July 2009
Vol. 32 • No. 7

The AOC Electronic Warfare Publication
www.crows.org

JED

The Journal of Electronic Defense

Advancing TWT Technology

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Advancing TWTs

The Traveling Wave Tube Lives On… and On

By Barry Manz

For generating truly impressive amounts of radio frequency (RF) power, especially over broad bandwidths at frequencies from 4 GHz to 100 GHz, nothing beats a vacuum electron device (VED) and, in particular, a traveling wave tube (TWT). As a result, while the markets for VEDs (vacuum tubes in the vernacular) are flat according to most reports; klystrons, crossed-field amplifiers, gyrotrons, magnetrons, inductive output tubes (IOTs) and TWTs will continue to generate hundreds of millions of dollars in revenue thanks to their use in defense, scientific and medical applications.

While solid-state RF power transistors are slowly creeping upward in efficiency, output power and frequency, their ability to produce the megawatts of power from a klystron at 40 GHz or 250 kW from a TWT remains far out on the horizon. RF power transistors based on gallium arsenide (GaAs), silicon (typically bipolar junction transistors or BJTs and LDMOS FETs) or gallium nitride (GaN) – the defense industry's compound semiconductor technology – are being deployed in improvised explosive device (IED) jammers and other comparatively low-power electronic warfare (EW) systems.

However, in many EW systems, performance over very broad bandwidth is paramount and tubes reign supreme and likely will remain so for years. In short, industry prophets and the media have predicted for years that VEDs of all sorts would soon be relegated to microwave lore, victims of the inexorable march of semiconductor technology. But as we move toward the second decade of the 21st century, VEDs still are not just viable but essential for military and commercial applications alike.

A TUBE, YOU SAY?

Vacuum tubes are not in the vocabulary of almost anyone born after about 1970, unless they happen to be amateur radio operators or audiophiles seeking that "tube sound." Even to designers in the commercial wireless industry, vacuum tubes either are archaic or irrelevant. However, designers of EW systems, satellite communications transponders or broadcast transmitters are well-acquainted with the unique benefits provided by TWTs. For proof, consider that there currently are at least 300,000 TWTs and other VEDs employed in nearly 300 US defense systems of various types, with radar, EW and satellite communications systems being the largest consumers.

Even though government funding of VED development has been spotty in recent years, TWT development is hardly standing still, not just in the United States but in many countries. This year's International Vacuum Electronics Conference (IVEC) in Rome, sponsored by the European Space Agency, included papers from the United States, Russia, China, Korea, Germany, Israel, Switzerland, France, Italy, Ukraine, Norway, India,

TWT and MPM Manufacturers

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Brazil, the Netherlands, Belgium, Canada, Taiwan and even Belarus. US TWT manufacturers spend considerable sums every year to advance TWT technology and manufacturers like dB Control (as well as L-3 Communications and others) are refining TWT and power supply integration to increase frequency coverage, efficiency and reliability and reduce TWT assembly size, weight and cost.

This is not to say that TWTs have short operating lifetimes; many can operate for 100,000 hours (more than 11 years) of continuous service at their rated RF output powers. While not a patch for conservatively operated solid-state power amplifiers, this is well-matched to the lifetime of satellite communications transponders, as well as radar and EW systems that can remain in service for decades. Replacing a TWT also is relatively easy and cost-effective, which cannot be said for amplifiers based on transistors, as the sheer number of them required to match TWT-level output levels makes for a complex design challenge.

THE TWT DEMYSTIFIED

A TWT is an inherently high-gain, low-noise amplifier that can operate over greater bandwidths than a klystron. It uses a slow-wave structure (either a helix or coupled-cavity circuit) that creates an interaction between a high-energy electron beam and an RF wave in a vacuum envelope. A heated cathode generates electrons in an electron gun assembly and launches them into the interaction region. An electrode turns the beam on and off by switching the bias of the control electrode either to positive or negative with respect to the cathode. The modulator in the transmitter switches the bias voltages that produce a transition from conduction to cut-off states.

The electron beam itself is focused by magnets that are placed along the axis of the TWT and is accelerated by a high potential between the cathode and the anode (collector). The result is that the RF wave propagates from the input to the output of the device through the slow-wave structure, the electron beam transferring energy to the RF wave as it travels along the tube's axis. This produces a high level of amplification at the TWT's RF output.

Critics point to the TWT's need for kilovolt-level power supplies that can be large, heavy and costly, an indisputable fact at least in TWT amplifiers (TWTAs) employed in very high-power EW and radar systems. But to be fair, the comparatively-low RF output of even state-of-the-art RF power transistors designed for high microwave or millimeter-wave frequencies means that dozens or even hundreds of them would have to be power-combined, suffering enormous combining losses in the process. In addition, they operate at low DC voltages, so a solid-state amplifier delivering the same RF output as a TWTA would devour large amounts of current, which either would require a large power supply or place considerable demands on the prime power source of the platform in which they are deployed.

SMALL WONDERS

The TWT got an enormous boost two decades ago when the US Department of Defense (DOD) recognized the continuing need for TWTs in defense systems, especially if they could be miniaturized and use lower-voltage power supplies. A panel supported by the Naval Research Laboratory (NRL) and populated by prime contractors and TWT manufacturers was created with the goal of meeting a demanding set of technical requirements focused on EW and radar applications over a frequency range of 6 GHz

to 18 GHz. Specifications included RF output power up to 100 W, 50 dB of gain, noise power density of -45 dBm/MHz and a package volume of 7.5 in. The program was called the Tri-Service Vacuum Electronics Program and was funded by NRL and the Defense Advanced Research Projects Agency (DARPA).

The five development teams included one from the Hughes Aircraft Electron Devices Division (now L-3 Communications Electron Technologies), Lockheed Sanders and Teledyne Electronic Systems (now BAE Systems and Teledyne MEC), Northrop (today's Northrop Grumman), Raytheon and Westinghouse and Varian Associates (now Northrop Grumman and Communications & Power Industries, or CPI). The result was the Microwave Power Module (MPM), which has been immensely successful in broadening the reach of the TWT into new platforms and bolstering the VED industry as whole.

Development of the "mini-TWT" was arguably the key element in this development. A shorter, lighter and lower-power version of a standard TWT that is about 7 inches long, the mini-TWT does not deliver as high an RF power output as a conventional TWT, nor does it require as large a power supply. For example, an 8-kW, X-band helix TWT typically employs an input voltage of about 14 kV and a 100-kW coupled-cavity TWT requires about 45 kV. A mini-TWT requires 3.7 kV to 7 kV. However, it is limited in RF output power to about 200 W CW (1 kW peak).

The MPM's advantages were (and remain) stunning when compared to its conventional counterparts, delivering a 5:1 reduction in size and weight, 100:1 reduction in noise and 50 percent improvement in efficiency. The success of the program spawned a broad array of other MPMs that today offer a wide

range of waveguide bands. MPMs did not initially find a home in EW systems; this came recently as unmanned aerial vehicles (UAVs) began to incorporate EW systems to complement their sensor and communications payloads.

The MPM is conceptually very straightforward. A solid-state RF power amplifier drives a mini-TWT, and the two amplifiers are integrated with power and control circuits in a very compact enclosure. Like any compact, high-power RF system, the power supply and its power management subsystem are critical components in an MPM, and they employ extremely-dense, intelligent power sources that incorporate various types of protection circuits. Current MPMs are available for continuous wave or pulsed operation from L-3 Communications, Triton, Crane Aerospace Electronics, TMD Technologies and other manufacturers with RF output power up to about 300 W CW (more than 1 kW pulsed) at frequencies from S-band to W-band (100 GHz region) with a 20-percent to 40-percent duty cycle, 100 to 400 µs pulse width and variable pulse repetition frequencies. They are housed in very small enclosures (11 x 2 x 6.5 in. for a dB Control MPM is a good example) and require prime power typically of 28 VDC or 110, 208 or 270 VAC.

TO TERAHERTZ… AND BEYOND

After effectively removing itself from VED development nearly 15 years ago, DARPA once again is tackling VED research, focusing on frequencies of 220 GHz and higher in its High Frequency Integrated Vacuum Electronics (HiFIVE) program. The program team is developing an integrated VED power amplifier circuit that can deliver more than 50 W of RF power with efficiency greater than 5 percent over a bandwidth of at least 5 GHz to 220 GHz. The ultimate goal is to produce an MPM that can operate without degradation for more than 100 hours in a broadband tactical communications link with data throughput comparable to optical fiber. The VED itself bears a resemblance more to a wafer-scale device than a "tube," owing to the minute wavelengths that must be realized using microfabrication techniques. It will incorporate a first-stage microwave monolithic integrated circuit (MMIC) driver circuit that is integrated into the overall amplifier along with the cathode, electron-beam and interaction and collection structures.

Every year, RF power transistors creep upwards in many areas of performance, including RF output power and frequency range. However, they are chasing a moving target because TWTs still have the highest power/bandwidth product of any RF-power-generating device and are annually increasing their abilities. There is no other single RF power source that can match their peak-to-average power and bandwidth. MPMs are a terrific match for UAVs, not just for communications links but increasingly for EW suites as well. This all but ensures their continued use in EW, radar systems and other applications for years to come.

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