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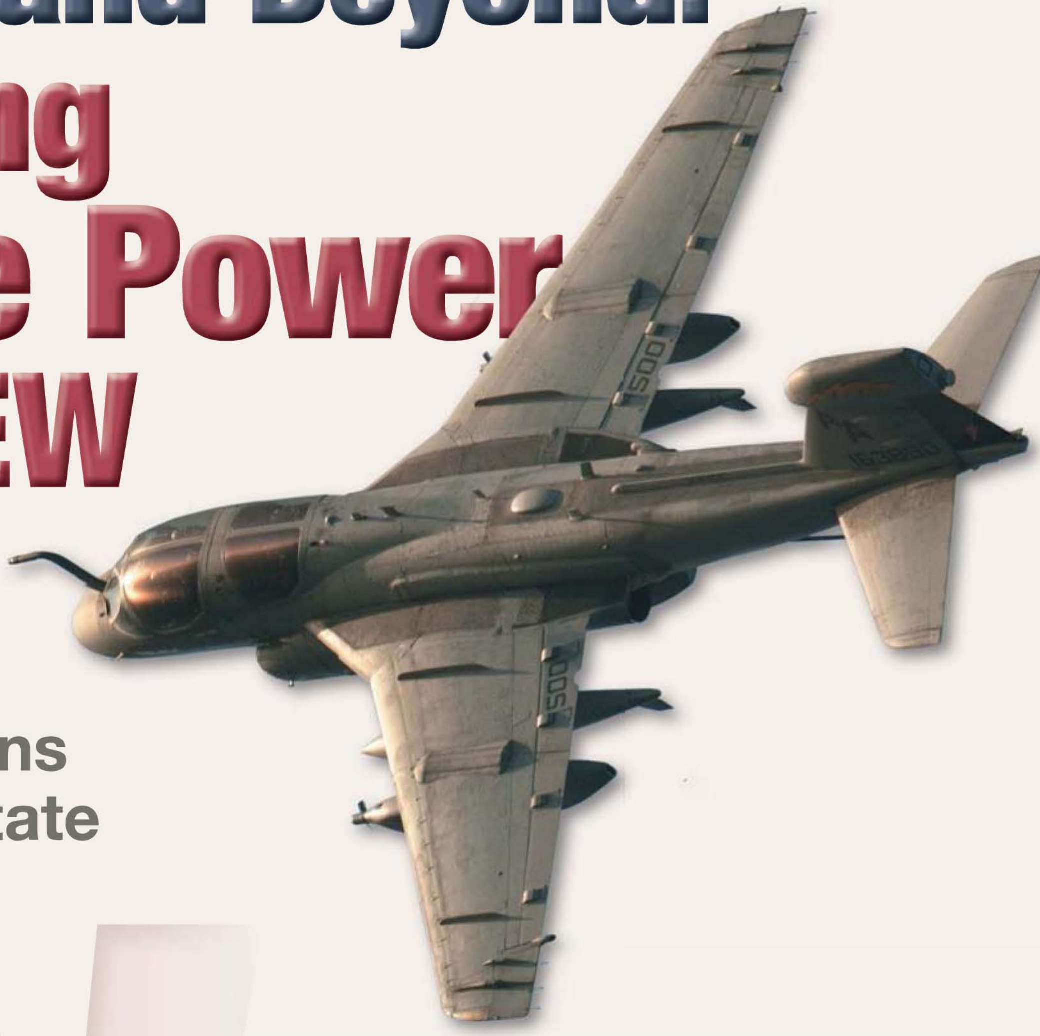
TWTs and Beyond: Putting More Power into EW

As GaN Pushes Ahead, the TWT Remains in a Solid State



By Barry Manz

When the Department of Defense demands the development of a new technology it almost invariably gets what it wants, albeit after a considerable outlay of cash. In the domain of microwave power generation, DoD's latest fair-haired boy is Gallium Nitride (GaN), a wide-bandgap compound semiconductor material that delivers higher power density per millimeter of gate length over a broader swath of spectrum than any other solid-state technology. In less than a decade, it has risen from an "interesting" technology with significant roadblocks in the path to commercialization to a potential challenger to gallium arsenide (GaAs) MMIC amplifiers, and with respect to EW RF power sources, the traveling-wave tube (TWT) amplifier. They key word, however, is "potential," as the day when this challenge occurs on a large scale may be a ways off.

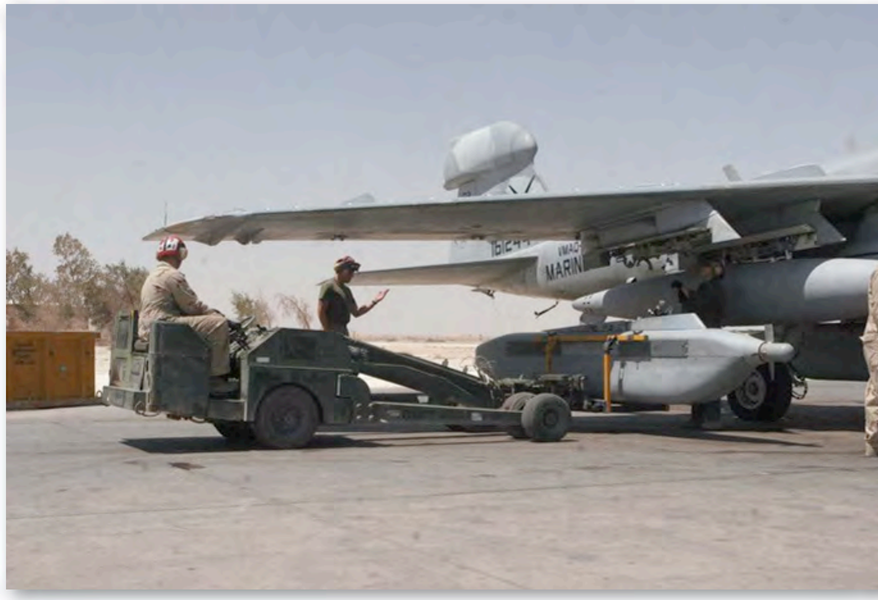
OUT WITH THE OLD....

For people who remember them at all, vacuum tubes (or more respectfully, vacuum electron devices or VEDs), conjure up visions of glowing glass tubes that powered mom and dad's radio or television sets whose CRT display weighed 50 lb. and "took too long to warm up." Just as the CRT-based TV has largely been relegated to the annals of electronics history by the LCD and other flat-panel, high-definition displays, the DOD hopes to replace the TWT with solid-state devices to power future generations of EW systems. The government and industry have already devoted nearly $1 billion and years of work to make GaN the technology that will make this happen through DARPA-funded efforts and other programs. One of the key goals of the Next Generation Jammer (NGJ) program is to foster the development of solid-state RF power sources and "TWT replacement."

To understand just how rapidly the star of GaN has risen, consider that only a few years ago the technology was considered too unreliable to be deployed anywhere. However, when US and allied ground forces began to encounter remotely triggered improvised explosive devices (IEDs) in Iraq, the Army determined that it needed small, broadband jammers that could be widely deployed throughout the theater – and it needed them "yesterday." Thus was GaN pushed from the womb into the battlefield to power the jammer amplifiers for counter-IED service. In any commercial market, building amplifiers based on multiple $800 transistors would be a non-starter. But when the DOD calls, industry answers. Today, there are tens of thousands of GaN-powered jammers in service. For the TWT, which for decades has been the dominant power source for ground, airborne, and shipboard jammers, the handwriting was starting to appear on the wall.

Nevertheless, for several reasons, the impending death of the TWT continues to be greatly exaggerated. First and foremost is the fact that the US inventory of TWT-based jamming systems is immense. Even as these systems are upgraded, many will retain their tube-based power sources. The spares market for the many EW systems alone will ensure the survival of the TWT for a very long time.

Perhaps just as important, regardless of how rapidly GaN's capabilities can be enhanced, the TWT still delivers the highest achievable levels of RF power over the broadest bandwidths at the highest frequencies. TWTs are also very reliable, with meantime between failure (MTBF) rates of about 100,000 hours (more than 11 years). As testament to this, consider that there are almost no solid-state transponders on commercial or military communications satellites, which are designed for service lives of more than a decade, and which are not all that convenient to replace. In satcom service, TWT amplifiers (TWTAs) routinely deliver efficiency of 70 percent, as their operating environment is comparatively benign and well controlled compared to that of an EW system, in which 30 to 40 percent efficiency is more typical.



THE TWT'S LAST FEDERAL STIMULUS

Similar to today's major GaN development initiatives, TWT technology was the subject of its own DOD-funded rejuvenation drive in the early 1990s, which will more than likely be its last. However, this program achieved substantial results. At that time, the DOD realized that archaic or not, the TWT was here to stay, at least for the foreseeable future. The Naval Research Laboratory and DARPA created and funded the Tri-Service Vacuum Electronics Program, and charged TWT and TWTA manufacturers with delivering major improvements to their products to make them smaller, lighter, and able to operate from lower supply power voltages.

The result was the "mini-TWT," a smaller, lower-power device that resulted in creation of the Microwave Power Module (MPM), which delivered a five-times reduction in size and weight, 100 times reduction in noise, and 50% increase in efficiency. The MPM is actually a hybrid power source, using GaAs MMIC amplifiers to drive the mini-TWT, and relies in very-high-performance power supply electronics and control circuits to produce a complete RF power source measuring about 11 x 2 x 7 in. and operating from 28 VDC or 110, 208, or 270 VAC. It continues to be widely used.

Since that time, funding for development of enhanced VED technology has nearly vanished, leaving future improvements to be developed by manufacturers, of which today there are only a handful. Representatives of TWT and amplifier manufacturers interviewed for this article uniformly agreed that a future "tube initiative" of any significance is highly unlikely, owing to the current mood of "TWT replacement" rather than "tube enhancement." Meppalli Shandas, vice president of technology at TWTA and MPM manufacturer dB Control (Fremont, CA), summed it up: "TWTs have been threatened for the last 30 years and everyone always said that next year they would die," said Shandas. "My take is that the TWT will be here for a long time, but with funding starvation, companies will have to do their own funding and if they are on sole source program will have to increase the price. The technology is not supported by academia or industry, so basically the technology is being starved to death."

While he and virtually everyone else interviewed recognized that GaN will have an increasingly important role in EW, they countered this with stronger feelings that the tube has a lot more room to grow. Thomas Grant, vice president of engineering at Communications and Power Industries' Microwave Power Products Division (Palo Alto, CA), one of the largest manufacturers of VEDs, told *JED,* "The TWT has a huge amount of potential. Our landscape is growing as fast as or faster than solid state is eating it up at lower power levels.

"We don't deal with lower power levels because we cannot compete there. But it will be decades and decades before solid-state gets to where we are [with TWTs]," Grant continued. "My question is, 'Why are we going to so much trouble [with solid state], when the whole world uses these things [TWTs], and there's so much potential for improvement? Frankly, I don't think it makes any sense. It's simply doing something new because 'new is better.' But there have been a lot of new things that have disappeared because people thought they were a hot idea and they weren't.

"I have always said that VEDs should have been invented after the transistor because then they would be the next greatest thing and all the funding would be going to VEDs as opposed to transistors," he continued. "And it would be in the correct order because the higher power, more efficient, longer lasting, more reliable devices would be the ones with the bright future."

LIVING LARGE ON LITTLE

One obvious question is how, in today's mood of "TWT funding starvation" and with only a few universities teaching thermionic technology, the TWT industry will continue even to exist let alone grow. The solution as articulated by Grant lies in taking the initiative. "We have a very strong college program here. We scour the West Coast for the best and brightest and bring them in here and train them. We have a whole army of new engineers that will take this business into the decades to come," said Grant. "We're not just a bunch of 70-year-old people waiting for retirement. We have lots of development programs. In the old days we had tube engineers, people who knew the 6 to 12 disciplines required to design and test a new tube.

"These days," Grant continued, "we don't have the time to train people on everything, so we work in teams with people taking a piece of the pie, giving them programs to work on, and helping them to be successful. They get their feet wet immediately and learn about the people and the factory. It's a completely different environment than the one I came into in the 1970s, which by today's standards was so slow that it took a long time to do things. Today we're efficient. The computer codes today are light years ahead of [the ones] back then. New engineers work on hardware, software, simulations, and learn on the job because it isn't taught in school. If it wasn't for what we do inside here, it would be impossible to keep the momentum going." Others in the industry echoed his sentiments and agreed that "home-grown talent" is the way the industry will improve VED and supporting technologies.

TUBES AND THE FUTURE

Two major issues that have long dogged the TWT are high operating voltages and the need for warm-up, both of which are or have been addressed by their manufacturers. "We do not see high voltage as an issue because our user never sees it," said Mike Sweeney, Director of New Business Development at L-3 Communications Electron Devices Division (San Carlos, CA). "We provide mostly MPMs that require 28 or 50 V and produce from 50 to 200 W. It's just not an issue." Said CPI's Grant: "If a device is supplied as an amplifier and not just a tube, the high voltage stuff is buried and you're just using line voltage. As for the warm-up issue, by changing the mass of the cathode you can get to almost instant-on, and we do that for some applications but generally most people do not need it."

There is plenty of optimism in the TWT business concerning its future in EW. "We have customers asking us for power amplifiers and they know we have thermally-efficient, low-voltage power supplies that complement tubes very nicely," said Bud Jewett, director of business development at Crane Aerospace and Electronics (Redmond, WA). "So I think the industry is fine now and for at least the near future. I may be an eternal optimist, but from what I see, and from what my customers tell me, they're not buying platforms. They want upgrades, spiral development in communications, ISR, and EW. These markets will continue because they want something better and the only way to achieve that is through enhancing existing systems."

L-3's Sweeney explained, "We are mostly being challenged by multi-octave demands. In the past, the bands have been split four to nine different ways, and they want to move from band-specific to 6- to 18-GHz and 2- to 18-GHz, with power requirements of 100 W to 12 kW, and beyond that from 18- to 40-GHz or thereabouts in two segments. There are a lot of advanced development programs going on that are not yet in procurement. We're looking to get TWT efficiency up to 50 percent on our long-term roadmap."

Confident though they may be that the TWTs have a long future in EW systems, Crane, CPI, and L-3 are working with GaN developers and foundries. "We're going long on tubes," said L-3's Sweeney, "and our position is that whether it's EW, communications, or radar, more often than not our customers are agnostic to whether it's solid state or tubes. We take the best of breed and provide solutions in order to eliminate the 'us versus them' aspect that's out there. We have really advanced power supply and thermo-mechanical packaging that we can wrap around a solid-sate amplifier."

Sweeney subscribes to the theory that new EW products may result in a mix of GaN and TWTs to cover the bands in the best way. "In some cases, the power and frequency range needed will be limited and power levels will be modest to low, which is perfect for a solid-state implantation. At higher frequencies through Ka band, a TWT solution would make the most sense, and both can be driven by the same power supply since there's low power in the high-power supply. It's not out of the question. The keyword is "SWaP" [size, weight and power], and we get that with efficiency."

"We face a giant beast of a marketing blast on the GaN front," said CPI's Grant. "We have GaN projects in progress at CPI, not just for EW but for other market segments, as well. The lower power levels will mean making compromises using antenna gain. But then, you can do it now with tubes, rather than waiting for 10 years. GaN is very efficient, but VEDs are very efficient too."

Bud Jewett at Crane confirmed that his company is looking at GaN as a TWT replacement. "However, we don't yet know what power levels we will be able to achieve, and managing the thermal problem is a big question. Some platforms can't carry around a lot of thermal equipment like liquid cooling, and these devices are just too hot for conventional cooling, so we'll have to see."

NGJ AND GaN: MORE QUESTIONS THAN ANSWERS

The question is not if GaN will make its mark in EW systems, but rather when, how, and in what types of designs and configurations. At this early stage in the development of GaN for communications, EW, radar, and other systems, there appears to be more questions than answers. US Navy program officials who are developing the Next Generation Jammer (NGJ), which aims to replace the ALQ-99 tactical jamming system with an active electronically steered array (AESA), solid-state jammer around 2019, have identified five major technology challenges in its development: power generation, exciters, beamformers, antennas and high-power amplifers. In this last category, the NGJ program needs high-power, wide bandwidth amplifiers that can support CW operation while offering good linear performance. Aside from simply generating the required power, the jammer design must also address what will likely be a significant waste heat removal problem, as well as amplifier reliability.

One of the keys to how some NGJ designs may unfold lies in two areas that fit together nicely. The first is the rapidly evolving idea of "smarter," more precise jamming that uses precise frequencies, narrow beams, and generates the right amount of effective radiated power (ERP) to defeat a particular target. (This, of course, is enabled by the wider use of advanced ESM systems that can detect, identify and accurately geolocate threat emitters.) The second is AESA technology, the 21st century version of the active phased-array in which there are many, sometimes massive, numbers of independent transmit/receive (T/R) modules, each capable of transmitting on a different frequency for each pulse and with different waveforms.

The AESA system can produce many sub-beams and can paint many targets over a very wide range of frequencies. The wonders of signal processing also make it possible for all of the beams to be processed simultaneously and combined to produce the appearance of a single beam. As they employ huge numbers of T/R modules, no one T/R module needs to deliver high RF output powers, as the gain the many antenna elements can generate dramatically increases the system's ERP. Passive and active electronically-steered phased-array radars have used solid-state amplifiers in their T/R modules based on GaAs MMICs for many years. However, the AESA approach when applied to EW (as well as radar) makes a compelling case for broadband, high-power-density, GaN-based amplifiers. While they can currently deliver only tens of watts at higher frequencies, these levels will unquestionably increase substantially by the time NGJ is be deployed. Somewhere in the middle is a hybrid NGJ approach, in which GaN-based amplifiers are employed at those frequencies where their use is desirable, and MPM-based amplifiers are used elsewhere.

GaN'S POTENTIAL

As MPMs are largely mature products, the spotlight now focuses on what GaN will bring to the party. In short, the current capability of GaN is leading its users in terms of handling the large amounts of heat that these high-density devices produce. The current situation is neatly summed up by Grant Wilcox, product marketing director for defense and aerospace standard products at TriQuint Semiconductor, a major developer of GaAs and GaN technology. "Suppliers are working hard to deliver reliable GaN products into the market that will revolutionize the RF power industry. However, with this increase in performance and resulting power dissipation, users are required to put much more emphasis on the thermal management of their system design than they ever have before," he explained.

"With GaAs, technology development would produce a transistor that delivered maybe 30 percent more power. With GaN, we are delivering 4 to 5 times that of GaAs, a step function our customers have never had to deal with," he said. "While the thermal ramifications of this may have been understood, suppliers and users have had to maneuver a steep learning curve in properly managing the resulting thermal dissipation."

Wilcox says TriQuint is working with TWT manufacturers at frequencies through Ku band for TWT replacements in both radar and communications. "We can write a paper about being able to produce 7 W/mm, but demonstrating capability does not mean customers can design with a particular technology. Our GaN products generally target 3 to 4 W/mm to assist in the thermal management. Even at this reduced level, we can still produce high-power broadband and narrowband amplifiers. Higher densities are achievable by modifying the gate geometries and optimizing the material to achieve higher voltage breakdowns. The tradeoff is typically in frequency, which results in a reduced cutoff frequency." The company has a 2.5 to 6-GHz 30-W power amplifier, a 14 to 16- GHz 20-W amplifier, and a 2 to 18 GHz distributed amplifier that produces 14 W CW output power. A variety of other amplifiers are being developed that will target slots historically served by TWTs.

GaN's power-added efficiency is equal to that of GaAs, but GaN's 4 to 5 times greater power density produces much higher power dissipation so the user must remove 4 to 5 times the heat from the unit. The efficiency of MMIC products in either technology ranges from 20 percent to 50 percent and among other factors is a function of the target bandwidth. Using X-band as an example, a GaN-based power amplifier can deliver more than 100 W with 40% to 50% efficiency. Such a product could support a 1-kW CW pallet through 4- or 8-way combining depending on power level of the building block.

In addition to its broadband capability and power density, the big differentiator between GaN and a TWT-based solution is longevity. While TWTs routinely demonstrate 100,000-hour lifetimes less (than the life of a typical EW system), a GaN-based amplifier should be able to operate continuously without failure for 1 million hours at a 200 degrees C junction temperature, without maintenance or device replacement – far longer than even the hoariest old EW system will remain in service.

Not too long ago, the question of GaN's reliability remained in question, but advances are continually being made and the ability to operate to a 10:1 VSWR (voltage standing wave ratio) is not unrealistic. When compared to GaAs, GaN has the advantage in broadband power while maintaining high efficiency. It simply outperforms GaAs – or any other semiconductor technology. TriQuint is active in developing GaN technology from S-band to Ka-band and even enhancement-depletion mode (ED) GaN at 200 GHz and higher. The company was recently awarded a three-year government contract to improve the overall manufacturing efficiency of its GaN technology.

TriQuint, along with its competitors, is also exploring the use of techniques that can potentially reduce device junction temperature, as this is a key factor in determining device lifetime. One such alternative, which just recently became commercially viable after two decades of development by Nano Materials International (NMIC), is the use of aluminum diamond composite material for heat spreaders, which while adding somewhat to device cost, has shown its ability to reduce junction temperature of GaN devices by 25 percent thanks to the unparalleled thermal conductivity of diamond. This is substantially better performance than traditional materials such as copper tungsten, copper molybendum and "copper molybendum copper" deliver.

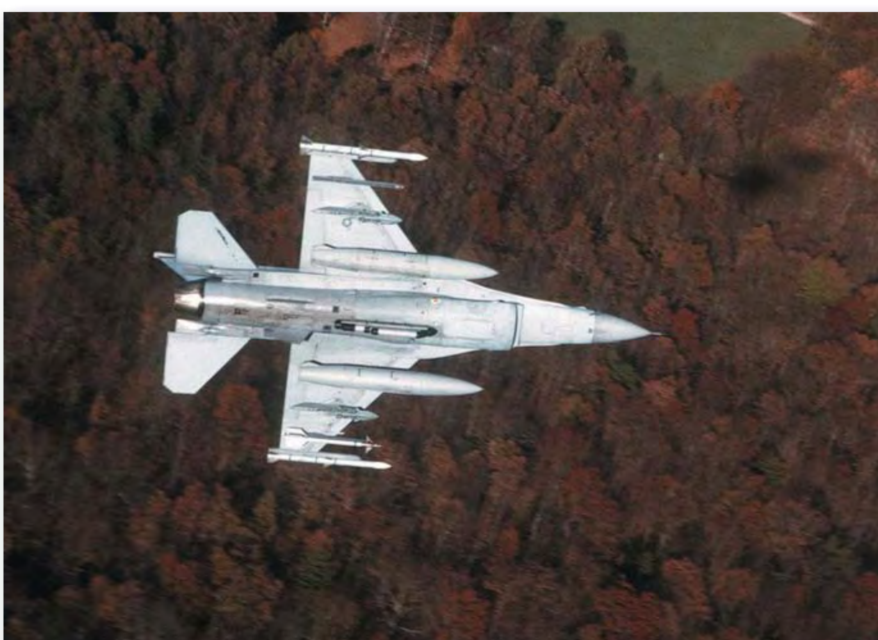
Nevertheless, dealing efficiently with the heat produced by GaN-based amplifiers remains the primary challenge for GaN users, which is why TriQuint has backed-off the power density of some products it delivering, and why at higher power levels some form of liquid cooling is likely in many applications.

POWER IN NUMBERS

Another promising approach to TWT replacement comes from the Spatium spatial combining technology from CAP Wireless (Newbury Park, CA). "We've developed a platform from 1 to 45 GHz in two or three separate segments as a TWT replacement," said Skip Hoover, vice president of sales at CAP Wireless. "It's a solid-state power amplifier that uses commercial or proprietary MMIC devices and our combining scheme to produce high-power amplifiers, currently up to 500 W CW and 5 kW pulse.

The patented technology, which mates a radial combining structure with MMIC power devices, is largely frequency independent, and can accommodate various combinations of power and bandwidth by changing only the devices. A tapered center conductor transitions from an SMA coaxial connector to a larger center conductor; once the enlarged-radius coaxial line is reached, multiple finline antenna elements arranged radially around the center gather all the microwave energy across a wide frequency spectrum and transition it to several microstrip transmission lines. Each line feeds a MMIC power amplifier housed in a resonance-free ceramic package where the signals are simultaneously amplified by equal amounts. The amplified signals from the MMICs are launched back onto microstrip lines that are then coupled to output finlines back into a coaxial waveguide, where the fields coherently combine. The output signal transitions through a tapered coaxial line back to an SMA connector, providing the high output power levels. The result is nearly identical phase and amplitude variation through all amplification channels, resulting in high power combining efficiencies. Typical 16-way combining efficiency from 2 to 20 GHz is less than 0.5 dB loss.

"We find a lot of interest in EW systems for ground, shipboard and airborne platforms, as well as data links in excess of 50 W, which is rare for a solid-state amplifier that is a reasonable size, and for satcom terminals and for test ranges," Hoover said. "We combine 16 devices, and the output is 16 times whatever the MMIC can deliver, which right now produces hundreds of watts over different bands. As the device power of GaN increases, our platform can leverage them to produce 15 times the power of a single device. There are GaN parts now up to 6 GHz with 30 W CW output, and we can combine them now to produce a 500-W solution. We believe that the inherent advantages of GaN – higher voltage and higher impedances for given power level – will let it operate at broader bandwidths versus GaAs or any other technology."



The company has been developing Spatium-based products for about 6 years and delivering them for 3 years. They have been integrated into the ALQ-161 jammer on the B-1B, the ALQ-135 on F-15, ALE-50 and ALE-55 towed decoys, as well as others, in each case replacing TWTs. "Our structure inherently gets heat out better than other combining techniques because of its radial 3D heat dissipation capability," said Hoover. "We have very high combining efficiency, so for any power we are more efficient than other types of combining approaches. If you look at the whole TWT market, we can service about a third of it, but we're not close to taking on very high power applications. We can get from 1 to 45 GHz at power levels that people have never seen before, such as 50 to 100 W in the 29 to 31 GHz satcom band."

AN UNPREDICTABLE DECADE

If anything can be taken away from these conversations with VED and GaN suppliers, it is that the next 10 years will be interesting, challenging, and unpredictable. More important, they will be also likely be profitable, as the perceived need by DOD for new and upgraded EW systems is strong. GaN will unquestionably play a very large role in how NGJ and other programs unfold, as will TWT technology, as it faces its first direct long-term competitor on platforms over which it has traditionally held all the cards.

Barry Manz has been writing about the RF and microwave industry since 1982. He is the former editor of Microwaves & RF magazine, co-founder of MIL/COTS Digest, editor of Military Microwave Digest and the owner of Manz Communications. He can be reached at manzcom@gmail.com.