A new generation of Gallium Nitride (GaN) based Solid State Power Amplifiers for Satellite Communication

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Abstract

The introduction of Gallium Nitride High Electron Mobility Transistors (GaN HEMT) in early 2000 has left an undeniable mark on the entire satellite communication landscape. It is now possible for the first time since the introduction of the Solid State Microwave Technology to design and manufacture Power Amplifiers that exceed by several orders of magnitude the reliability, linearity, power density and energy efficiency of all existing technologies, being GaAs, LDMOS, or TWT.

A comparison study between these technologies is presented in the current paper, with emphasis on linearity and efficiency.

The Technology

Today for both military and commercial satellite markets, GaN-based technology, without a doubt, is a hot topic. GaN –based devices began to surface in the commercial applications about 8 years ago. They were primarily used for low-frequency L, S, and C-band applications like radar, cable TV and power management.

In early stages of technology Advantech has realized the tremendous potential of these new types of devices for high frequency satellite communication. As a result, and ambitious R&D program was put in place back in 2006 to design and manufacture a complete line of C, X, and Ku-band Solid State Power Amplifiers, able to meet the most demanding and stringent requests.

In partnership with key technology providers, Advantech engineers have focused on technology transition to high frequency, high efficiency, and high performance, as demanded by the growing Satcom on the Move, Mobile, man pack, broadcast and teleport markets

Early challenges were identified in the non-linear characteristics of these devices, difficulties in processes and materials and in biasing new devises, as well as in their poor yield and hence very high cost, making them an exotic material.

A number of patent pending technologies were developed during the last six years that have succeeded in obtaining the highest linearity ever achieved on the market by both Solid State and linearized TWT techniques.

Initially, it seemed GaN-based devices would be affordable only for expensive military applications, like radar, electronic warfare, and high security communication systems. Recent hard work of scientist in many fabs around the world, led to the material maturity, yield improvement, development of lower cost substrates; and increase in demand, have driven the GaN-based devices cost and now they are a very viable economical option to the current GaAs solid state technology as well as to TWTA.

What is Gallium Nitride (GaN)?

Gallium Nitride (GaN) is a binary III-V direct band gap semiconductor. The material used to create working transistors is actually a crystal, and these crystals are grown layer-by-microscopic layer, using a precise mixture of different gases, flowing into a reaction chamber. The electrical properties of GaN make it an ideal choice of material for optoelectronic, high-power and high frequency devices. Because GaN offers very high breakdown voltage, high electron mobility and saturation velocity, it is also an ideal candidate for high-power and high-temperature microwave applications like RF power amplifiers at microwave and mm frequencies, and high-voltage switching devices

The entire GaN semiconductor is grown into a crystal lattice structure material that has a very high threshold for electron mobility, hence behaves similarly to the diamond: can be both subject to very high temperatures before performance degradation and has excellent thermal conductivity properties, allowing high temperature operation and effective heat transfer. Therefore the devices using GaN can operate at very high temperatures (up to 350 degC) and can dissipate all the heat generated by these devices at very high temperatures.

Obviously, the best match is to grow GaN transistors on GaN substrates, because they have an identical crystal lattice structure; however this is slow growing and hence expensive process. Recently non-lattice-matched substrate materials have been developed and now are commonly used. Among them, silicon carbide is the current favorite because of the low cost/high performance combination. Therefore due to these technological advancements and refinements of the processes and use of composite materials, GaN devices can be produced in large volumes relatively cost effective. Future ramp up in the demand will drive the price down to make it competitive and to match or surpass the price of the similarly rated GaAs FETs, making GaAs HPA, spatial combined HPA and TWTA disappear.

First, a thin layer of high-purity mono-crystalline GaN is grown, ranging from one to two microns thickness. Next, a separate layer of aluminum gallium nitride, 15-25 nanometers is made. These two layers, with dielectric passivation adding an insulation layer to the device surface, form the basic transistor layer structure. Metallization layers are then added to make electrical contacts, and to form the transistor drain, gate and further interconnects.

Finally, the wafer is reduced in thickness in order to establish the electrical source and ground links through via holes that connect the front face to back. This is by no means a trivial process, because the silicon carbide material is a very hard material. That implies grinding the wafer down from 500 microns to around 100 microns, and chemically etching around 50 micron-diameter via holes.

It can take on average 3 to 4 months to grow and fabricate a batch of GaN devices, and the thread of contamination, crystal strain, structural mismatch or other defects is very high and real. If the defects and surface passivation layers are not properly controlled, a rapid degradation in device performance can be noticed.

Performance

Generally regarded as the most promising semiconductor since Shockley discovery of the silicon transistor, gallium nitride (GaN) works much better at higher voltages and temperatures than silicon (Si) or widely used at high frequencies gallium arsenide (GaAs).

Today GaN is a mature, robust technology with extraordinary reliability. Compared to GaAs and Si, GaN has much higher breakdown voltage (~ 100VDC) and power densities, enabling applications not possible with competing process technologies. GaN high power density also allows for smaller devices, reducing the capacitance, enabling high impedances, wider bandwidths, and reduced size and cost. Additional benefits include industry-leading efficiency of operation, reduced cooling requirements, and lighter weight.

Significantly for space applications, GaN is also inherently radiation-resistant, surpassing in performance GaAs and it can perfectly withstand the EMP.

European Space Agency (ESA) has identified GaN as a "key enabling technology " for space, and has established the "GaN Reliability Enhancement and Technology Transfer Initiative " (Great2), bringing together leading research institutes and manufacturing industry to set up a supply chain to manufacture high-quality GaN space based components.

In space applications, the vacuum tube based traveling wave tube amplifier (TWTA) is still used, because of high Power Added Efficiency (PAE). However, because the TWTA uses the filament in electron gun, that is subject to wearing out with time and needs an extremely high voltage of the order of several thousands of volts (~10KV), and reliability is considered not ideal due to the hot electrons and vacuum depletion in tube with time, the solid-state power amplifiers (SSPA) is often considered to be a favored solution. GaN based SSPAs are now in development, in order to replace TWTAs in many space applications and plans are in place to soon launch GaN SSPAs into space.

For the traditional SSPA manufacturing, while GaAs HEMT and LDMOS have traditionally been widely used, GaN HEMT offers the major advantages:

- Higher Power Added Efficiency (PAE), which not only saves electrical power usage (OPEX), but also can reduce the size and cost of SSPAs, due to lower amount of heat dissipated, and ease of manufacturing (CAPEX). For instance in C-band GaN devices have up to 48% efficiency, as compared to 25-30% for GaAs. As a result cubical volume of the power supply can be reduced by factor of two, or for the given volume the greater derating can be utilized. As failures of the power supply are critical failures, this translates in much higher MTBF, and reduced OPEX
- High Operating Voltage - GaN HEMT operates with a power supply of up to 50 VDC, similar to the range of power feeder voltage of 48 VDC, which is commonly used for communication equipment. Furthermore, for any given output power and supply voltage, the operating current can be reduced, when comparing with other technologies. It is to be noted that the breakdown voltage for GaN devices is above 100VDC, which makes them extremely difficult to damage
  This translates into a much more reliable power supply design, as output current is reduced up to 75% on average. Operating voltage is moving from 10VDC required to operate GaAS FETs to 20-48VDC, but there is no fear that if interlock in TWTA power supply is failed, of personnel to be electrocuted as it could happen with TWTA, due to high voltage (~10KVDC) anode power supply required to operate TWT.
- GaN HEMT devices have higher impedance then other technologies. Hence, the SSPA design engineer can use the benefits of GaN to enhance the performance, such as wider frequency band coverage, and higher PAE, depending on the required performance of the SSPA.
- Much higher reliability - The crystal lattice structure, and the high temperature handling capabilities of the GaN device, makes them an extremely robust and reliable part of the SSPA design. It is known that the traditional GaAs FET transistor will stop operating, or will rapidly degrade at junction (channel) temperatures higher than 175 deg Celsius. At 175 deg Celsius junction temperature, GaN devices have many millions of hours MTBF.

From the reliability point of view, for all SSPAs designs, the power supply which needs to generate high current and the RF output stage where all the heat is generated, are the highest stress, highest points of failure, and 90% of failures are indeed fall into these areas.

By using power supplies with lower power consumption and higher operating voltages, we can reduce operating current by 75%, and that solves one of the key design issues.

By using GaN devices in RF and microwave frequencies we can handle much higher operating temperatures, and that addresses the second reliability aspect. Having these two key elements addressed with a much more robust design, increases the reliability and the MTBF numbers of the SSPA by orders of magnitude.

SSPA Performance, GaN versus GaAs, and versus TWTA

Advantech Wireless has developed in the last 6 years a full line of GaN based SSPAs and SSPBs (Block Up Converter integrated with SSPA). The product line, launched at Satellite 2010 in Washington, included up to 200W Ku-band offering, the first product line worldwide.

Since then, major deployments in both the commercial and military markets have been taken place, with thousands of devices operating now in the field. This is now a mature, stable, low OPEX, high reliability technology. By using patent pending technologies and in close cooperation with key technology suppliers, Advantech Wireless has managed to perfect the design, and to raise the performance of GaN based SSPA/SSPB above all existing technologies.

These units now exceed the linearity, energy efficiency, and reliability of anything that existed prior to their introduction to the market, being it solid state or TWT based products.

For the purpose of performance analysis and comparison, the following section will compare Advantech Wireless made SSPAs, using GaN vs. GaAs technology, as well as third party TWTAs with the same or similar operating power rated performance. The main focus is on linearity, noise power density and PAE characteristics, as well as reliability.

Linear Power

For the purpose of link budget, or satellite system design, choosing the right amount of requested RF Transmit power to meet a required link margin is not always obvious. The system designer will have the option of selecting between Solid State or TWTA technology, but both of them define RF Power in a different way.

TWTAs will define Saturated Power, or Power at the Flange, as well as Third Order Intermodulation Products.

Third Order Intermodulation Products will specify what is the maximum total transmitted power with two equal carriers, for which the third order (odd order) Intermodulation products will not exceed a specified value. It is commonly known that these undesirable products are in-band products, and therefore cannot be filtered. They have to be kept low by proper design of the high power amplifier (HPA) by utilizing either inherent devices linearity (GaAs), or deploy linearization techniques like analog or digital predistortion, feedback amplifiers (not commonly used due to their low efficiency) and that known as feed forward amplifiers (TWTA and GaN).

Below is the description of the tests performed for the linearity measurements. The currently most used method is to apply to the HPA two equal carriers with combined output power backed off 3-4 dB (OPO) from P1dB and measure the unwanted in-band intermodulation products.

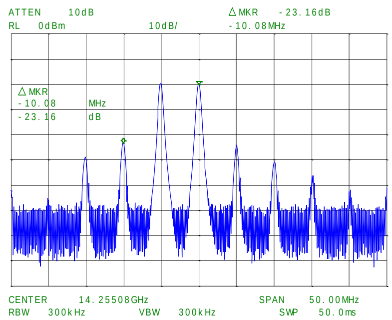


Figure 1. Third Order Intermodulation Products

Solid State technology has introduced a new concept, P1dB, or 1dB compression point. This is transmit output power at which gain will be reduced by 1dB. P1dB, more then anything else, will define a power level that should not be exceeded when operating a single carrier. In Solid State, the difference between P1dB and Psat is typically within 1 dB, and operating about P1dB and above will generate rapid grows of odd order in-band intermodulation products, or spectrum re-growth and hence degradation of link performance in terms of BER.
Intermodulation will also be specified, same as for TWTA, but general performance, depending on manufacturer is 3 to 4 dB better on GaAs Solid State as compared to TWTAs.

In order to compensate for this, the later will use various linearization techniques described above, but these are usually narrow band, and analog, non-adaptive ones require periodic adjustments due to aging.

None of the parameters specified above, Psat, P1dB, Third Order Intermodulation products, or Third Order intercept point (yet another concept), will give much usable information to the satellite link designer, in case the application requires just one carrier, or multicarrier, but more than two carriers.

Operating in single carrier mode depends on data rate, and on modulation type. Neither Psat nor P1dB can give much information in this case.

Operating in multi carrier modes (three or more) will raise questions, which are not answered by Third Order Intermodulation products, as the behavior will be totally different.

In order to answer these questions, Advantech is aligning its own specifications, to a new, uniform, more explicit set of standards. These standards have emerged few years ago, with the intention to allow the system designer to select the right product, from the multitude of offerings, based on his own application. Standardization institutes, as well as military organizations now adopt them (as an example MIL-STD-188-164 standard).

The new set of standards is not mentioning P1dB any longer, due to the above-mentioned limitations.

They specify “ Linear Power” as:

- Operating Power at which Spectrum Regrowth for a single carrier, operated in a certain modulation type (usually QPSK or OQPSK), at a certain data rate, at a certain offset from carrier (1 or 1.5 symbol), will not exceed a specified value. Spectrum Regrowth will cause unwanted “shoulders” on the main carrier, that will spill over into the next satellite channel, and create inter symbol interference among others.

- Total operating power for which two equal transmitted carriers will generate Third Order Intermodulation Products below a specified value (usually 25 dBc).

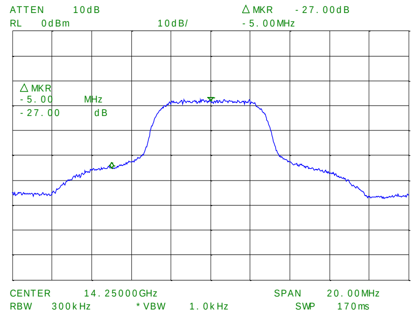


Figure 2. Spectrum Regrowth, one carrier, QPSK, 5 Msps, 1 Symbol Offset from carrier

Linear Power - Spectrum Regrowth

A number of Spectrum Regrowth tests were performed on Advantech made 400W Ku-band SSPAs using GaAs and compared with GaN versions.

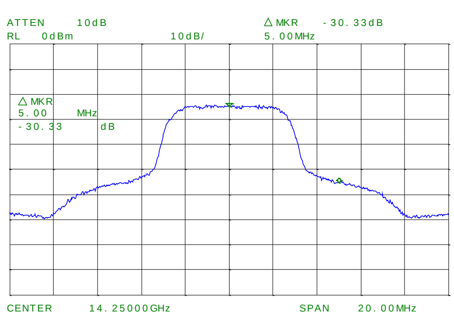
Both the units are tested with an QPSK signal, 5 Mbps, 1 Symbol rate offset. The desired target specification is –30 dBc.

The 400W Ku-band GaN is specified as Psat=56 dBm.
The 400W Ku-band GaAs is specified as P1dB = 55 dBm, and also Psat = 56 dBm

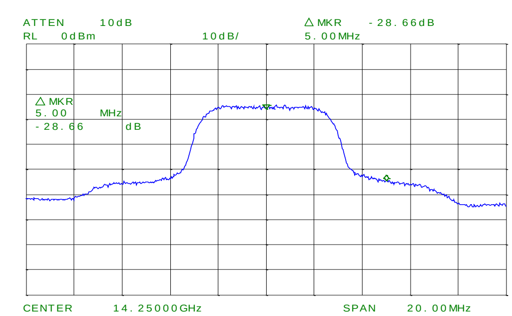
The results are summarized in the table below, and the areas highlighted in green indicate that the required performance is met:

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

Table 1. Spectrum Regrowth, GaN versus GaAs, 400W Ku-band SSPA



GaN SSPA, 55 dBm output



GaAs SSPA, 55 dBm Output

The test results outline the net benefit of GaN technology.
Advantech XXX-series 400W Ku-band GaN SSPA will outperform by 2 dB a 400W Ku-band GaAs SSPA when operated in single carrier mode.

In fact, in terms of linearity, as defined by single carrier operation mode (Spectrum Regrowth), a 400W Ku-band GaN SSPA will be the equivalent of a 600 W Ku-band GaAs SSPA!

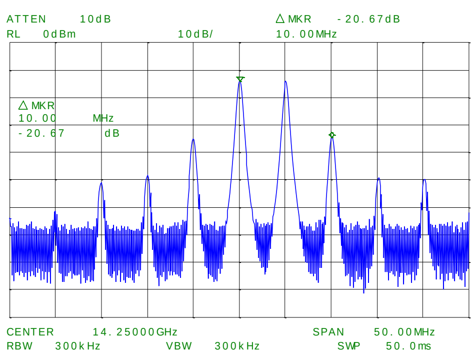
Linear Power – Third Order Intermodulation

In order to determine the linearity under two carrier operations, a number of Third Order Intermodulation tests were performed on the same 400W Ku-band SSPAs, build with different architecture, i.e. GaN versus GaAs. The results are also compared with published data of similar power rated non-linearized TWTA.

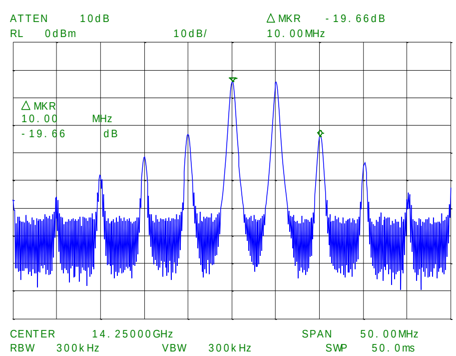
The desired target specification is –25 dBc

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

Table 2. Third Order Intermodulation products, GaN versus GaAs, versus TWTA



Intermodulation 400W Ku-band GaN, 54dBm



Intermodulation 400W Ku-band GaAs, 54 dBm

The measured results indicate that 400 W Ku-band GaN will exceed by 1 dB the performance of the same rated 400W Ku-band GaAs and by 2 dB the performance of 750W Ku-band non linearized TWTA.
In fact, in terms of linearity as specified by two carries transmission (third order intermodulation), a 400W Ku-band GaN SSPA is equivalent to a 500W Ku-band GaAs SSPA.

Linearity as AM/PM conversion

Another important parameter that will define the linearity performance in presence of high order modulation schemes is AM/PM conversion. An amplitude modulated signal going through a non linear system, will generate phase degradations (rotations).
The test is performed by applying a power swept signal at the input of the SSPA, and monitoring the phase change at the output

The desired performance is 1.5° / dB. The parameter is critical when higher order modulation schemes that use both Amplitude and Phase modulation (16 APSK/QAM and higher) are used.

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

Table 3. AM/PM, GaN versus GaAs, versus TWTA

The test results indicate that the GaN SSPA will exceed the GaAs SSPA performance by 2 dB, and by 4 dB the TWTA performance .
In other words, in terms of AM/PM performance, a 400W Ku-band GaN will be the equivalent of a 600w Ku-band GaAs, and outperform a 750W TWTA.

All the tests above indicate that GaN SSPAs exceed by far the performance of GaAs SSPAs and similar output power rated linearized TWTA.

This remarkable performance is even more interesting, considering the large reduction in size and energy consumption achieved by GaN SSPAs. Table 4 below presents the results, using the same models as tested above:

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

Table 4. Weight , volume, and energy consumption GaN versus GaAs, versus TWTA

It is to be noted that a 400W Ku-band GaN is just 37% the weight of the 400W GaAs SSPA and 81 % the weight of the TWTA.

In terms of energy, the 400W GaN consumes 37% less then the GaAs variant, and 12% less then the TWTA. A remarkable 80% reduction in volume as compared with the GaAs variant is achieved, as well as a 60% reduction versus TWTA.

For the first time to our knowledge, the Solid State Technology achieved the lower weight, lower volume, has less energy consumption and can operate at 2dB higher output power, comparing to the TWTA counterpart

Adding to this impressive array of performance, is the drastic increase in reliability, the increased tolerance to high ambient operating temperatures, confers to the GaN SSPA all key indicators of a true disruptive technology. Regarding the space applications, this technology is by far better suited than both TWTA and GaAs based SSPA.

