GaN as a Catalyst for Ultra-High-Power Directed Energy
(Invited)

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Abstract

High-power RF amplifiers that offer best-in-class performance characteristics while simultaneously delivering size, weight and power (SWaP) advantages to amplifier designers were uncommon a decade ago. Today, they are being routinely designed – with gallium nitride (GaN) transistors at the core. System architects that once leaned heavily on traveling wave tubes (TWTs) as their default, now entertain GaN-based solid-state power amplifiers (SSPAs) as a viable alternative in most every high-power microwave project. Defense-oriented directed energy (DE) systems represent the latest technology tipping points which move the needle into higher power realms for gallium nitride – and point the way forward.

INTRODUCTION

When the Office of Naval Research (ONR) underwrote the fundamental research leading to the recognized viability of wide bandgap semiconductors (WBGS) during the 1980s and 1990s, few would have predicted the mainstream position that gallium nitride has ascended to in 2023. In the early days, scientists and academics envisioned the twin merits of high voltage and high current for addressing ever-increasing market demands for RF power. ONR's cornerstone support led to DARPA's further investigations via the Wide Bandgap Semiconductors for RF Applications (WBGS-RF) program beginning in 2001. WBGS-RF researchers sought to "leverage the proven promise of GaN into an industrially relevant technology that could further the cause of national defense."[1]

With its deep roots in defense and decades of R&D to draw from, GaN is now field proven in numerous radar, jammer, base station, tactical radio, SATCOM and electronic warfare systems. As 5G buildouts continue around the world, infrastructure builders are further mainstreaming solid state GaN-based amplifiers with each new deployment. GaN is finding a home in the latest remote radio heads (RRHs) and advanced antenna systems. Once an outlier, GaN-based 5G systems are commonly found alongside their silicon-based LDMOS counterparts – outperforming them in some areas.

At the cutting edge of the ecosystem, ultra-high-power microwave (uHPM) uses cases are emerging for GaN's well-established thermal, power density and operating voltage capabilities. GaN's supporters are raising expectations for high-power microwave (HPM) DE systems and redefining what's possible in the defense sector, in communications markets, and beyond.

TUBE TRANSITIONS

Displacement of vacuum tubes for solid-state approaches has emboldened developers to ratchet up their SWaP expectations since the very beginning. With the frenetic pace of new product development in the digital age, it's easy to forget just how transformational transistor radios were when they eventually reached the mass markets and how "solid state" defined a new era in consumer electronics.

Surpassing and supplanting tube designs often requires a generational departure -- with all ecosystem influencers onboard for the migration. That was certainly the case in the early 1950s as the giant radio OEMs of the day were not the first movers during the introduction of portable transistor radios. Perhaps not so eager to cannibalize their home console radio sales, it wasn't until consumers recognized the previously-inconceivable freedom of listening to music or tuning into a baseball game on a pocket-sized device outside the confines of their living rooms that the large electronics companies jumped in with both feet.

GaN's appeal crossed over from defense to consumer electronics some time ago. GaN has replaced some traditional silicon-based designs and energized a variety of consumer electronics migrations in a relatively short period of time, from the emergence of bright white LED lights to Blu-ray Disc™ players to ever-shrinking laptop power supplies and a wide spectrum of new mobile phone chargers.

In many modern high-power applications, GaN becomes an attractive consideration where tube-based approaches come with reliability issues, high sensitivity in terrestrial environments and myriad human factor issues that must be addressed.

Our GaN thesis for directed energy has its roots in airborne electronic attack (AEA); another pivotal transformation within the defense sector.

Fig. 1. Epirus' Leonidas™ counter-electronics system

Airborne Electronic Attack

The US Navy's tube-based ALQ-99 Tactical Jamming System (TJS) was an innovative solution designed to target enemy radar and communications systems and suppress integrated air defense systems. In service since 1971, the ALQ-99 was architected as an external carriage system mounted to the EA-6B Prowler aircraft with eventual upgrades enabling it to be transitioned to the EA-18G Growler beginning in 1980.[2]

To maintain air superiority and support the stealth capabilities of warfighters confronting the latest radar, a major performance upgrade would eventually be required. In order to most effectively disrupt, deny, and degrade air defense and ground communications systems, it became apparent that increased power and jamming capability at longer ranges was necessary. Increased reliability was also deemed to be paramount. Development for the ALQ-249 Next Generation Jammer (NGJ) program was underway by 2014, with the latest digital software and active electronically scanned array (AESA) technology designed in.[3] The NGJ program also represented a milestone shift in the high-power realm: the transition from tubes to GaN.[4]

Directed Energy

There has been a great deal of media attention focused on the emerging threat of drone swarms, and decades of high-power microwave research has been applied to directed energy-based systems in recent years. Advances in the capabilities of small, unmanned aircraft systems (UAS) have been matched by the emerging discipline of counter-UAS.

The 2023 announcement that the U.S. Army's Rapid Capabilities and Critical Technologies Office (RCCTO) had selected the Leonidas™ directed energy system from Epirus for its Indirect Fire Protection Capability-High-Power Microwave Program was yet another milestone that further positioned GaN in the highest tier of high-power amplifier design.

The Next Wave

High-power vacuum tubes still play a decidedly significant role in many communications, space, defense medical, scientific and industrial markets. Innovators continue to produce large amounts of energy via vacuum tubes, just as their predecessors did during the formative years of AM radio.

It stands to reason that as gallium nitride and other wide bandgap materials become more advanced, that they will show capabilities that make them more competitive than traditional approaches.

Directed energy applications were previously defined by creating electromagnetic pulses with as much effective radiated power (ERP) as possible, but recent breakthroughs now allow us to consider energy and waveform complexity in addition to ERP.

Conclusions

GaN-based electronics are being used to fundamentally raise the bar and answer the demand for increased power and frequency requirements for defense and commercial systems. We can expect to see the consumer electronics calling cards of smaller, lighter, and "uses less energy" in the most demanding defense applications going forward.

Just as in the early days of the transistor, new solid-state designs can enable radical new uses cases that were either impossible, impractical or not commercially viable with tubes.

References

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Acronyms

AEA: Airborne Electronic Attack
AESA: Active Electronically Scanned Array
DARPA: Defense Advanced Research Projects Agency
DE: Directed Energy
ERP: Effective Radiated Power
GaN: Gallium Nitride
HPM: High-Power Microwave
LDMOS: Laterally-Diffused Metal-Oxide Semiconductor
LED: Light-Emitting Diode
NGJ: Next Generation Jammer
OEM: Original Equipment Manufacturer
ONR: Office of Naval Research
RCCTO: Rapid Capabilities and Critical Technologies Office
RRH: Remote Radio Head
SSPA: Solid-State Power Amplifier
TJS: Tactical Jamming System
TWT: Traveling Wave Tube
uHPM: Ultra-High-Power Microwave
WBGS: Wide Bandgap Semiconductors