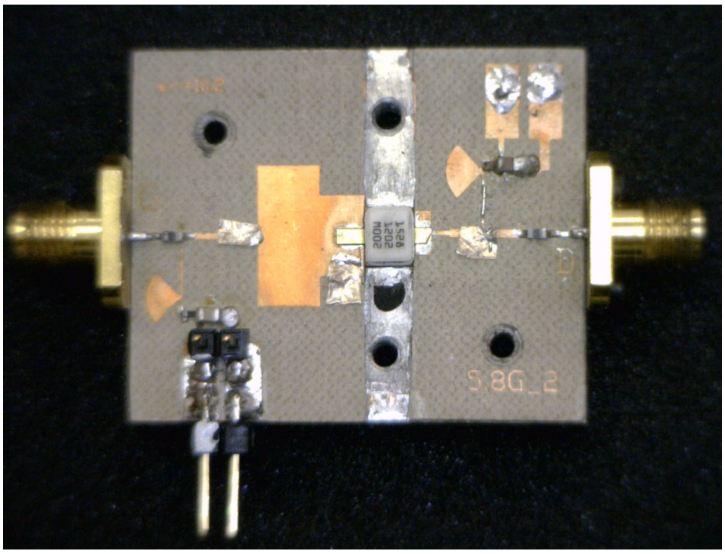


Figure 10: 5.7 GHz PA using TriQuint T1G6001528-Q3

Test frequency	5760 MHz
Small signal gain	12 dB (11.9 dB)
Power output	21 W (20 W)
Power gain	9.0 dB (8.9 dB)
PAE	53% (51%)
Drain voltage	30 V
Drain Current (RF off)	220 mA
Drain Current (RF on)	1160 mA

26 W on 5.7 GHz

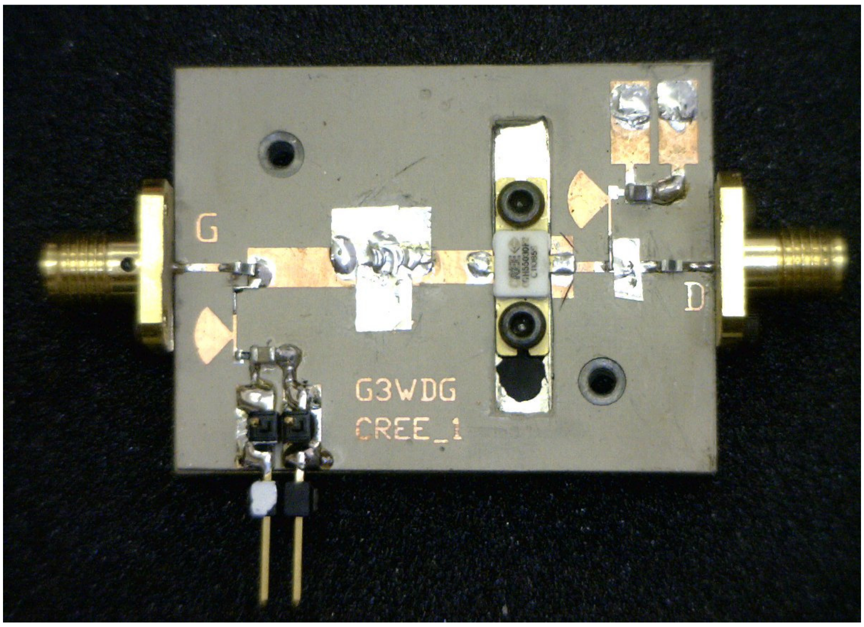


Figure 11: 5.7 GHz PA using Cree CGH55030F2 [5]

Test frequency	5760 MHz
Small signal gain	11.3 dB (9-11 dB)
Power output	26 W (20-30 W)
Power gain	8.7 dB
Drain efficiency	60% (50-60%)
PAE	52%
Drain voltage	28.5 V
Drain current (RF off)	250 mA
Drain current (RF on)	1521 mA

Combining GaN PAs

The feasibility of combining two GaN PAs was investigated. A second 70 W PA was constructed using a randomly selected TriQuint T1G4005528-FS device (but with the same date code as the transistor in the other amplifier) and was assembled with the original PA and two branched-arm 90° hybrids, to form a balanced amplifier as shown in Figure 12.

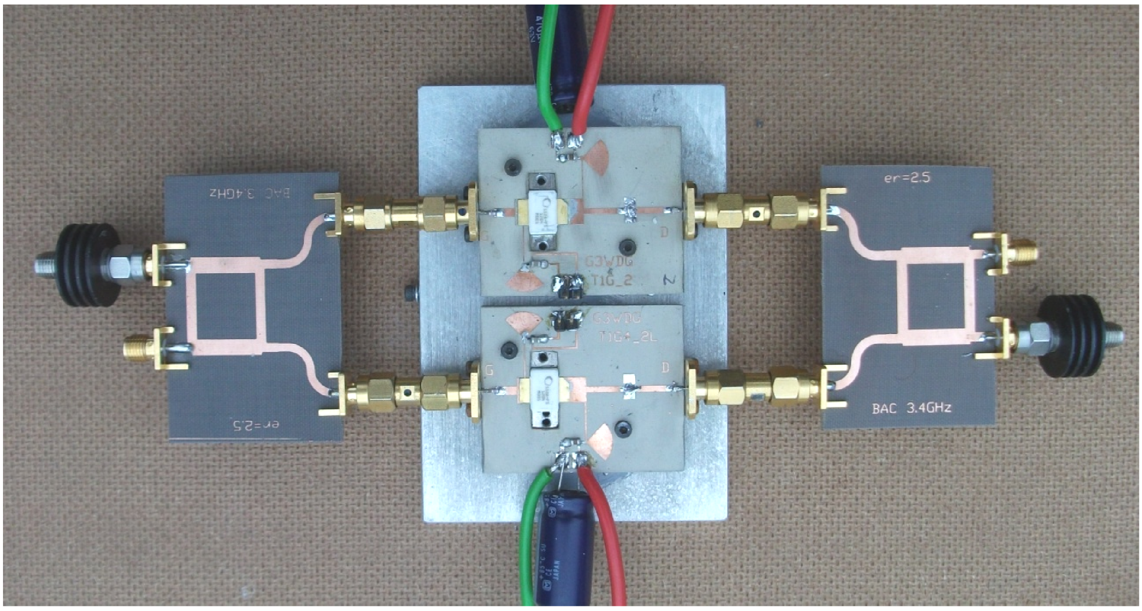


Figure 12: Balanced amplifier using 2 x 70 W GaN amplifiers

The performance obtained from this configuration is shown in the table below.

Test frequency	3400 MHz
Small signal gain	15.5 dB
Power output	131 W
Power gain	13 dB
PAE	45%
Drain voltage	30 V
Drain Current (RF off)	400 mA
Drain Current (RF on)	9100 mA

Can a Feedhorn be used as a Heatsink?

One of the potential advantaged of GaN's high efficiency is to remove the need for large and heavy heatsinks, allowing the possibility of mounting the PA directly at the feedpoint. It occurred to me that it might even be possible to use the feedhorn itself as the heatsink under certain circumstances. To test this idea the prototype 3.4 GHz 25 W PA was mounted on the rear of a DJ3FI septum feed, as shown in Figure 13.

The feed is constructed out of relatively thick aluminium and some tests were performed to see if it could act as the heatsink for the PA. The PA was driven to 25 W RF output (into a dummy load) and was dissipating 16 W of heat. The amplifier was run for about 10 minutes until the temperature of the PA chassis had stabilized. A temperature rise of 23°C above room temperature was measured. The thermal resistance of the horn was calculated as 23/16 = 1.44°C/W.

For an ambient temperature of 15°C and a maximum chassis temperature of 85°C (typical of many devices) this means the feed would be and adequate heatsink for GaN PAs dissipating up to nearly 50 W continuously (or more under normal operating conditions with <100% duty cycle).

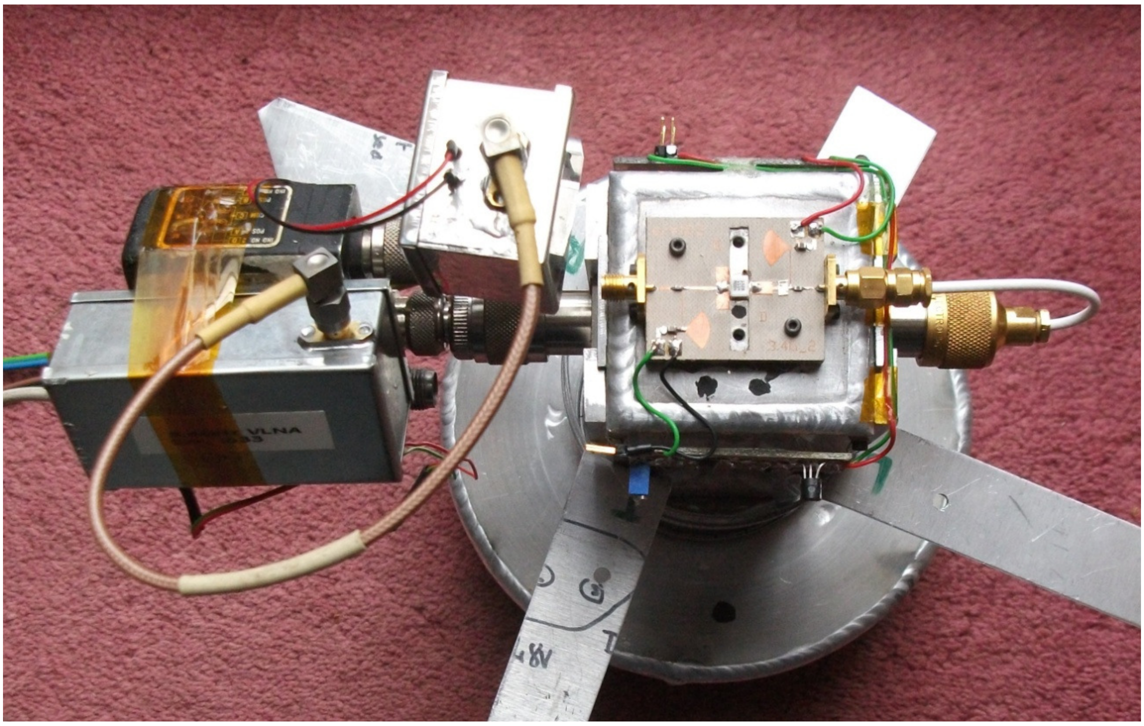


Figure 13: 25 W 9 cm GaN PA mounted on rear of DJ3FI feedhorn

EME results on 9 cm with a GaN PA

Having established the thermal resistance of the feedhorn as a heatsink as described above, the 25W PA was replaced with a 70W output PA and tried out on-air. Good echoes were obtained, as shown below in Figure 9. On the following evening six QSOs were made using the GaN PA, and very good reports were obtained.

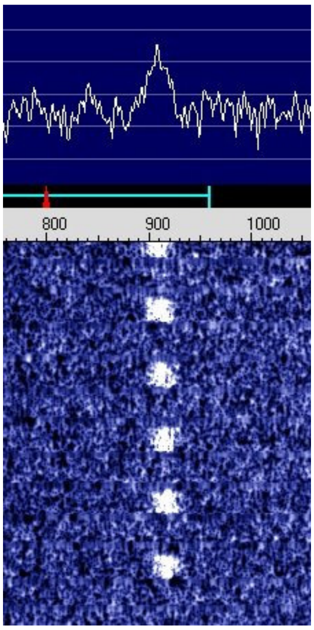


Figure 9: EME Echoes obtained on 25 June 2012 using a 70 W GaN PA and 10 ft dish

References

1. UMS CHK040A-SOA device data: http://www.ums-gaas.com/telechargement.php?id_page=0-42-19&file=CHK040A_SOA_Full_1359_1.pdf
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3. TriQuint T1G6001528-Q3 data: http://www.triquint.com/products/p/T1G6001528-Q3
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5. Cree CGH55030F2 data: http://www.cree.com/rf/products/gan-hemts/packaged-discrete-transistors/cgh55030f2-p2