A New Approach to Solid-State High-Power FM Amplifiers

Timothy B. Anderson, CSRE/DRB, CBNT
Harris Corporation
Mason, Ohio

INTRODUCTION

There is high interest among broadcasters and RF network operators in new RF power amplifier technology offering improved efficiency over what is presently available. Continued innovations in transistor design and manufacturing have led to a new generation of solid-state RF power amplifier devices providing significantly higher output power density, and greater efficiency resulting in lower purchase and operating costs with improved RF performance, and robustness on par with tube based RF power amplifiers. These improvements in cost and efficiency are making solid state transmitters more cost competitive with their tube based counterparts.

The benefits of higher power amplifier efficiency include: AC power consumption savings, reduction in physical size, reduction in cooling requirements and reduction of carbon footprint in support of green initiatives.

Recent advances in LDMOS (Lateral Diffused Metal Oxide Silicon) device power density and performance have contributed to significant improvements in RF power amplifier linearity, efficiency and reliability. These devices can be applied to broadcast transmitter designs for terrestrial transmission of traditional radio and television as well as multimedia content, including analog and all worldwide digital transmission standards. Broadcasters around the world are implementing new networks to provide over-the-air transmission of analog and digital content to an ever-hungry audience that demands high quality, reliability of reception and a wide choice of content. The challenge for the broadcaster or network operator, is to provide these services in the most cost-effective and efficient manner, with a minimum of initial investment and lowest long-term cost of ownership.

Harris has been developing transmitter solutions that leverage this latest device technology with new platforms offering significant size reduction and modular architecture for scalability, ease of installation, serviceability and minimal maintenance.

The authors will discuss the history of solid-state FM and the architectures used in FM transmitter RF amplifiers as well as the most recent developments in solid state device technology along with the challenges and solutions of high-power RF amplifier design, cooling, combining, control and power supply systems for the next generation of solid state, high-power, digital / FM transmitters.

TUBE VS. SOLID-STATE

Solid-state power amplification has many advantages over tube technology. Redundancy and soft failure modes, lower maintenance requirements are the hallmarks of solid-state transmitters. Broadband output tuning makes possible N+ 1 configuration where a single backup transmitter can cover multiple frequencies without the need for retuning for each frequency.

Aside from the obvious safety advantage, lower power supply voltage requirements also reduce the size of the power supplies and RF systems.

FM broadcast transmitters with solid state power amplifiers up to approx. 10 kW provide equal or better overall AC to RF efficiency than tube-based power amplifiers.
Still, single-tube transmitters at power levels above 10kW offer a significantly lower purchase price and long term operating cost.

EARLY FM SOLID-STATE

Solid-State FM transmitters were rather slow to take off compared to solid-state MW AM. Successful solid-state AM broadcast transmitters were introduced in 1975 with the Harris MW-1.

Solid-state FM transmitters were much slower to appear due to the lack of suitable devices for VHF frequencies. Higher power solid-state FM transmitters (above a few hundred Watts) took even longer to develop.

The first solid-state FM transmitter was introduced at the 1974 National Association of Broadcasters Convention by Sparta. Their Model 600B was a 250 Watt all solid-state transmitter using 2 combined 150 Watt amplifiers. The amplifiers each used two parallel driven BM70-12 12 volt bipolar transistors made by Communications Transistor Corporation.

Figure 1 - Sparta 600B Transmitter

With 12 Volts and 36 Amperes of collector current, when properly tuned, the 600B could deliver 250W at 58% PA efficiency and around 38% AC-RF efficiency. The 600B including exciter sold for $6,500 in 1974 or about $28,500 in today's dollars, a bargain at less than $100/Watt. The first four units were sold to The Canadian Broadcasting Corporation and a total of 38 units were ultimately sold.

In 1983, Elcom-Bauer introduced the SS-250 using 24 volt amplifiers made by Acrian. Both the 600B and the SS250 were designed by well know Bauer Engineer Richard B. Johnson.

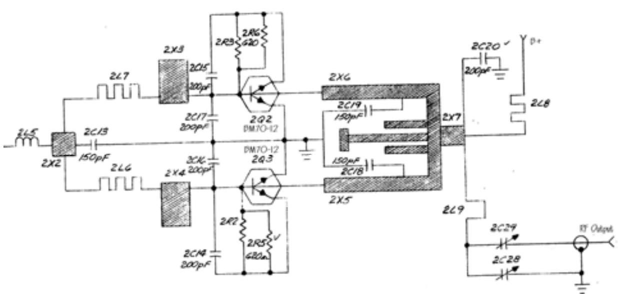

Figure 2 - Sparta-Bauer 600B PA Schematic

In December 1983, QEI delivered the first solid-state 1kW transmitter.

The QEI 695T1KW, employed three Wilkinson combined power blocks of four each 50 volt, Acrian S175-50 Watt bi-polar transistors The 695T1 carried a list price of $16,990 or $35,600 in today's dollars which brought the price down to less than $36 per Watt. Solid-state FM had begun to become affordable.

With the availability of higher power devices in the early 90's, higher and higher power levels were being achieved by several manufacturers. In 1996, Harris introduced the Platinum Z line of solid-state FM transmitters with power capabilities of up to 10kW in a single cabinet and multiple cabinets could be combined up to 40kW. At 10kW, the Z10 could be purchased for around $36, 000. In today's dollars, that comes to about $58,000 or less than $6 per Watt.

Figure 3 - QEI 695T1KW 1 KW Transmitter

As new, higher power devices have been brought to market, the cost of solid-state transmitters has continued to decrease. Today, the purchase price of a quality 10 kW FM transmitter is under $5 per Watt.

EVOLUTION OF SOLID-STATE AMPLIFIER TECHNOLOGY

Bipolar Transistors

The invention of the Bipolar Junction Transistor or BJTs in 1948 began the revolution in electronics that we continue to witness today. RF power amplification requiring relatively large, fragile, power-hungry vacuum tubes became theoretically achievable with small, mechanically rugged, power-thrifty silicone devices.

A bipolar transistor is the simplest and earliest form of the semiconductor devices used for power amplification. Bipolar transistors work as current-controlled current regulators restricting the amount of current passed from the emitter to the collector (NPN) according to a small, controlling current applied to the base.

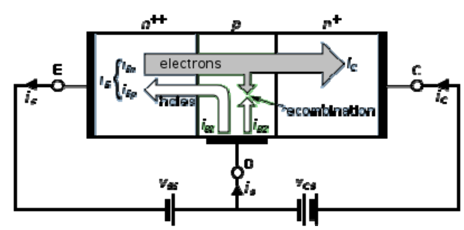

Figure 4 - Bipolar Junction Transistor Structure

The earliest solid-state FM transmitters used 12 volt BJTs such as the CTC BM70-12 configured as a common-emitter amplifier where the input drives the base and the collector delivers the output while the emitter is grounded. Two or more devices were often driven in parallel to lower the output impedance and provide higher output current.

BJTs have significant short comings as VHF FM RF amplifiers. Because of the very low input and output impedances of the devices, the matching networks were quite High-Q resulting in a very narrow bandwidth making them difficult to match and decouple. They have relatively low gain and low efficiency. BJTs have a positive temperature coefficient and are prone to thermal runaway. As the device draws more current its temperature rises, hence even more current is drawn resulting in a further temperature increase until the device fails. These characteristics make bipolar transistors too fragile for high-power RF amplifier applications.

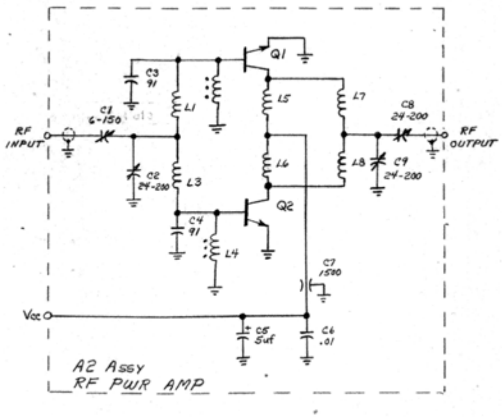

Figure 5 - QEI 300W PA amplifier

VMOSFETs

The vertically-diffused Metal–Oxide-Semiconductor Field-Effect transistor or MOSFET was a game changer when it was introduced in the late 1980s. In MOSFETs, a small control voltage on the oxide-insulated gate electrode can induce a conducting channel between the two other contacts called source and drain. It has become by far, the most common RF transistor supplanting the BJTs that once held that title.

As RF amplifiers, MOSFETs have superior characteristics when compared to BJTs on the following points:

- Thermal stability
- Frequency stability
- Improved linearity
- Higher gain
- Increased ruggedness
- Lower noise
- Lower feedback capacitance
- Simpler bias circuitry
- More easily matched input impedance
- Better IMD performance
- Lower thermal resistance

MOSFET devices are best suited for RF amplification of digital modulation waveforms requiring high peak power capability, wide frequency range, high linearity and good ruggedness performance. They can be used in class AB mode by reducing the output power until the desired linearity is achieved, where as a comparable bipolar transistor could only attain the same linearity in class A mode, requiring high current consumption and very low efficiency.

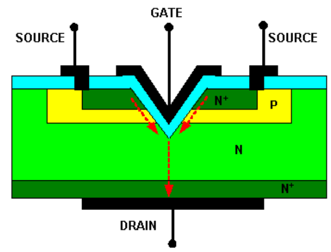

Figure 6 - VMOSFET Structure

The Vertically diffused MOSFET transistor is named after the V-shaped groove architecture shown in Figure 6. The increased gate surface area provides higher current handling and blocking voltage capability, better reliability and improved stability even in the presence of severe mismatch. The power, stability, reliability, and efficiency of high frequency MOSFET RF Power Transistors make them especially well suited for many RF power amplifier applications. VMOSFET power devices such as the Freescale MRF-151 and the NXP BLF-177, have been used for high power FM RF amplifier applications since the early 1990s and are currently used in Harris' Platinum Z and ZX lines of high power FM transmitters.

ENTER THE LDMOS-FET

The Laterally Diffused Power MOSFET (LDMOS) is an asymmetric MOSFET designed for low on-resistance, higher blocking voltage and current handling capability than their VMOS counterpart. Combined with a short channel length and high breakdown voltage, these characteristics make them very attractive for high power RF amplifiers in many applications. Harris has had a great deal of experience with these devices. LDMOS devices are currently used in Harris' Maxiva™ UHF and VHF television transmitters, as well as the Platinum™ series L-band television transmitters. LDMOS power amplifiers are also used extensively in communication base stations, cellular systems, wireless communications and radar systems.

Recent developments in LDMOS device technology have resulted in major improvements in power density and maximum power output. VHF Band II LDMOS that use a 50 volt structure realize a dramatic increase in power per device, linearity and efficiency.

The gain of each device is approximately 21 dB, a substantial increase over the current 48 Volt VMOS devices that typically offer 14 to 15 dB gain per device. This increased gain allows a reduction of the driver stage's power of by up to half.

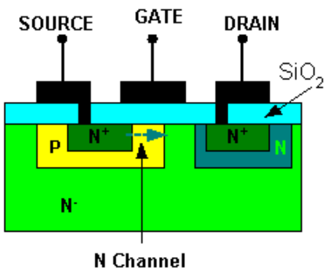

Figure 7 LDMOSFET Structure

Another important feature of the new 50-volt LDMOS devices is the ruggedized qualities with which they have been designed. This ruggedization allows them to tolerate extreme VSWR reflections of up to 65:1, pulsed at full rated power, at all phase angles and then to operate at their full 1250Watts rated power..

POWER LEVEL REQUIREMENTS

A wide range of power levels is required to fulfill the varying needs and applications of FM broadcasters around the globe. Some analog FM stations have transmitter output powers of 40 kW or higher. On the other end of the scale, there are low-power transmitter requirements that can be less than 100 Watts. As you can imagine, a 400:1 range in power levels cannot easily be accommodated with one design, or a single technology approach.

With the advent of HD Radio™ in the US and other digital formats around the world, higher average power, higher peak power and higher efficiency solutions are needed. FM transmitters must be linearized for digital mode amplification. Typically, linearized transmitters run in class AB mode where the amplification devices are never fully driven to cutoff. This is relatively easy to accomplish in modern solid-state or tube transmitters but linearization comes at the price of power and efficiency. Typically, with the linearization and the additional headroom required for the high peak-average ratios of OFDM modulation, transmitters need nearly twice the peak power of that required for analog. Using the new LDMOS devices, with a peak envelope power rating of 1.25kW running at an average power of 850W the new devices have sufficient headroom to allow minimal back-off when running HD Radio™ or other digital high peak-to-average modulations .

The desire for higher power densities, lower cost per watt and increased operating efficiency has driven the development of solid-state amplifier technology. For many years Tube based amplifiers have reigned supreme in these categories. For the most frequently used power range of 1 kW to about 10 kW average digital power, these new solid-state devices that can readily fulfill the requirement, providing important benefits — safety, simplicity and stability —over tube-type designs.

POWER DENSITY

Amplifier power density is the key to reducing both the size of the transmitter and the cost of manufacturing and purchase. 50 Volt LDMOS makes possible fewer devices in a more compact and lower cost transmitter than ever before. Contemporary solid-state FM transmitter designs can achieve about 10 kW analog power per 19" rack cabinet or put another way, about 625 Watts per cubic foot. By taking advantage of the higher per-package power levels of these new devices to develop new transmitter with nearly double that power density, we can achieve 20 kW in the same 19" rack or around 1250W per cubic foot.

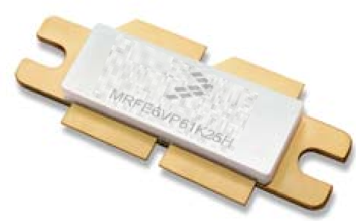

Figure 8 - New 50 Volt LDMOS Gemini Flat-Tab Package

The new 50 Volt LDMOS device shown in Figure 8 is a dual "Gemini" device package rated at 1.25 kW of peak envelope power. This is nearly 4 times the power of the VMOS devices used in previous-generation transmitters as well as many current-generation transmitters using 250 W "single" VMOS power devices.

A new RF pallet has been developed to conservatively deliver 825 Watts of analog power using a single Gemini device operating in a push-pull configuration.

POWER DENSITY AND COST

The cost increase of higher power in solid-state transmitters is linear and is at a premium at power levels above about 15kW with the current VMOS technology as compared to tube based transmitters. There is a 1:1 ratio for power vs. cost. Doubling the power output requires doubling the size or number of power supplies, the number of output modules and the number of combiner ports used thus doubling the manufacturing and acquisition costs. The cost of tube based transmitters flattens at higher powers.

The most practical method of reducing the cost of solid-state high power FM transmitters is to dramatically increase the density of the power supplies and power RF amplifiers. By reducing the cost per Watt of the devices themselves it is possible to gain a significant advantage by tilting the cost model line slope in a downward direction. As shown in Figure 9, by leveraging the lower cost of higher power density devices, it is possible to raise the solid-state "premium" power level to well over 20kW, on parity with tube based transmitter costs.

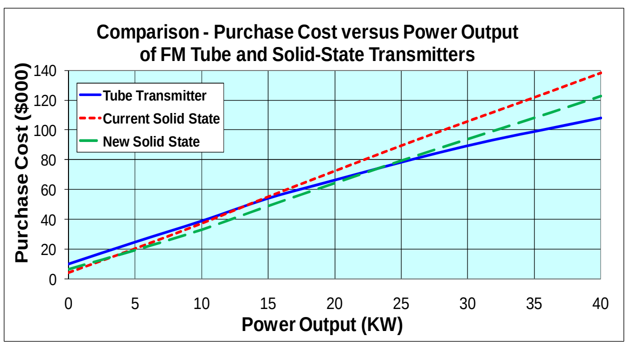

Figure 9 Cost vs. Power for Tube and Solid-State Transmitters

DEVICE SELECTION FOR A NEW GENERATION

Several LDMOS devices were initially evaluated as possible candidates for the new high-power FM module.

With similar specifications, several devices met or exceeded our requirements in power density, gain and efficiency.

These devices have been successfully used in industrial, scientific and medical (ISM) markets where there are potentially destructive impedance mismatch conditions encountered in applications such as CO^2 lasers, plasma generators and magnetic resonance imaging (MRI) scanners

The LDMOS device ultimately selected passed all of our stress tests for incorporation into Harris' next generation FM module

AMPLIFIER PALLET DESIGN

The RF amplifier pallet design uses a single Gemini package with the two LDMOS devices driven in a push-pull configuration which suppresses even-order harmonics. The devices are biased into class C operation when running FM analog and class AB operation when operating in digital modes. Load lines are optimized for maximum efficiency at the top of their power curve at 50 volts. Automatic drain voltage control is utilized to maximize efficiency as output power is decreased. Onboard control and monitor circuits provide protection for the devices.

DISSIPATION AND COOLING

Temperature is the silent killer in the semiconductor industry. For the most part, metal migration at high temperature and current, is the primary concern when dealing with high temperature. Other parasitic problems may be onset by high junction temperatures.

The high efficiency of the LDMOS devices reduces the overall power dissipation into the heat sink. In addition, the lower thermal resistance of the LDMOS device architecture reduces the junction operating temperature making the device easier to cool. Keeping the maximum temperature under the worst operating condition below the recommended 180°C becomes challenging when working with 1000W devices. Designing for the worst dissipation conditions, we must not only consider maximum ambient temperature, but maximum VSWR at which the device may be operated at full power.

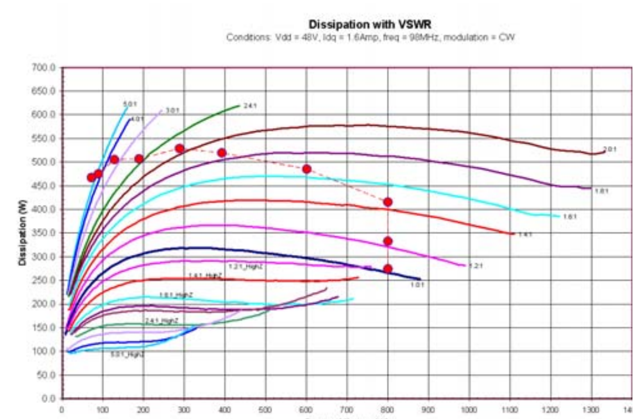

Figure 10 - Impact of VSWR on Dissipated Power

Under the worst angle of reflection, dissipation power in excess of 400 Watts may be expected. This translates into over 60°C of temperature rise across the device. With 55°C ambient temperature, the temperature drop across the heat sink cannot exceed

60°C, imposing a very careful selection criteria on the air cooling system.

NEW ARCHITECTURE FOR HIGH POWER

A modular approach was taken in the overall design of a transmitter system that accommodates the new LDMOS amplifier. A 16 RU, 10kW, power unit is the primary building block of the system. The 10 kW block consists of a chassis frame containing a dual redundant IPA, 7 hot-swappable power supply modules, 7 hot-swappable power amplifier modules and a compact, high-efficiency 14-way Wilkinson coaxial combiner, low-pass filter, and directional coupler unit. Transmitter control, user interface and optional modulator are located in the upper compartment bay. The power amplifiers are air cooled. Airflow is provided by five rear-panel mounted 6” variable speed fans. The maximum fan speed produces around 900 CFM of airflow and is regulated by system temperature. Air is drawn in from the front and exhausted to the rear.

Figure 11 - 1725 Watt PA Module

This transmitter architecture uses two identical RF pallets per 7”x 10” x 4.6” plug-in PA module, resulting in a very compact and power-dense module design. The PA module shown in Figure 11 is rated at 1,725 Watts analog power and over 2400 Watts of peak dissipation.

As the PA module power has doubled, so too has the power supply module requirements. To improve the power supply density, a new high-efficiency switch-mode power supply was implemented. Each PA module is powered by an independent 2750 Watt power supply. Voltage to each module is automatically optimized for best PA efficiency for a given power output. The supplies are universal power input and will operate from 190-264 Volts, 50 or 60 Hz AC and may be wired as single or 3-phase as needed. In the case of 3-phase, the loss of one or two phases will still permit the transmitter top operate at reduced power.

PA control functions including mute, fault monitoring, and protection logic are located on each PA module. Current, forward power, VSWR, and temperature are monitored on the module and reported to the hardware based system controller. A hardware-logic based system controller manages the Automatic Power Control, ON, OFF, Raise and Lower control as well as providing metering telemetry of the system providing basic life-support architecture. Data and command control from the hardware based system controller are passed to an advanced microprocessor based controller which runs the front panel user interface as well as Web server and SNMP interfaces.

By combining power blocks with modular “in-rack” hybrid combiners and the integrated control system, power levels of 20, 30 and 40kW can be achieved. The system is designed to provide 20kW per 19” x 44 RU rack with two racks providing up to 40kW and is scalable to 80kW and beyond.

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