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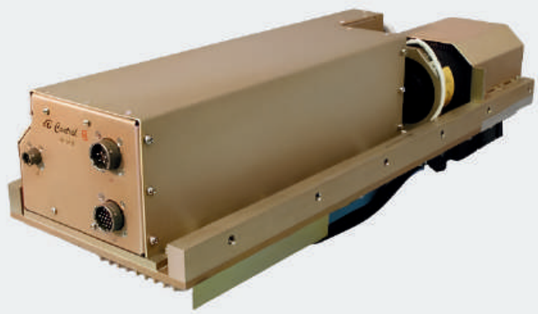
Traveling Wave Tubes Still Best Solution for High RF-Power EW Systems

dB Control

Even as GaN devices continue to grow in efficiency, power density, and the amount of power available from a single device, when it comes to generating serious amounts of RF power, traveling wave tubes (TWTs) continue to be the power solution of choice for electronic warfare (EW) systems. With 80 years of in-the-field experience, TWTs deliver reliable RF power levels in the millimeter wave and even terahertz regions of the spectrum. That's excellent news for EW systems designers who must meet the challenges of today's military environment.

Before delving into why TWTs are the best choice, it helps to understand this device's long history and how it works.



TWT Invented by Austrian Architect Turned Physicist

The history of the TWT began in 1943 with Rudolf Kompfner, an Austrian architect who immigrated to England where he became fascinated with physics. After much research and experimentation, Kompfner invented a split-beam oscilloscope tube. That invention inspired him to investigate microwave technology and velocity modulation.

After World War II, Kompfner was recruited by the University of Birmingham's Physics Department where the British Admiralty had set up a secret tube research center. Originally, he was assigned to develop a low-noise klystron amplifier. However, after two discouraging years, he invented the TWT instead.

In 1951 Kompfner joined Bell Laboratories in New Jersey to continue his work on microwave tubes and backward-wave oscillators. He went on to make groundbreaking advances in antennas and optical communications that led to the development of the Echo satellite. For his achievements, he received the IEEE's highest award, the Medal of Honor, and America's highest civilian scientific honor, the National Medal of Science.

TWTs Provide Reliable High-Power RF for EW and SATCOM

During the postwar years, TWTs began to appear in radar systems, satellite communications, and EW systems, all of which required a reliable source of high-power RF across a wide range of frequencies. The TWT was especially in demand for EW applications due to its ability to handle dynamic environments by switching quickly between different frequencies. In addition, its wide bandwidth allowed EW systems to interfere with multiple radar systems across a broad frequency range.

During the Cold War, the U.S. made massive investments to achieve technological superiority over the Soviet Union. The ability to disrupt or deceive enemy radar and communication systems became a strategic priority. This led to the rapid growth of EW as a distinct field within military science, encompassing everything from radar jamming to signal interception.

In the 1960s and 1970s, the use of TWTs in military systems expanded, especially as the U.S. and its NATO allies sought to counter increasingly sophisticated radar threats from the Soviet Union. TWTs proved their ability to provide reliable power for jammers and electronic countermeasure (ECM) pods on aircraft and in communications systems.

One of the most successful uses of TWTs in EW was during the Vietnam War. The Soviet Union had supplied North Vietnam with advanced radar-guided missile systems that posed a significant threat to American aircraft. In response, the US built TWT-powered systems and mounted them on aircraft to jam enemy radar. This prevented missiles from being launched and caused launched missiles to lose their lock on the target.

TWT's Wide Bandwidth and fast Response Time Perfect for Signal Jamming

As radar technology evolved, so did jamming techniques. Frequency-hopping radars, which quickly switch between different frequencies, became a significant challenge for EW systems. TWTs played a crucial role in countering these advancements as their wide bandwidth and fast response times allowed jammers to follow the frequency-hopping patterns and continue disrupting the radar.

Even though a TWT has a shorter operating lifespan (typically about 100,000 hours) compared to the million-hour lifespan of a solid-state device, it is still one of the most robust components in many systems, especially those in space. In fact, the communications systems of every NASA spacecraft are powered by a TWT! For example, the Voyager 2, which was launched in 1977, continues to deliver data to NASA's Deep Space Network more than 48 years after its launch. In addition, as TWTs can still outperform solid-state devices in RF output power and bandwidth, particularly in the higher microwave and millimeter-wave bands, they will remain a crucial part of modern EW systems.

Anatomy of a TWT

A TWT is an inherently high-gain, low-noise amplifier with a wider bandwidth than that of a klystron. It uses a slow-wave structure (either a helix or coupled-cavity circuit) to create an interaction between a high-energy electron beam and an RF wave in a vacuum envelope.

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.

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. 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.

Amplifying the RF Power

As TWT technology matured, it was integrated into more sophisticated systems that became Traveling Wave Tube Amplifiers. TWTAs 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 TWTA requires an input voltage of about 14 kV while a 100-kW coupled-cavity TWTA requires about 45 kV input voltage.

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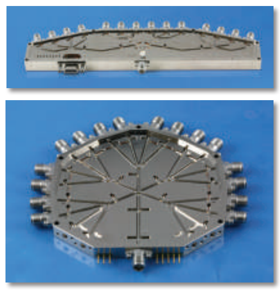

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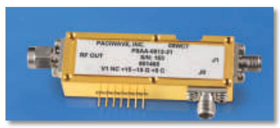

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Physically smaller mini-TWTAs operate with input voltages from 3.5 to 7 kV. A good example of a TWT Amplifier (TWTA) application is the radar transmitter shown in Figure 1, which is typical of transmitters using other types of microwave tubes as well.

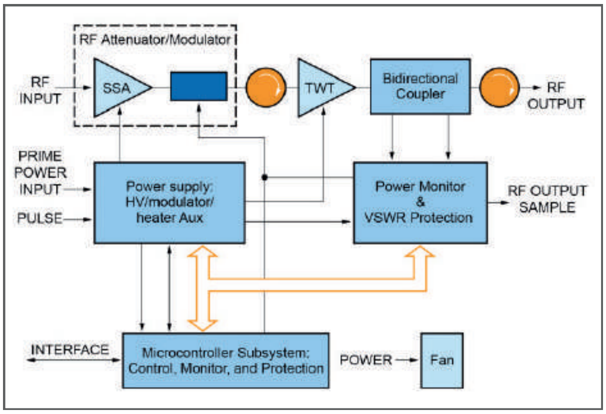

Figure 1. Block diagram of a TWTA-based radar transmitter.

TWTs from various manufacturers vary considerably in many respects, and only through experience can TWTA manufacturers such as dB Control determine which one is best suited for a specific application. As the core element of a radar transmitter, the TWTA affects nearly every aspect of performance. When selecting a TWTA, important considerations include SWaP (size, weight and power) requirements, operating voltage levels, thermal design and size and a demonstrated record of reliability under harsh environmental conditions.

Power-Combined TWTAs Provide Even Higher Power

A power-combined TWTA uses multiple wideband, periodic permanent magnet (PPM)-focused TWTs to amplify CW, AM, FM or pulse-modulated signals. Compared to a single TWT approach, a power-combined TWTA provides higher saturated output power and improved harmonic performance. Losses from power combining are minimized by carefully matching the TWTs and other RF components for amplitude and phase over the entire frequency range.

For its power-combined TWTAs, dB Control designs and manufactures high-voltage power supplies in-house to provide superior reliability. The company also utilizes proprietary transformer fabrication, encapsulation and high-voltage potting techniques it developed specifically for demanding military applications. The power supply section of the TWTA employs a modular architecture and low-noise power supply topology using high-efficiency solid-state power conversion circuits.

An embedded microcontroller provides the interface, control and protection functions, as well as extensive fault diagnostics and status indication.

dB Control offers eight power-combined TWTAs operating in the 2 GHz to 18 GHz frequency range providing from 3.4 kW to 15 kW. With only one RF input and one RF output (similar to amplifiers utilizing a single TWT), power-combined TWTAs are extremely easy to operate; no RF switches are required. Figure 2 illustrates two of the company's power-combined TWTAs.

Figure 2. The dB-3911 power-combined TWTA (shown on the left, without cabinet), 9-10 GHz, 12 kW pulsed power with a 6% duty cycle. The dB-4507 power-combined TWTA (shown on the right in a cabinet), 7.5-18 GHz, is unique as it combines four TWTs to provide 1 kW of continuous wave power.

MPMs – A Smaller, Lighter TWTA

To create a smaller, lighter hybrid amplifier, in 1991 the Department of Defense launched its Tri-Service Microwave Power Module (MPM) program under the auspices of the Naval Research Laboratory. Several TWT manufacturers, including Varian Associates, were awarded development contracts. dB Control's VP of Business Development Steve Walley was at Varian when they built their first MPMs with a CPI mini booster tube and outsourced power supply. Today, he continues to play a significant role in the development of MPMs at dB Control.

An MPM combines a solid-state RF power amplifier (SSPA) with a "mini TWT" and a power supply, using the SSPA to drive the TWT to achieve higher output power (Figure 3). This effectively exploits the benefits of both technologies to achieve a compact, lightweight, relatively high-power amplifier small enough to be used in SWaP-constrained platforms such as small aircraft and UAVs. MPMs also offer improved thermal management, as their integrated design allows for more efficient cooling solutions.

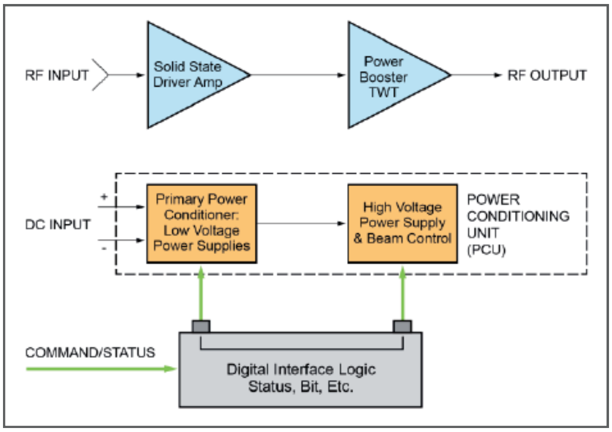

Figure 3. A top-level block diagram illustrating three sections of a Microwave Power Module: the driver amplifier, small TWT and power supply.

Folded Waveguides Minimize Signal Loss

A folded waveguide is a specialized type of waveguide structure in which the wave's path is folded or bent, creating a more compact form. Rather than allowing the wave to propagate in a straight line as in traditional TWT structures, the wave is guided through a series of turns or bends, which shortens its length while maintaining the same path length for the wave. This is important for maintaining proper phase relationships.

The folded waveguide is based on the principle of total internal reflection, which allows the wave to reflect off the walls of the waveguide as it follows the folded path. The wave travels in a zigzag pattern through the folded sections, but the energy remains confined within the waveguide walls, ensuring minimal signal loss. By folding the path, engineers can achieve the desired phase shift or delay while reducing the device's overall size. A folded waveguide saves space, which is why it's increasingly used in MPMs. Because of its more efficient use of materials, it also offers improved thermal management and reduced manufacturing costs.

Millimeter-Wave Applications Shape the Future of TWT Manufacturing

The shift towards operation at millimeter-wave and higher frequencies shapes the future of TWTA manufacturing. This evolution requires reducing the size of components as frequencies increase. Consequently, the long-standing fabrication techniques and machining equipment that have served the industry for decades are becoming obsolete.

In their place, a new era of micromachining equipment is emerging, bearing resemblance to semiconductor fabrication processes that can craft with micrometer-level precision, a requirement for the increasingly miniaturized components of high-frequency TWTAs.

In future electronic warfare scenarios, adversaries will likely employ increasingly complex and agile signals, making it necessary for defense systems to have powerful and flexible signal amplification capabilities. TWTAs can meet this challenge by delivering high power over a broad spectrum, enabling jamming systems to disrupt enemy communications and radar with greater effectiveness. Additionally, TWTAs can be integrated into advanced radar systems, enhancing detection and targeting precision even in highly contested environments where stealth technology and signal interference are prevalent.

The continued development of TWTAs will also support electronic countermeasures by allowing systems to transmit stronger signals, outpowering enemy radars or communication networks. This ensures that friendly forces can maintain the upper hand in electronic warfare by controlling the electromagnetic spectrum more effectively. The durability and reliability of TWTAs in high-power, high-frequency operations will further solidify their role in the future of electronic warfare, particularly in scenarios where rapid adaptation to shifting threats is vital. ■

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