Recent developments in High Power Solid State Power Amplifiers

A European Perspective

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***Abstract*—this paper reviews the progress made over the last 5 years and the current status of high power SSPAs and some of the application areas. Rather than dealing with headline research performance commercially available products and systems will be reviewed. There will also be a degree of speculation as to where there developments will go.**

Keywords – SSPA, Solid State Power Amplifiers, High Power RF & Microwave Applications.

I. INTRODUCTION

High power RF is used in a wide range of applications from particle accelerators to microwave ovens, fading denim to self-cauterising surgical scalpels. Traditionally the highest power levels have the domain of Vacuum Electronic Devices (VEDs) such as klystrons, magnetrons and Travelling Wave Tubes (TWTs). There has been much speculation about the demise of these solutions each time solid state technology breaks a new performance barrier, and yet a (diminishing) number of companies continue to develop VEDs and turn a profit. They may look enviously at the R&D budgets that the DoD have ploughed into solid state over the last 20 years, but particularly in the space industry, they have been able to win large scale multi-year projects. However, over the last few years more and more of these companies have started to offer either a hybrid solid state - VED amplifier or their own range of SSPAs.

Whilst it would be overly bold and somewhat naive to announce the death of VEDs, it is certainly true that an ever increasing proportion of their market is now under direct threat from solid state. With this in mind, now is an appropriate time to ask regarding solid state power amplifiers, “Where does Europe stand in this import segment of the technology industry?”

II. EUROPEAN SOLID STATE DEVICE SUPPLIERS

When discussing such market areas it is important to define the boundaries to prevent a paper becoming a tome! In this case this is more difficult than it may at first seem. For example, if we were to try and establish a frequency limit, say from 20MHz to 100GHz we would at the one end have to decide whether we were to include high frequency switching applications and at the other power levels measured in the mW. So for the purposes of this report we will consider applications where the RF signal is an output in itself and where peak power levels exceed 100W. Thus the semiconductor technologies that will be considered are Laterally Diffused Metal Oxide Silicon (LDMOS), Gallium Arsenide (GaAs), Silicon Carbide (SiC) and Gallium Nitride (GaN), in packaged, chip and Monolithic Microwave Integrated Circuit (MMIC) formats.

Two companies dominate the LDMOS market, Freescale and NXP, with the mobile communications base station market providing the impetus for product development and the volumes necessary to significantly drive down prices, currently \$0.25/W (U.S.) is achievable in reasonable volume and applications where the target is closer to \$0.10/W are seriously under consideration.

Making direct comparisons between the performance of manufacturers devices is difficult due to differences in emphasis on characteristics and application space. For example, many of the Freescale devices are quoted in terms of average as opposed to peak power levels, whilst NXP frequently quote maximum CW power. Figure 1, is based on published data sheets for CW power at a particular

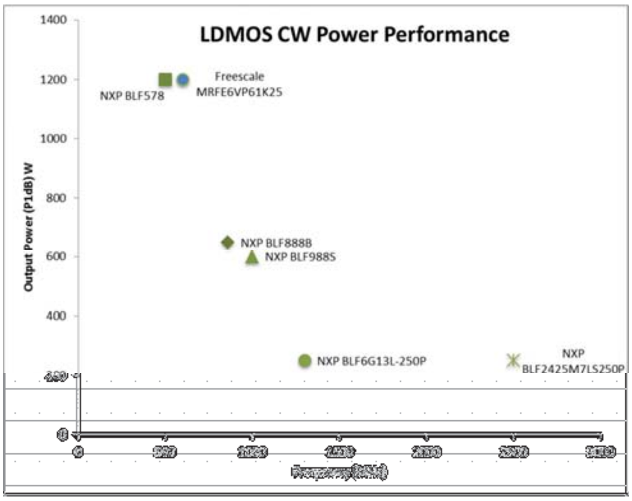

Figure 1, Maximum CW power quoted by manufacturers of LDMOS devices.

frequency. Both companies have a 1.2kW device, NXP rating theirs at 500MHz and Freescale at 600MHz.

The achievement of significant power levels at 2.5GHz shows the maturity of silicon processing, and is driven by the opportunity for large numbers of devices in lighting and heating applications. The 'fabled' solid state microwave oven will use different approaches from conventional ovens; for example multiple antennas, in phased arrays, obviate need for turntable, the rotating field strength possibly based on 'recognising' the contents to be heated. This is indicative of how low in price LDMOS is thought to be able to be driven. Similarly plasma light sources intended to replace high power halogen bulbs will only be viable with access to low cost silicon power RF devices.

Since the start of the millennium there have been some dramatic improvements in LDMOS transistor performance, Table 1. The increase in operating voltage results not just in a decrease in current for the same power level, but also the ability to construct high efficiency operating mode (e.g. class J) based amplifiers, where for example the peak voltage could be up to 3x that of the supply. This, coupled with the almost 5x decrease in thermal resistance has led to the huge increase in power handling. The latest generation of devices can do the job of 10 from the turn of the century.

Year	Device	P1dB (CW)	Rth (°C/W)	V_D (V)	η_D (%)	Load Tolerance
2000	BLF647	120	0.6	28	>55	10:1
2005	BLF369	500	0.26	32	>60	10:1
2009	BLF578	1000	0.14	50	>75	13:1
2012	BLF178XR	1200	0.11	50	>80	65:1

Table 1, Key performance characteristics reported by NXP since 2000.

Furthermore the improvement in device ruggedness has meant that new applications with extremely poor load impedances have become addressable, and others which may have required complex and temperamental auto tuning systems can now be driven directly by these transistors.

The GaAs transistor market has been dominated by suppliers from the Far East. European suppliers such as UMS and Ommic have carved out niche areas in frequency bands above 30GHz. The loss of the sole UK foundry at Newton Aycliffe, despite having some success in GaAs switches for mobile communications and MMICs for military electronics warfare, radar and jamming applications, is indicative of the difficulty in getting a permanent foothold in a well-established market.

Clearly a further threat to GaAs suppliers is the trend towards GaN devices. As can be seen from Figure 2 the GaAs segment is being squeezed from above and below in terms of power applications. GaAs HBT devices still command the majority of the handset power amplifier market; silicon pressure comes from device integration and cost, whilst GaN has taken a dominant position in the wideband power applications. The question about whether

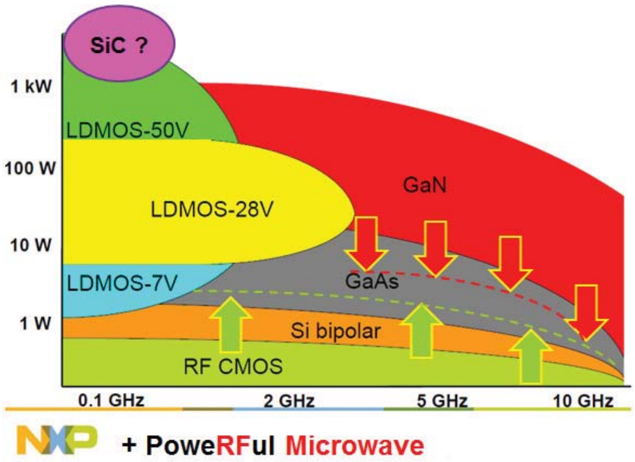

Figure 2, Semiconductor division of the market from NXP with additions by the author.

we are about to see the death of GaAs, a topic covered in an open panel session at the International Microwave Symposium in June this year, does not yet have a conclusive answer, and probably there is enough existing GaAs wafer capacity to meet demand for a good number of years to come. Perhaps the real question is, "will anyone be prepared to invest in new GaAs fabs?"

It has been argued that to some extent the push for GaN has been led by marketing and there have certainly been cases where designs have been proposed that make little commercial sense, for example in earlier generation mobile communications base stations, where the cost advantage of LDMOS far outweigh any performance advantages. On the other hand 4 and 5G systems requiring wider bandwidth and greater efficiency make a strong argument for GaN based amplifiers. The high knee voltages of GaN make them unlikely to ever become a threat in the handset market, but in applications above 2.5GHz the lower output capacitance per watt of output power and the higher output impedance and voltage breakdown will make GaN the dominant amplifier technology.

One fly in the ointment is the dominance of U.S. GaN suppliers. Many European defence market system manufacturers are extremely worried about the use of ITAR to give U.S. based companies an unfair competitive advantage. Although currently there is relatively easy access to GaN devices, they are still export controlled. This has provided impetus to invest in GaN, but the track record is not particularly good. Qinetiq's research sponsored by the MoD came to an abrupt end and Ommic offer a process with a breakdown voltage of only 15V, which seems of little use. UMS have a 0.5µm 50V process which quotes a not overly impressive 1.7W/mm. and is available in 15 and 40W packages. UMS GaN is also available through NXP in their own packages. A 25V 0.25µm process, although touted for a couple of years now has not yet been put on general release. Impressive performance for 6-18GHz MMIC amplifiers was reported at IMS, EuMC, and ARMMS amongst other conferences in 2011/12. These devices produce about 2.5x the power of a similar GaAs MMIC. A few European defence companies are rumoured to have used them in 400W X band PAs, but lack of commercially available devices brings into question yield/reliability. The rated supply voltage of 25V does not take full advantage of GaN capabilities and although some results are quoted as running at 30V, looking a little further shows that these are pulsed measurements. The reported performance of the chip is quite impressive at 37W and 46% PAE; they certainly compare well with the best devices around, but there has to be a question over the performance achievable in production. It is notable that with the production release state of the art now a 50V operating voltage and the announcement by RFMD that they will be migrating to 6” wafers in 2014 [1] it appears that Europe is in serious danger of missing the RF GaN bus.

One group of devices that seemed to be bypassed by the RF community are SiC based transistors. The nature of the semiconductor limits device structure to MESFET, which in turn limits the upper frequency range. Cree offered SiC RF devices in the early 2000s, but has stopped their development in favour of GaN. In Europe Infineon have continued with SiC development for high voltage/power switching applications and as will be discussed later in this paper Siemens are pursuing European development work in the field of SiC high power RF; however its commercial application is not yet clear.

III. INDUSTRIAL AND MEDICAL APPLICATIONS

In a number of applications the RF section of a system is referred to as the ‘power supply’, e.g. Magnetic Resonance Imaging (MRI) and gas lasers. In these applications they are generally narrow band, being targeted at a particular resonance, with very high power levels, up to 10’s of kWs, and can be either pulsed or CW. Ruggedness of the devices tends to be an important parameter due to the poor loads they drive. In the case of exciting plasmas this is also a dynamic load, the impedance of which can change significantly at ‘striking’. Water cooling is usually available, mainly because the driven element of the system, be that the magnet or the lasers themselves tend to be inefficient, and this coupled with the high efficiencies achievable in the amplifiers themselves, results in these applications using some of the highest power RF transistors available.

Gas lasers are becoming increasingly attractive in manufacturing. The tightly controlled beams, no tool wear, very high beam movement speed, and precise power control makes them suitable for volume production lines. Besides cutting, the accurate control allows material texturing. Recently the faded jean market has seen a significant increase in demand as developing countries literally clean up their acts and move away from chemical bleaching to laser fading. Patterns/text/images can be applied to denim jeans, which can be changed instantly when, for example, someone goes out of favour after their most recent tweet! In the food and drink industry, rigorous product control calls for date coding and individual piece identification. The traditional printing approach is being replaced by a laser marking system which is faster, more reliable and has no ink to block nozzles or needing to be refilled.

Micro plasmas generated by high frequency (~2.5GHz) RF signals have applications not only in the cutting and welding industry but also in the automotive for use in spark plugs for a more efficient, dynamically controlled ‘burn’ [2]. Micro plasmas experience the same problem as faced by CO2 lasers, which is the impedance changes before and after ignition. In the approach cited, the change corresponds to a movement in frequency of about 40MHz. To track this frequency shift the match ‘seen’ by the source is measured and the frequency adjusted to compensate for the shift as shown by the block diagram of Figure 3. In this case the design concentrates on producing enough energy to strike the plasma; the sustaining power required is lower.

For laboratory applications including EMC, bandwidth,

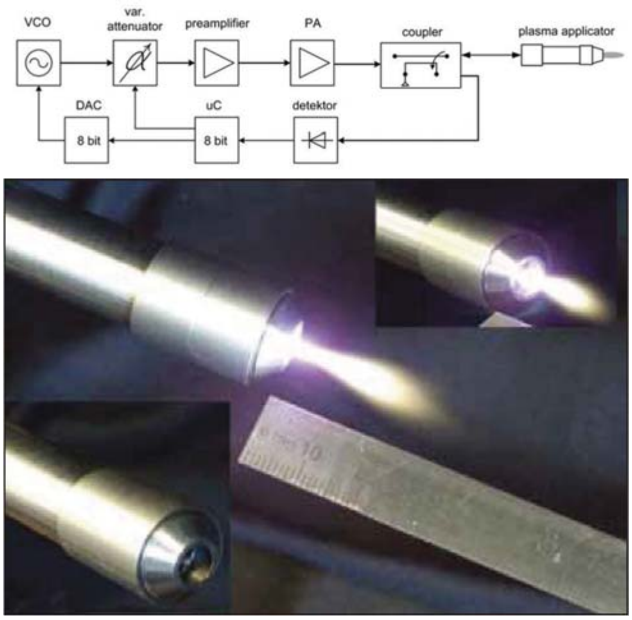

Figure 3, 2.45GHz argon plasma jet for cutting or welding applications at 3400°C.

stability and robustness tend to be the key requirements. Cooling is generally by forced air and although efficiency is not in itself a key parameter, higher efficiency leads to smaller form factor which in itself can be important to customers. The robustness has resulted from the high reliability required by the industry which has led to some suppliers offering 5 year warranties and 48 hour repair turn around on their instrumentation amplifiers. Whilst communications testing often requires high linearity and are therefore run backed-off, Electro-Magnetic Compatibility (EMC) testing tend to run saturated, provided the harmonic power levels are low enough. Another feature of this market is an upgrade path, both in terms of frequency and power so that the customer's investment is protected for longer term evolution of applications. Solid state is the preferred solution in these markets due to robustness, instant availability (no warm-up or preparation time), lower noise figures and lower cost of ownership. European companies fare very well in the market with Milmega and Vectawave both having strong reputations. Interestingly it has now attracted the interest of Rohde & Schwarz who have a long and impressive reputation in the broadcast market.

Although previously Silicon MOSFETs dominated below 1GHz and GaAs above, GaN has made significant inroads into this market which will only increase as the price of GaN falls.

IV. Space Applications

In Space applications spectrum is severely limited due to frequency band allocations and atmospheric propagation loss. In communications systems linearity rather than raw power, tends to be the key Figure of Merit (FoM) for amplifiers, and thus it is important to make comparisons at the actually operating points. An interesting difference in this market segment is the flexibility that solid state amplifiers offer in terms of physical construction and size; travelling wave tube amplifiers tend to be limited by the length required for the tube.

One of the interesting recent developments to improve average efficiency has been to optimise the bias at each power level, similar to a form of Envelope Tracking that has become flavour of the month in the terrestrial communications world, (driven by 4G LTE), such as that championed by the UK company Nujira. Astrium have demonstrated this Electronic Power Control in a 200W GaN amplifier as shown in Figure 4. As can be seen this method extends the >40% PAE band down to an output power of ~69W compared to >170W without EPC. Other methods such as Doherty for increasing efficiency are also applicable.

The space industry is inherently conservative in approach and where possible will tend to re-use a proven technology rather than risk a new development. Despite predictions that by 2015 all UHF and L band flight power amplifiers would be solid state, [3] Europe has opted for TWTA in the Galileo system, -L band, bucking the anticipated trend. It is important to remember that amplifiers don't stand on their own but as part of a total package. A choice made to take a "lower tech" (using existing proven technology) may be made for many reasons, including being first to market. We know that the technically 'best' system doesn't always win in a competitive market.

An important consideration for space systems is radiation hardness; although it has been assumed that GaN will intrinsically be a better material due to the higher band gap energy levels there are not that many published papers relating to this on commercially available devices.

In a study [4] on SAR (Synthetic Aperture Radar) to measure Earths Biomass the high power transmitter was identified as the key risk area. The group decided to test

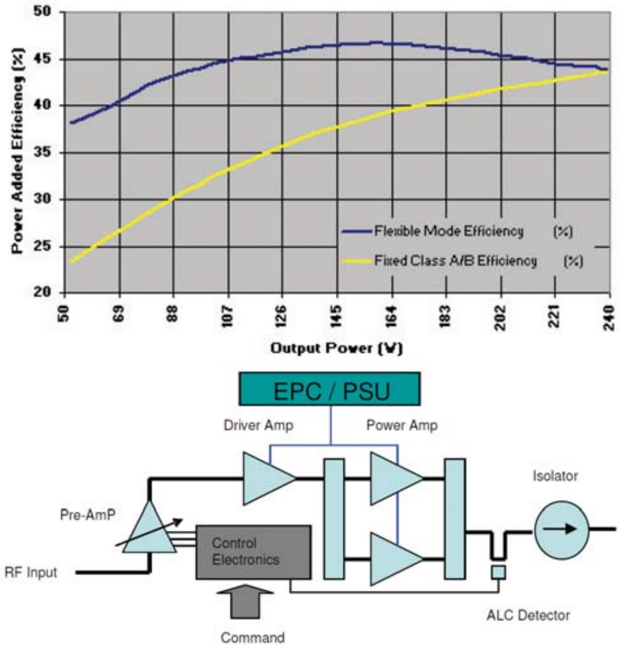

Figure 4, Astrium 200W GaN demonstrator performance using drain bias adjustment for increased PAE.

some realistic LDMOS and GaN amplifiers to see how they stood up in terms of radiation hardness. Although the tests were not directly equivalent, (which shows something of the difficulty in comparing like with like in terms of amplifiers), some comparison can be made. An argument could be made that GaN is more robust, but not exactly quantifiable differences were determined.

In more general radar applications solid state offers lower phase noise, greater modulation flexibility and bandwidth and faster switching than the conventional magnetron approach. A further benefit of the solid state approach is that the output power level can easily be adjusted. Designs tend to be based around the combination of power blocks whereas a magnetron is designed for one particular power level. Until recently these SSPAs were dominated by GaAs devices, now the advent of 50V 0.25µm GaN is expected to make a significant impact on this market.

V. High Energy Physics Applications

In the High Energy Physics (HEP) application space there has been a significant migration from tube based systems to solid state, led primarily by work done at Soleil in France. These systems show how far the building block approach can be taken. Using core amplifier module bricks and repeated parallel combing output power levels of 150kW at 350MHz have been achieved, Figure 5. Using individual LDMOS devices (balanced pairs in a single package) a low cost, highly repeatable module was constructed and the tower system greatly enhanced ease of both build and maintenance. The modular construction also assisted with project risk management; focussing effort on getting the lower power modules right at the start of the project made control of both cost and time scales easier.

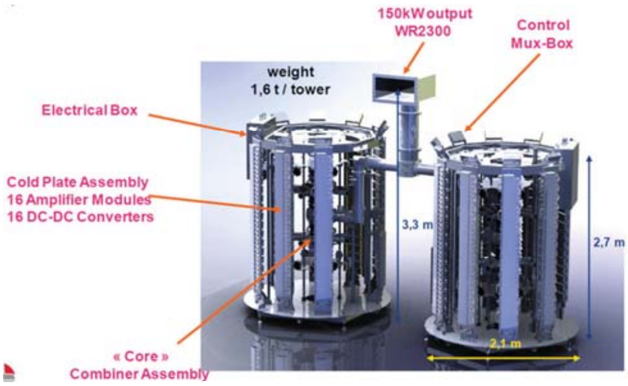

Figure 5, 150kW 350MHz RF source developed by ELTA for ESRF.

The other main advantages listed by the HEP facilities for the move to a solid state modular approach were:

- Increased beam availability
- Distributed heat generation
- No warm up sequence
- MTTR 15 mins
- Lower spares holding costs
- Fault tolerance/preventative maintenance

The approach also allows for device evolution. The original Soleil design was based on 320W modules. A successor project based on the Soleil approach doubled the module output power to 650W [5].

Above 1GHz there has only been one band where solid state has made a significant impact, 1.3GHz, and again with LDMOS devices. Lower power (250-1000W) GaAs power amplifiers have been used in control systems such as the Longitudinal Damping System at the light sources at Stanford and Berkley [6] however the cost and size has prohibited their use at higher frequencies and power levels. Klystrons had been the mainstay of 1.3GHz RF sources however when German accelerator HZDR decided to upgrade its RF source (doubling the power to 80kW at 1.3GHz) they noted that klystron costs had tripled since 1998, whilst SSPAs were falling over the same period. The SSPA solution was significantly larger, 42U 19" rack, however development of the 10kW unit was completed in 9 months from order placement to completion of the first prototype, again because of the modular approach. One problem that occurred due to the adoption of the SSPA approach was due to the 10x greater bandwidth of the SSPA design over the klystron. This was good for temperature stability however it enabled spurious modes to propagate. The solution was an improved Low Level RF (LLRF) unit with high stability and lower phase noise and ramping the lower levels circuits to prevent the modes being generated.

As mentioned earlier in this paper there is some speculation that SiC may find a niche in the HEP and medical accelerator market. Siemens have been conducting research on devices in Germany and Russia to produce very high power pulsed sources, Figure 6, [7]. Operating at drain voltages in excess of 300V, these modules have produced up to 3kW peak and when 32 were used in parallel around the circular power combiner 84kW were achieved. The duty cycle is not clear but could be of the order of <0.1%.

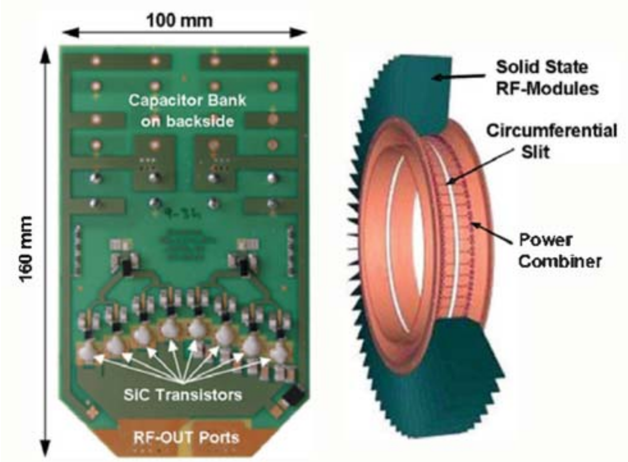

Figure 6, High power SiC module and system under development by Siemens for accelerator applications.

VI. Communications & Broadcast

There has been a significant move to increased modulation bandwidth and complexity as the cost of and competition for spectrum increases whilst the demand for higher data rates seems insatiable. This has seen an increase in peak powers, which has driven the development of systems that can be efficient at the backed off power levels where the systems spend most of their time whilst still having the peak capability. Early solutions at the amplifier level were based upon feed forward techniques were largely unsuccessful and were replaced by digital pre-distortion. Latterly however, Doherty topology has been combined to give increased efficiency over wider power ranges. Working at the handset level much store has been set by systems based on an Envelope Tracking (ET) approach. The almost complete dominance of solid state technology in the mobile communications and the digital broadcast markets is an indication that when it comes to high performance and volume manufacturing there is little alternative (as compared to the high volume low performance of, for example, conventional microwave ovens or the magnetron based marine radar).

VII. Conclusion

The VED industry is a mature market which displays all of the classic traits of reduced innovation, increasing costs and reduced investment. On the other hand solid state device technology is moving at a considerable and increasing pace. The most mature part of this sector, silicon processing is still benefitting from process and materials improvements as shown in Table 1. Observing the development of silicon devices, predictions can be made as to what can be achieved with newer materials such as GaN if the same patterns are followed. Extrapolating the results of smaller geometry, high voltage operation and larger wafer size give relatively predictable accurate results.

Whilst Europe seems to be in a good position to exploit the recent developments in semiconductor technology and in LDMOS is amongst the world leaders through NXP, in GaN we appear to be an also ran. Unless this situation changes drastically, and there is little indication of why or how this would happen, there will be no competive source of European GaN.

VEDs will remain a method of achieving very high power levels particularly above 3GHz for the foreseable future, but below this frequency the operational benefits and the cost of new developments will hand an increasing proportion of the market to SSPAs.

VIII. Acknowledgment

This work was originally started for a workshop as part of IMS2013. Many people contributed their insights and I would like to express my thanks to them, whether I used the material they provided or not; regrettably there isn't the space to do so in this paper.

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