

## TWTs Still Drive High-Power Systems

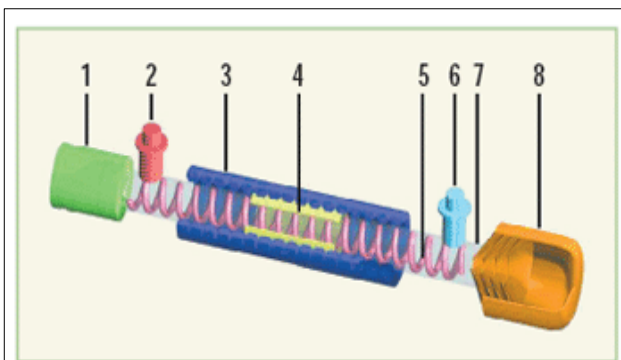
**Vacuum tubes may not have the sizzle of their solid-state counterparts, but in radar, satcom, EW, ECM, and other applications, their power/bandwidth characteristics remain unchallenged.**

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Vacuum tubes were once the active devices of choice in high-frequency systems. With increasing use of solid-state devices, however, vacuum electron devices (VEDs) play less dominant roles in microwave and millimeter-wave systems, although they still offer the most power per device for most applications. Vacuum tubes such as klystrons, crossed-field amplifiers (CFAs), gyrotrons, magnetrons, inductive output tubes (IOTs) and, in particular, traveling wave tubes (TWTs), continue to retain their solid position in defense applications and even in some commercial and industrial applications as well. The fact remains that at high microwave and millimeter-wave frequencies, monolithic microwave integrated circuits (MMICs) and RF power transistors can't match the power/bandwidth product that these "mature" devices can deliver.

Of course, this "dollars per watt" scenario changes every year, as devices based on GaAs, silicon and, increasingly, gallium nitride (GaN) offer higher power levels at higher frequencies. These improving performance levels help chip away at vacuum tube bastions such as broadcast transmitters, and electronic warfare (EW), electronic countermeasures (ECM), and radar systems. However, they have a long way to go before they will be able to produce megawatts of power at 40 GHz like a klystron or gyrotron, or 250 kW like a coupled-cavity TWT. The challenge of reducing the staggering losses incurred in power combining networks alone would be enough to scare away even the most ardent supporter of solid-state technology.

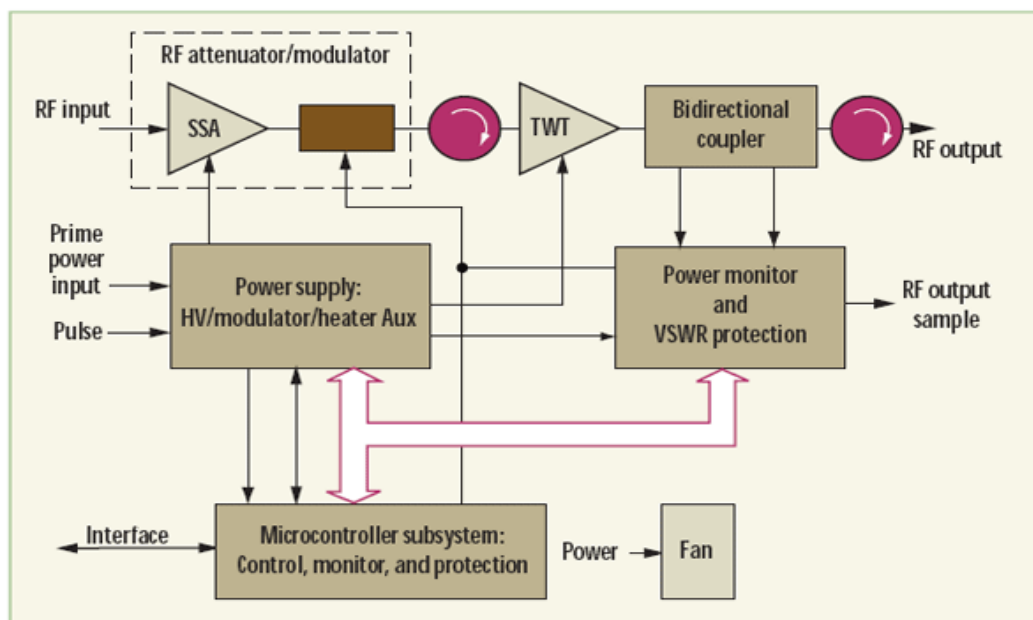
The TWT is arguably the most widely used VED for microwave defense, instrumentation, and satellite communications applications. It provides the extremely high output-power density required by these applications at microwave frequencies, with time-tested reliability. Development continues on the devices as well as the amplifiers and transmitters they enable, and the power supplies whose characteristics are critical to ensure the performance and longevity of TWTs. A TWT is an inherently high-gain, low-noise amplifier with wider bandwidth than that of a klystron. The TWT ([Fig. 1](#)) uses a slow-wave structure (either a coupled-cavity circuit or for purposes of this discussion, helix) to create interaction between a high-energy electron beam and an RF wave in a vacuum envelope.



1. This cross-section of a TWT shows the key elements of the device including the electron gun (1), RF input (2), magnets (3), attenuator (4), helix coil (5), RF output (6), vacuum tube (7), and collector (8). [Graphic courtesy of Wikipedia.]

In a TWT, electrons are generated by a heated cathode in an electron gun assembly and launched into the interaction region. The electron beam is controlled by an electrode that switches it on and off by changing the control electrode potential (bias) to either positive or negative with respect to the cathode. The switching of bias voltages is performed by the modulator in the transmitter to transition the device from a conduction state to a cutoff state. The electron beam is focused by magnets along the axis of the TWT and the beam is accelerated by a high potential between the cathode and the anode (collector). The RF wave propagates from the input to the output through the slow-wave structure, and the high energy electron beam gives up energy to the RF wave as it travels along the axis of the tube, providing amplification before the high-frequency signal reaches the RF output port.

Unlike their solid-state counterparts, TWTs require high voltages to be applied to their electrodes, with proportionally higher voltages needed to produce higher RF output levels. For example, an 8-kW, X-band helix TWT requires an input voltage of about 14 kV while a 100-kW coupled-cavity TWT requires about 45 kV input voltage. Physically smaller mini-TWTs operate with input voltages from 3.5 to 7 kV. A good example of a TWT amplifier (TWTA) application is the radar transmitter shown in [Fig. 2](#), which is typical of transmitters using other types of microwave tubes as well.



2. The radar transmitter employs a TWTA but is representative of amplifiers using other tube types as well.

A pulsed signal from the radar waveform generator is applied to an amplifier that employs RF power transistors to produce an output that drives the TWT. This signal is sent to the input of the TWT where isolators are used to ensure proper input matching and inter-stage isolation, and a PIN-diode switch is present to shut off the driver's output to protect the TWT from overload. In addition to the TWT, the RF output section includes a dual-directional coupler to determine the RF output level as well as the reflected power level to protect the TWT from damage in high VSWR conditions.

Other components include an isolator and often a harmonic suppression filter and waveguide switch that can divert the TWT's output to a dummy load for testing. An arc detector is generally included in very-high-power transmitters, which senses breakdown in the waveguide and turns off the RF drive power to the TWT at high speed to prevent damage to its output port window. Other protective mechanisms cover excessive current in the high-voltage power supply, modulator, and TWT, which are carefully designed to prevent false alarms while providing high levels of safety.

TWTs from various manufacturers vary considerably in many respects, and only through experience can amplifier and transmitter manufacturers such as dB Control determine which one is best suited for a specific application. There is ample reason for this caution since as the core element of the transmitter, which is the TWT, affects nearly every aspect of performance. Key TWT considerations include power supply requirements, operating voltage levels and power consumption, thermal design power dissipation and thermal design, size and weight, temperature, altitude and vibration performance, and demonstrated record of reliability.

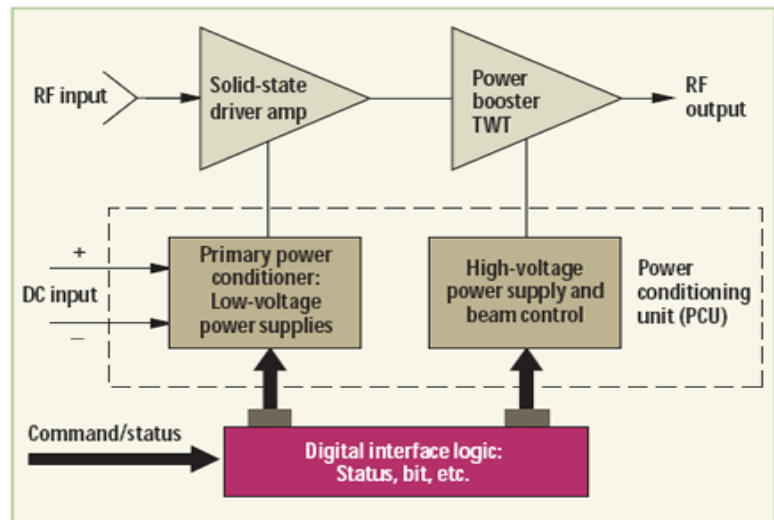
TWTs used for transponder amplifiers in satellites, where power is limited, are typical examples for the high efficiency and reliability figures that can be achieved by careful design of TWTs. The RF output power to prime power input ratio that describes real efficiency is greater than 60 percent for these devices, and recent reports show that efficiency of nearly 70 percent has been achieved. These TWTs also have proven to be highly reliable and have long operating lives (greater than 20 years) to provide uninterrupted service in communication and radar applications. Even today, for Ku-band and higher frequencies, TWTs are the only amplification devices used in satellites.

The applications for TWTs include those that pose minimal constraints on size, weight, and power consumption. However, in others such as satellite transponders and most recently military unmanned aerial vehicles (UAVs), the RF power generation section must share the available space with massive amounts of signal processing, avionics, power supply, and other hardware. A solution to this problem was the creation of the mini-TWT which, as its name suggests, is a small version of a conventional TWT (typically about 7 in. long) and requires a lower-voltage power supply (to 8 kV). However, it is also limited in RF output power to about 200 W CW (1 kW peak), although retaining its broadband, high-frequency capabilities. These devices are available at frequencies to about 50 GHz.

Impressive though the mini-TWT may be, it has greater potential when incorporated into a microwave power module (MPM). The MPM resulted from a tri-service (United States Air Force, Army, and Navy) vacuum electronics initiative launched in 1990, which had the goal of combining the best characteristics of VED and solid-state technologies to produce common, medium-power building blocks for radar, EW, and ECM systems that could be manufactured in high volume at reasonable cost.

The ultimate goal of the program was to produce extremely small modules but ultimately resulted in modules that were considerably larger. However, they still consume less space than a traditional TWTA, are comparatively light in weight, and operate from power supplies ranging from 28 to 270 VDC. Today, dB Control and other manufacturers offer a wide array of MPMs for operation from S-band to W-band frequencies in CW and pulsed configurations, with RF outputs from less than 20 W to more than 1 kW with a 20 to 40 percent duty cycle, 100 to 400  $\mu$ s pulse width, and variable pulse repetition frequency.

In a classic MPM ([Fig. 3](#)), the RF signal path consists of a mini-TWT and a solid-state driver amplifier accompanied by an electronic power conditioner that acts as the high-voltage power supply for the TWT and control circuits. The power produced by the driver amplifier typically negates any reduction in gain resulting from the shortened helix length in the TWT. The MPM fully exploits the power-handling capability, bandwidth, efficiency, and heat-tolerance inherent in TWTs.

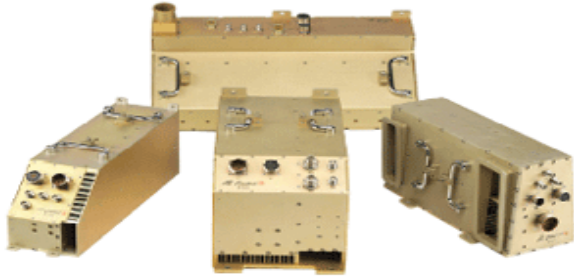


3. The standard configuration of an MPM includes a driver amplifier and TWT along with their power supply conditioning and interface circuits.

MPMs are highly regarded not just for active electronically steered array (AESA) radar applications, but in synthetic aperture radar (SAR) systems in which long pulse widths are required, EW and ECM suites, and commercial and military satellite communications systems. dB Control MPMs are used in transmitters for radar and ECM applications. These products have exceeded all performance goals and are now in continuous production. The MPMs are employed in many UAVs in which the platforms' prime power, size, and weight are very limited and long failure-free operation is essential.

The MPM is also useful as a transmitter module in an AESA system because power output can be increased one or more orders of magnitude greater than the power achieved with the solid-state power amplifier in the transmit/ receive (T/R) module. MPMs also have wider bandwidths and greater heat tolerance than solid-state amplifiers. AESA systems using MPMs as transmitter modules have been deployed in octave- bandwidth ECM systems and in airborne data link systems. Complete MPM-based transmitter line replaceable units (LRU) are also available.

An example of a MPM-based transmitter suite for ECM applications developed by dB Control is shown in [Figure 4](#). The suite operates from aircraft three-phase 115 VAC power. It consists of four MPM-based CW and pulsed transmitters covering 2 to 7 GHz and 6 to 18 GHz to produce the total 2-to-18-GHz frequency coverage. The suite was designed for the harsh conditions encountered in airborne environments, and can withstand gunfire vibration, operation at +100°C for short periods, and is compliant with MIL-STD461E.



**4. This 2-to-18 GHz ECM transmitter suite was designed to survive extreme environmental conditions. It features a frequency-segmented design to cover the full frequency range with a total of four 2-to-7-GHz and 6-to-18-GHz TWT-based MPMs.**

In addition to the solid-state driver amplifier, the RF input section includes isolators, directional couplers for sampling at various stages, bandpass filters, switches for selecting specific filters, and a TWT gain equalizer. A dual-directional coupler, forward and reflected power monitoring, and high-VSWR protection circuit follow the TWT. In many respects, the power supply is as important to performance, reliability, and longevity as the TWTs themselves. It must deliver the high voltages required by the TWTs, filter and condition the prime power, and generate and regulate all voltages required by the circuits in the ECM suite. The importance of the power supply led dB Control many years ago to begin manufacturing its own power supplies and even many of the individual components for those power supplies in order to ensure quality control.

The ECM suite successfully met demanding requirements for performance over temperature, altitude, vibration, shock acceleration, explosive atmosphere, rain, humidity, and other factors, as well as EMC compliance. The suite delivers RF output power of 250 W under CW or pulsed conditions from 2 to 7 GHz and 100 W from 6 to 18 GHz, 1.5 kW peak (6-percent duty cycle) from 6 to 18 GHz, and to 300 W under CW or pulsed signal conditions from 6.5 to 18 GHz from its dual-transmitter “high-band” section.

Despite the continuous increases in the performance of RF power transistors and MMIC amplifiers, and the use of high-power combining techniques to efficiently add the contributions of numerous high-power transistors into a common output, the TWT remains the power source of choice for a broad range of defense systems and some commercial and industrial applications with RF power outputs to 2.5 kW CW and 25 kW pulse at frequencies to 95 GHz. No single solid-state amplifier can deliver this level of peak-to-average power and bandwidth for most applications. In fact, the vast majority of EW and ECM systems both deployed and in development rely on either TWTs or some type of VED, and this is likely to remain the case for many years to come.