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Producing Power With Tubes And Transistors

High-power RF and microwave signal levels are produced by both vacuum tubes and transistors in military systems, with demands for ever-increasing efficiency and smaller size.

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High-power amplification at RF and microwave frequencies still involves vacuum tubes in many military systems. Such devices as traveling wave tubes (TWTs) in TWT amplifiers (TWTAs) and cross-field amplifiers (CFAs) are capable of hundreds of watts of continuous-wave (CW) power and kilowatts of pulsed (peak) power in ground-based and airborne systems, and they have served as reliable RF/microwave amplifiers even in space-based applications. But in recent years, claims of “vacuum-tube replacements” from solid-state device manufacturers have been often bold and loud, touting newer device technologies such as silicon carbide (SiC) and gallium nitride (GaN) as the solution for producing the high power levels needed at high frequencies in electronic warfare (EW), electronic countermeasures (ECM), radar, and other military and aerospace systems. What is the truth about real RF/micro-wave power? Can transistors deliver the power levels at the same frequencies as their vacuum-tube counterparts? The answers can be found by comparing the technologies and the power levels available from each, along with related issues, such as power consumption, efficiency, and linearity.

Long before power transistors were being considered for military and space transmitter applications, TWTs were boost-ing signals in satellite communications and other systems in which reliability was of the utmost importance (see sidebar). The reliability of these devices has been impressive over the years, but military system designers have long sought amplification solutions that are smaller in size and lighter in weight, especially in space-based and airborne systems. Because of this search for more compact solutions, military research dollars over the last several decades have helped with the development of semiconductor materials that support higher-frequency, higher-power transistors, such as gallium arsenide (GaAs), gallium nitride (GaN), and silicon carbide (SiC). And, while TWT and TWTA suppliers may have grown weary of hearing about the phenomenal potential performance levels of these newer transistors, they have also benefitted from the military need for more compact forms of amplification, in their development of small but powerful microwave power modules (MPMs) based on miniature TWTs.

So what is the truth? Can transistors match the power levels of vacuum-tube devices such as TWTs and CFAs? As a wise man once said, “that depends.” It depends on many factors, including frequency range, instantaneous bandwidth, and how many devices are needed to reach a given power level. And this last factor is one of the chief differences in how transistors and tubes are used within a system because, at some frequencies, a solid-state amplifier can be designed and built with the same output power as a TWTA, although it will generally require multiple transistors to match the output power of a single TWT. While it is possible to sum the contributions of many power transistors to achieve relatively high power levels, it also requires sacrificing some of that power to the insertion loss of power combiners in multiple-transistor amplifiers.

TWTs are elegant in their simplicity and reliable because of the small number of parts. TWTs can be designed with different types of components, but common to all types are some form of electron gun, a slow-wave structure, such as a helix, high-power magnets to focus the emitted electron beam, a collector, and some form of input and output couplers to inject and collect an RF or microwave signal. In essence, the injected RF/microwave signal interacts with the electron beam in the slow-wave structure, with a resulting transfer of energy from the electron beam to the electromagnetic RF/microwave signal. The amount of energy transferred is characterized by several TWT parameters, such as output power, gain, and efficiency. As its name implies, the collector is the end point for the electron beam and is designed to effectively dissipate its remaining energy.

Two of the more popular TWTs in use in military systems are those with a helix slow-wave structure and coupled-cavity TWTs, which use a slow-wave structure formed of a series of cavities coupled by slots. Over the years, improvements in the cathodes used as electron guns have increased the reliability of TWTs and TWTAs, while also supporting higher current densities. Also, smaller, higher-powered magnetic circuits, such as periodic structures, have resulted in smaller tubes without sacrifices in output power. These smaller tubes and tube amplifiers are particularly attractive for weight-sensitive airborne applications requiring high transmit power, including in unmanned aerial vehicles (UAVs). By applying three-dimensional electromagnetic (EM) simulation software, TWT designers have also been able to closely study the EM field interactions of different tube components in order to refine physical structures and improve output power and efficiency. In addition to TWTs and CFAs, high-power vacuum-electronic devices employed in military systems include kly-strons (usually as amplifiers) and magnetrons (usually as oscillators).

On the transistor side, the variety of power devices seems to be growing decade by decade. Early high-power devices were silicon bipolar transistors used mostly in pulsed applications with short duty cycles. But following the development and qualification of enhancement-mode silicon MOSFETs, they were found suitable for both CW and pulsed applications, and generally required much simpler impedance matching networks for broadband operation. Yet, both devices were limited in frequency range, prompting development of higher-frequency substrate materials, including indium phosphide (largely used for lower-power, millimeter-wave frequencies) and gallium arsenide (GaAs) in both discrete device and integrated-circuit (IC) forms. Major investments, including the DoD’s microwave and millimeter-wave monolithic microwave integrated circuits (MIMIC) program of the mid-1980’s and early 1990’s, have made GaAs the material of choice for both low-noise and power microwave transistors. Still device developers have sought higher power densities from transistors using a number of substrate materials, including GaN, SiC, GaN on SiC, or mat-erials with excellent thermal conductivity, such as sapphire or diamond.

Transistor Power

How do the amplifiers based on these advanced transistors compare with TWTA designs? Perhaps a sampling of available devices and amplifiers might better tell the story. ECM and EW systems are among the most demanding of military applications, both for their power requirements and their multi-octave bandwidths. Although solid-state devices are capable of tube-like power in pulsed operation, most if not all of the devices are targeted at narrower bandwidths. For example, Microsemi supplies the old and the new, offering both silicon bipolar transistors and newer devices based on SiC. The firm's model 3134-100M is a common-base silicon bipolar transistor that operates from 3100 to 3400 MHz with 100 W output power when driving pulsed signals with 100-microsecond pulse width and 10-percent duty cycle. When operating from +36 VDC, the device achieves 40-percent collector efficiency and 9.3 dB gain, requiring an input signal at 16 W to reach the rated output power level.

The firm also offers a series of SiC static-induction-transistor (SIT) devices and power amplifier modules, including the model 0405SC-1000M transistor, rated for 1000 W pulsed output power from 406 to 450 MHz when operating from a +125-VDC supply. The output power is achieved at 450 MHz with 50-percent minimum drain efficiency when using 300-microsecond pulses at 10-per-cent duty cycle. In addition, Microsemi supplies a series of solid-state devices and modules for S-band radar systems. Models 3134-65M and 3134-100M are power transistors with 65 and 100 W pulsed output power from 3100 to 3400 MHz while models 3134-180P and 3134-200P are power amplifier modules rated for 180 and 200 W from 3100 to 3400 MHz. Designed for use with 100-microsecond pulses at 10-percent duty cycle, the transistors prom-ise better than 40-percent col-lector efficiency.

In that same 3.1-to-3.4-GHz S-band radar range, Cree supplies its model CGH31240F high electron mobility transistor (HEMT) based on GaN. When operating with 300-microsecond pulses at a 10-percent duty cycle, the device achieves 240 W peak power with 16.6 dB gain and 50-percent efficiency at 2.8 GHz. The firm's model CGH40120F GaN HEMT is an unmatched +28-VDC device rated for 120 W saturated output power. It has been used in a reference amplifier with 1200-to-1400-MHz instantaneous bandwidth, 100 W CW typical output power, 16-dB typical small-signal gain, and 75-percent typical power-added efficiency.

Based on silicon MOSFET technology, the model HVV0912-150 transistor from HVVI Semiconductors is designed for use from 960 to 1215 MHz in L-band avionics applications such as TCAS, IFF, and DME systems. It provides 150 W output power with 20-dB gain when driving 10-microsecond pulses at a 10-percent duty cycle. It can operate on supplies from +24 to +50 VDC and delivers 43-percent efficiency. Its unique vertical device structure allows it to operate into mismatches as severe as a 20.0:1 VSWR without damage.

Among the higher-power silicon bipolar transistors, the IB1011S1500 from Integra Technologies is designed for L-band radars at 1030 and 1090 MHz. When fed with a 150-W pulsed (10-microsecond, 1-percent duty cycle) input signal at 1030 MHz, it yields 1432 W peak output power with 48.8 percent efficiency. For more broadband use, the firm's model IB0912M600 bipolar handles L-band TACAN chores from 960 to 1215 MHz. It offers 845 W peak output power and better than 56-percent efficiency at 960 MHz when driving a 90-W pulsed input signal. Both transistors are housed in beryllium-oxide (BeO) packages for good thermal dissipation.

In terms of continuous power and bandwidth, the model NPT1007 GaN-on-silicon transistor from Nitronex can provide 90 W CW power from 500 to 1000 MHz, and 200 W CW output power at 3-dB compression (saturation). The device is usable from DC to 1200 MHz. Usable with supplies from +14 to +28 VDC, the transistor boasts 63-percent typical drain efficiency at 3-dB compression. Additional high-power transistor suppliers include Freescale Semiconductor, with its model MRF6V1430H silicon LDMOS device delivering 330 W peak output power with pulsed (300-microsecond, 12-percent duty cycle) signals from 1.2 to 1.4 GHz, TriQunt Semiconductor, with Powerband GaAs PHEMT devices capable of 50-W pulsed output power from 0.5 to 2.0 GHz, and IXYS RF, with 150-V MOSFETs capable of as much as 550 W CW output power at 175 MHz, and P1dB (www.P1db.com), with silicon bipolars offering as much as 200 W output power in DME and TACAN applications from 960 to 1215 MHz.

Continue on Page 2

Designing transistors into amplifiers, CTT, Inc. has developed a compact GaAs FET unit capable of 80 W pulsed output power from 9.1 to 9.7 GHz in UAV SAR applications (*Fig. 1*). It is designed for use with 250-microsecond pulses at 25-percent duty cycle and provides as much as 54 dB gain with noise figure of 10 dB. It measures 7.0 x 9.0 x 1.2 in. and draws 5.1 A maximum current from a +28-VDC supply. The firm has also created a multi-band amplifier system for use at X- and Ku-band radar frequencies. It combines two amplifier subsystems operating at 10.1 to 10.6 GHz and 13.9 to 14.4 GHz, with at least 28 W (+44.5 dBm) saturated output power in both bands.

At lower frequencies, Power Module Technology supplies high-power amplifiers based on LDMOS technology, including model PM400-1000-200, with 200 W output power at 1-dB compression from 400 to 1000 MHz. It features 19-dB typical gain and 40-percent efficiency. The pallet amp (*Fig. 2*) measures 2.3 x 6.5 x 1.0 in.

Empower RF Systems has leveraged GaN transistors into its broadband model 2143-BBS6A8CHM Class AB amplifier, which offers 50 W saturated CW output power (but 20 W at 1-dB compression) from 3 to 6 GHz. It provides at least 47 dB gain and can hit 0-dBm input signal. It is ideal for a number of applications including testing when sup-plied in a rack-mount housing.

Herley Power Amplifier Systemsincorporates liquid cooling to create some of the highest-powered solid-state amplifiers in the industry, albeit at limited bandwidths, using six bands to cover 1.5 to 3000 MHz. Units operating from 1.5 to 30 MHz are available with as much as 10 kW peak output power, while amplifiers working in the highest frequency band (1900 to 3000 MHz) offer as much as 100 W CW output power. The amplifiers are designed for fixed and mobile EW jamming applications.

TWT Power

Communications and Power Industries, among several other companies, sells amplifiers based on TWTs and transistors, sometimes in the same unit. The firm's research into GaAs FET and TWTA amplifiers operating in satellite communications systems from 5.9 to 6.4 GHz (available in the form of a paper on its web site by Stephan Van Fleteren, “Traveling Wave Tube versus Solid State Amplifiers”) points out similarities in performance between the technologies, although with key differences in gain and efficiency favoring tubes.

In addition to the company's legacy (as the former Varian Associates) in TWTs, its Beverly Microwave Division has long been known for high-power CFAs. The model SFD 251H, for example, is capable of 500 kW output power from 9.5 to 10.0 GHz for use in X-band radar systems. It operates with 1-microsecond pulse widths at 0.001-percent duty cycle and features a water-cooled anode to enhance reliability. In addition to helix and coupled-cavity TWTs and MPMs, L-3 Communications Electron Devices (www.l-3com.com/edd), with a legacy from Litton Industries, offers CFAs from L to X-band, with power levels from 60 kW to 5 MW peak for advanced radar systems, including the Aegis AN/SPY-1 and the Patriot missile system.

dB Control, which recently joined the HEICO Electronic Technologies Group of companies (www.heico.com), has developed a series of TWT-based MPMs for military applications requiring smaller, lighter sources of RF/microwave power, including in manned and unmanned airborne platforms. The firm's model dB-4118 MPM (*Fig. 3*), for example, is a conduction-cooled MPM that delivers 100 W CW output power from 6 to 18 GHz.

Suitable for airborne use, it features a high-speed modulator for pulse modulation at pulse repetition frequencies (PRFs) to 250 kHz. Another compact MPM, model dB-3758 MPM, generates 1 kW peak output power from 9 to 10 GHz at a 6-percent duty cycle. Designed for X-band radars, it synchronizes the power supply switching frequency with a radar system clock and performs blanking during the pulse to minimize noise.

e2v, formerly English Electric Valve, is a long-time supplier of high-power vacuum-tube devices for military applications and has made considerable progress in recent years in the development of smaller TWTs for broadband applications (see sidebar). The company's model N10110 is a TWT with two helix sections and PPM focusing. It measures just 330 x 50 x 62 mm with SMA input connector and WRD-650 waveguide output, but delivers at least 180 W CW output power from 6 to 18 GHz with at least 38-dB gain and 18-percent efficiency. Model N20181 is a helix TWT designed for use from 4.5 to 18.0 GHz. It provides at least 100 W CW output power at 4.5 GHz, 130 W at midband, and 120 W power at 18 GHz. The minimum gain across the bandwidth is 42 dB. The tube has served as a baseline for the design of the model N20180 (*Fig. 4*), a single TWT capable of more than 100 W CW output power from 2 to 18 GHz.

The TH 4092 TWT from the Thales Group incorporates a four-stage collector for high efficiency of better than 50 percent. It delivers 350 W CW output power and as much as 500 W peak power from 27 to 31 GHz with typical gain of 46 dB.

AR-RF/Microwave Instrumentation incorporates TWTs in broadband amplifiers for test applications. The company's model 2000T8G18 transforms 0-dBm input signals from 7.5 to 18.0 GHz to 2 kW CW minimum output power (minimum gain of 63 dB). The forced-air-cooled system is not small, occupying four rack-mount enclosures measuring 22.1 x 63.0 x 32.4 in. and weighing 2600 lbs.