The Traveling-Wave Tu

By Barry Manz

After more than a half century of development, it seems logical that the traveling-wave tube (TWT) has become all that it can be. If that's so, then it's equally logical that as solid-state technology marches forward, TWTs will slowly fade away, to be found only in museums, textbooks and a page on Wikipedia. Neither assumption is likely. What's more likely is that everyone reading this will have expired before the last TWT rolls off the production line.

This rather contrarian projection flies in the face of the experience of other technologies that have tried and failed to survive the onslaught of semiconductors, but it's happening today with TWTs and other Vacuum Electron Devices (VEDs). How will the TWT survive? The answers range from the mundane (hundreds of thousands of TWTs installed in an enormous number of air, sea, land, and space EW, radar and communications systems require spares), to technical (no other technology can generate as much power from a single device, especially at millimeter wavelengths).

The technology is also still vibrant after all these years with active research being conducted throughout the world. Some of the results are already in production, as techniques have been developed to increase operating life by 50 percent, "light up" time has been reduced from minutes to a second, and RF output power levels of hundreds of Watts – CW – can be achieved at 80 to 90 GHz and up to 40W at 230 GHz. Combine this with the already impressive bandwidths achievable by helix-type TWTs, reasonable efficiency, reliability high enough to power transmitters in space for more than 15 years, and the result is a technology that is, if not in ascension, then certainly competitive for many years.

Of course, like all technologies, TWTs have disadvantages. Unlike gallium arsenide (GaAs) and gallium nitride (GaN) devices, they can't be used to power the tiny transmit/receiver (T/R) modules required by AESA-based systems like the Next-Generation Jammer or the Air and Missile Defense Radar (AMDR). They still require kilovolts of DC power to create their electron beams, and (currently) have a maximum operating lifetime of 100,000 hours, while GaN power amplifiers can (potentially) achieve 1 million hours of operation.

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There is no question that GaN discrete transistors and MMICs will power most of the radar systems and possibly EW systems in the future, thanks to the exceptional characteristics of this compound semiconductor technology. GaN can produce more RF power than any other competing solid-state technology (at least 4 times higher than GaAs and 10 times higher than silicon) and it can do so on a die the size of a pinhead. Based on published data, commercially-available GaN devices have a power density (the RF power that can be produced from a square millimeter of die) of about 11 W/mm^2.

This is an amazing feat from a technology that has been used in the field for less than 15 years, and the true power density number is probably higher, as the most recent data is either classified or closely held. GaN is also more efficient than GaAs and silicon and can operate up to 225° C, has a lower noise figure than GaAs, and could potentially operate into the millimeter-wave region. GaN is just beginning to flower and won't achieve anywhere near its full potential for many years and possibly decades. But even then, there will still be a need for VEDs operating in the millimeter-wave region.

TWTS DEMYSTIFIED

To understand the future of the TWT requires some understanding of their components and their basic operation. A TWT, or any VED for that matter, bears no technological resemblance whatsoever to its solid-state counterparts, electrically, mechanically or physically. Using a helix type as an example, the device consists of a hermetic electron gun, interaction circuit, and a collector, as well as magnets that surround it on the outside. The component materials of the tube are made of heat- and corrosion-resistant metals like tungsten and molybdenum, as well as iron, high-purity copper, and high-temperature ceramics.

A high voltage is applied to the cathode, which heats up to about 1000° C and produces a stream of electrons that are then highly focused using the magnets surrounding the tube to form a very thin beam that travels axially away from the cathode. Along the way to the collector at the other end of the tube, this pencil

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beam of electrons passes inside of a helical coil (the helix) at the beginning of which an RF input signal is injected via an RF coupler.

The result is that the beam current, which was unmodulated as it entered the helix, now has an RF component at the input frequency. The modulation induces electromagnetic fields on the helix, which then act on the electrons, producing a massive amount of gain, dramatically increasing RF power. This RF energy, now amplified but still at the input frequency, is removed from the tube with another RF coupler.

However, only about a third or less of the beam power is converted to RF energy, and the rest is sent to the collector, so if the collector can extract more power then the TWT's efficiency will increase. To obtain this benefit, modern TWTs use a depressed collector with up to five stages (a multi-stage depressed collector or MSDC), which is essentially a series of electrodes. "Collectively," they can recover more than 80 percent of beam energy that would otherwise be lost. Overall efficiency of 65 percent or greater can be achieved this way.

Helix-type TWTs are inherently broadband, with the ability to cover over two octaves and a maximum operating frequency of about 70 GHz. Their disadvantage versus the coupled-cavity type is that being a wire supported by thin dielectric rods, the helix is limited by its power handling capability to a comparatively low RF output power. The coupled-cavity type solves this problem by replacing the helix with a series of coupled cavities placed along the beam, producing a solid metallic structure that can handle much higher power levels. However, it can only operate over a 10 percent bandwidth and is considerably heavier than the helix type.

The EA-18G's ALQ-99 pods rely on TWTs to generate the power needed to perform its support jamming mission. DOD IMAGE

ADVANCES CONTINUE

As noted earlier, regular advances have been taking place in VED technology over the years, resulting in achievements that have reduced some of their limitations and expanded on their capabilities. For example, TWTs generate their electron beams through thermionic emissions (i.e., producing electrons from a heated source) and it has traditionally taken 3 minutes or more for the cathode to heat up to temperature sufficient to produce the desired emission level. In many applications (and especially in missile seekers) rapid warm-up times are critical, so techniques have been developed to reduce warm-up time to between 1 and 3 seconds.

Although TWTs have demonstrated exceptional reliability up to about 100,000 hours, their life is ultimately limited by the heated cathode that uses a barium film as the means of "liberating" the electrons from the cathode structure. "When you run out of barium, you run out of life," says Mike Cascone, vice president of technology for the Satcom and Medical Products Division of Communication & Power Industries (CPI). "If the cathode is too cold, it doesn't have enough energy to overcome the work function on the cathode surface, and if it is too hot, arcing can occur and the evaporation rate of the barium will be too high, reducing its life."

"We determined that operating a very hot cathode is not necessary and have developed a technique that decreases barium evaporation over time by dynamically controlling the heat to the cathode," Cascone continues. "This can extend the life of the tube from between 30 percent and 50 percent, and I believe it will ultimately double the life." The company also uses another technique to measure the amount of barium left on the cathode, tracking its evaporation to provide information (in percent) of how much life is left in the tube.

Advances have also been made in Microwave Power Modules (MPMs), which are essentially small "mini-TWTs" and a solid-state driver amplifier combined with an electronic power conditioning circuit. They operate at lower supply voltages than traditional TWT amplifiers and compensate for the gain reduction caused by the shortened helix with the driver amplifier. "For EW 10 or 15 years ago, we were operating from 2 to 6 GHz and 6 to 18 GHz with 100 W and 20 percent efficiency," says Mike Lee, director of sales and marketing at dB Control. "We now see 200 W with 30 percent efficiency in the same footprint." dB Control, for example, manufactures MPMs that can deliver up to 400 W CW and 2 kW pulsed power and maximum operating frequencies up to 40 GHz.

SMALL WAVES, BIG BENEFITS

The Department of Defense and other agencies have long considered the millimeter-wave or Extremely High Frequency (EHF) region a potentially lucrative resource waiting to be exploited, if only technology could allow it to be done. Although EHF officially begins at 30 GHz it extends to 300 GHz where the low-infrared optical region begins. Nothing is simple at EHF, where wavelengths are measured in millimeters or microns. But there are significant benefits to be obtained there, which is why the Defense Advanced Research Projects Agency (DARPA) and other agencies are increasingly interested in it. The TWT is one of the key technologies that will allow radar, communications and EW systems at these frequencies to be built.

TWTs are used in jamming systems that protect the DOD's largest aircraft. DOD IMAGE

Strangely perhaps, the normally hostile propagation characteristics of millimeter wavelengths can be beneficial. For example, in the Earth's atmosphere, RF energy at these frequencies is attenuated by almost anything and propagates only over very short distances, which makes communication difficult at best. The only way to do it is by using very high gain, very-directional antennas that develop large amounts of gain by concentrating the beam over a very small area, effectively increasing the output of the RF power amplifier by a factor of 10 or more. As the beam is narrow, the signal is also very difficult to detect or jam. To deal with this problem, EW systems must be able to deliver even greater power, for which solid-state devices are wholly inadequate. Advantage: tubes.

In space, the hinderances of the atmosphere don't exist, which makes remote sensing at EHF a very interesting challenge with huge rewards. It's possible to capture images with exceptionally high resolution, communicate over huge distances, and send data at the highest rate a system can generate, as bandwidth is basically unlimited. But once again, generating RF power is a key factor, and semiconductor technologies, if they work in this region at all, produce miniscule amounts of power. TWTs, on the other hand, can produce "real power" at frequencies well into the hundreds of GHz, and climbing.

An excellent example of what is currently being achieved in this area is an MPM for high-resolution airborne radar

SEARCHING FOR TALENT

The biggest single threat to the TWT industry and its suppliers isn't a competing technology; it's the fact that few graduates of engineering schools, even those with advanced degrees, rarely have much or even any knowledge of vacuum tube technology. For them, as well as people in general, tubes are what people used before there were transistors. This situation is nothing new; it's been an increasing problem for years. In the US, the problem is exacerbated by the fact that the major tube manufacturers are in California, where housing, if available, can be notoriously expensive.

To solve the first problem, manufacturers have become tube talent scouts, scouring colleges and universities for likely candidates, bringing them into the fold as interns to show them that tubes are here to stay and that there are lots of terrific electrical and mechanical design challenges remaining to be solved. One of the most important takeaways for potential candidates from these activities is (or should be) that expertise in VEDs makes a design engineer a rare breed. That is, with comparatively few new engineers coming into the industry, short of committing some heinous crime, they'll never want for a job, and have one that pays very well.

"We look at the technical colleges and there are a lot of really good schools for engineers in California, so it's easy for us to recruit there," says Amanda Mogin, director of investor relations at CPI. "One of the great things about this company is that when we bring in an engineer, he or she gets hands-on work pretty quickly in many areas, which is typically not something you would get at many other Silicon Valley companies."

To address the second issue, the company recently moved its satellite tube division to South San Jose, where housing is available and reasonably affordable, and commuting isn't as great a problem. The facility is also the company's newest design center, where many of its design challenges are addressed. "The older people mentor the younger ones," says CPI's Cascone. "If a new person wants to advance into management, the tube industry is a great place, because you have a lot of people who are ready to retire and [they] will teach you everything they know and promote you quickly." – *B. Manz* designed and built by L3 Electron Devices. It has an instantaneous bandwidth of more than 3 GHz from 231.5 to 235 GHz (G-band) and produces a peak RF output power of 32 W with drive of just 10 mW and efficiency of about 9 percent.

The MPM is based on a serpentine waveguide TWT that uses high-energy-density, temperature-compensated samarium cobalt magnets to focus the beam, and a very small, 20-kV electronic power conditioner. Beam power density through the slow-wave circuit is about 5 MW/cm^2. The input and output ports are chemical vapor deposition diamond, and a four-stage MSDC is employed for beam energy recovery. The MPM operates from a 270-V power source. The radar sensor has been flown on an airborne test bed with high resolution real-time video imagery obtained under cloud-obscured operating conditions.

The serpentine structure, a variant of the coupled-cavity architecture, is a meandering reduced-height TE10 rectangular waveguide that "shines at higher frequencies because it can handle high power levels and can also be useful at lower frequencies at even higher power levels," says David Whaley, chief scientist at L3 Electron Devices.

"We use an all-copper structure, because at these frequencies the device becomes very small. You have high heat loads, so copper construction allows you to keep things cool. In addition to the 230-GHz devices, we have others working at 84 and 94 GHz using this structure." It also does not have the abrupt rectangular bends of a folded waveguide circuit that it otherwise resembles, which makes wideband coupling to the structure easier with less gain variation from internal reflections and fewer problems with stability.

The beam collector was designed for the 50 percent duty cycle needed for the radar application. A four-stage collector is used to recover up to 90 percent of beam energy. The serpentine-waveguide TWT design can be scaled both down and up in frequency so, for example, power levels of 600 W at 50 GHz and 20 W at 300 GHz are achievable. At frequencies high than 300 GHz, "tens of Watts" can be realized with a modified version of the serpentine waveguide.

FUTURE PERFECT?

If any tube concept could be considered the Holy Grail, it's the cold-cathode TWT. Although early work on the cold cathode was done in various places, the seminal work is generally attributed to Charles "Capp" Spindt and Kenneth Shoulders of SRI International, who published a paper in 1966. Their approach remains the most likely to succeed today.

For more than five decades, researchers have been trying to surmount the formidable challenges posed by the cold-cathode TWT and have managed to overcome some of them while others remain to be solved. When these challenges are overcome and the first cold-cathode TWT is introduced, it will be a momentous day for the TWT. First, it operates at ambient temperature, so a cathode heater isn't required. And, as the cathode isn't heated, the traditional factor limiting tube life ceases to exist. That is, according to Whaley, "there is no

inherent degradation mechanism, so it could presumably last forever."

Without a cathode to heat, warm-up time would be eliminated from the list of TWT disadvantages, as operation would be virtually instantaneous. Current density (the amount of current emitted per unit area) could be much higher as emission would no longer be limited by operating temperature, so focusing the electron beams would be much easier. The beam's current could be modulated directly at the cathode, as well.

The biggest challenge to the cold-cathode TWT has always been reliability, as the cathode consists of tens of thousands of micrometer-size molybdenum cones deposited on a circular silicon substrate with an area of about one square millimeter. The high fields within the structure and the thin-film gate electrode make it possible for an electrical short to occur between the gate and one of these cones. When that happens, the entire array of emitters burns up and the device fails catastrophically. In a traditional thermionic TWT, degradation is "graceful," allowing its end of life to be predicted by the amount of barium remaining.

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In 2015, Carter Armstrong, vice president of engineering at L3 Electron Devices, reported that their colleagues at SRI International had developed a way to reduce the damage caused by such a short. They were able to interrupt the breakdown path between the base of the cones and the gate by adding a dielectric layer between them. L3 tested the SRI cathodes in a TWT that generated up to 10 W at 18 GHz and the results showed that the cathode better resisted individual emitter failures.

So, when will the breakthrough occur that will pave the way for the cold-cathode TWT to move toward a commercial product? Armstrong said in a 2015 IEEE Spectrum article that he believed it will be sometime in the early 2020s. However, "I have some cold cathodes sitting here from SRI," says Whaley, "whose configuration has been shown to improve device life, and we need to test them. We have a thousand hours of life over four prototypes. But when they fail they fail and we are working on trying to solve that."

TUBES FOREVER?

Hopefully, this discussion has demonstrated that not only are TWTs still viable, they have a significant roadmap for the future. For example, many of the advances being developed today haven't even reached fruition, and some are still years away. As the radars and communications systems of potential adversaries move to higher and higher frequencies, EW systems powered by TWTs will be the only solution able to deliver the required RF output power to counter them. And finally, the EHF region is still to be explored and especially for radar and remote-sensing in space, offers immense potential.