Vacuum Electronics for Missile Seeker Radars

Technical Report

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Stellant

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Stellant Systems

Missiles incorporating autonomous radar transceivers for terminal guidance and intercept have been in use for many years. Known as active missile seeker radars, these sensors have been developed at frequencies from X-band to W-band, with individual performance specifications dependent on the target engagement, radar modes, and operating environment. For long range engagement of high velocity objects, transmitter characteristics such as high repetition rate, high peak power and high duty may be required, while for long range engagement of stationary or slow-moving targets lower repetition rate and duty can be acceptable. Similarly, frequency bandwidth is beneficial for range resolution and anti-jamming capability, while high frequency (short wavelength) operation provides benefits for reduced probability of intercept and imaging resolution.

For all seeker implementations, low transmitter size, weight and prime power consumption (SWAP) is of paramount importance due to limitations on missile packaging space and battery power. “Hot at launch” is another key tenet for missile sensor payloads. And since the time and scope of conflicts is not known in advance prudent planning requires having a stockpile of assets on hand. When taken in aggregate it is not surprising therefore that affordable, long-shelf-life, fast turn-on vacuum electronics devices, with their well-known characteristics of high power, high frequency and high efficiency, continue to find widespread use in missile seeker radars.

Of the global vacuum electronics companies Stellant Systems has by-far the largest portfolio of vacuum devices and integrated amplifiers for missile seeker radars. The Stellant product line spans both the crossed-field and linear beam vacuum device families, with crossed-field amplifiers (CFAs) and magnetrons in X-band and Ku-band, and linear beam traveling wave tubes (TWTs) in I/J-band, Ka-band and W-band. Of note, Stellant is the only vacuum electronics company that can provide an integrated missile seeker power amplifier solution including both the vacuum device and high voltage power supply.

A discussion of Stellant’s vacuum devices and supporting technology for active missile seekers follows in this survey.

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I. Crossed-field devices

a. Magnetrons

Crossed-field microwave devices, in which the magnetic field used to confine the electron beam is oriented at right angles to the applied DC electric field, include magnetrons and crossed-field amplifiers. In the microwave device family magnetrons set the bar for power and efficiency in a small physical footprint. CW magnetrons have been developed producing from 1 kW to over 100 kW, for heating and industrial processing, while pulse magnetrons generating from kW's to MW's have been developed for use in radar and for powering X-Ray sources for radiation oncology and cargo screening. Industrial magnetrons can have efficiencies of up to 90%.

Magnetrons, specifically, and crossed-field devices, in general, are known to be cost effective on a dollar per RF watt basis – a feature fully exploited in the commercial product world as exemplified by the $7 magnetron in your kitchen microwave oven. Besides its attractiveness for commercial use, the low cost per watt of the magnetron can also be an enabler for defense applications, for example, use on expendable platforms, such as missiles and decoys.

Magnetrons, however, such as those used in everyday microwave cooking, are oscillators. As a free running oscillator, the magnetron's use for radar can be found wanting due to jitter in its start-up phase from pulse to pulse as well as an inevitable drift in frequency from thermal effects during operation. The magnetron however, as with other oscillators, can be made coherent (i.e. providing an output signal with a well-defined phase with respect to a reference standard) through the process of phase locking where a signal from a highly frequency stable source is used to "lock" the oscillator frequency. [The magnetron frequency can also be locked by modulating the device voltage or magnetic field in a phase locked loop arrangement.]

Stellant is a leader in the development of injection locked magnetrons (ILMs). The bandwidth over which a free running magnetron can be phase locked depends on the injected drive power and the frequency separation between that of the drive source and the magnetron's free running oscillation. It is given by the well-known Adler phase locking equation, $\boldsymbol{\Delta f = 2f_o/Q_e G^{1/2}}$ where $\boldsymbol{\Delta f}$ is the locking frequency bandwidth, $\boldsymbol{fo}$ the frequency of the free running oscillator, $\boldsymbol{Qe}$ the external quality factor of the oscillator, and $\boldsymbol{G = Pout \,/\, Pinj}$, the ratio of the output power to injected locking signal power. An effective gain in decibels (dB), given by $\boldsymbol{10\ log\ (Pout\ /\ (Pinj)}$, can be defined for an ILM. While typically in the low teens, higher 'gain' on the order of 20 dB or more can be achieved by cascading individual phase locked oscillators (magnetrons) in a master/slave configuration, albeit with some reduction in overall locking bandwidth. A notional

RF circuit representative of this approach is shown in Fig. 1 where a 5 W reference input signal serves to frequency lock a 75 W magnetron whose output is then used to lock a 1 kW magnetron. Circulators are used in the RF chain to prevent unwanted feedback. As shown in the example an overall net 'gain' of 23 dB is obtained.

Figure 2 shows a picture of a Stellant product implementation of this concept. The L4110/L4111 magnetron injection locked pair shown provides 800 W (min) in Ku-band at duties greater than 15% with a locking bandwidth of 70 MHz. The magnetron-pair efficiency is 35%. Harmonic and spurious signals, in-band and out, are better than -30 dBc, with interline noise of -110 dBc/Hz. A fast heater warm-up time of 2 seconds is supported by the magnetron pair. The Stellant injection locked pair is designed to perform under harsh environmental conditions, including 50 G shock and 40 G acceleration, temperature extremes from – 54°C to 100°C, and altitudes up to 70,000 ft.

The low operating voltages of the 60 W driver magnetron (825 V, nom) and the 800 W output magnetron (1800 V, nom) make for an extremely compact configuration, as shown in Fig. 2. The low voltage requirement of the magnetron pair has the additional system benefit of simplifying the pulse modulator design. The Stellant Ku ILM pair has been employed in a missile seeker radar.

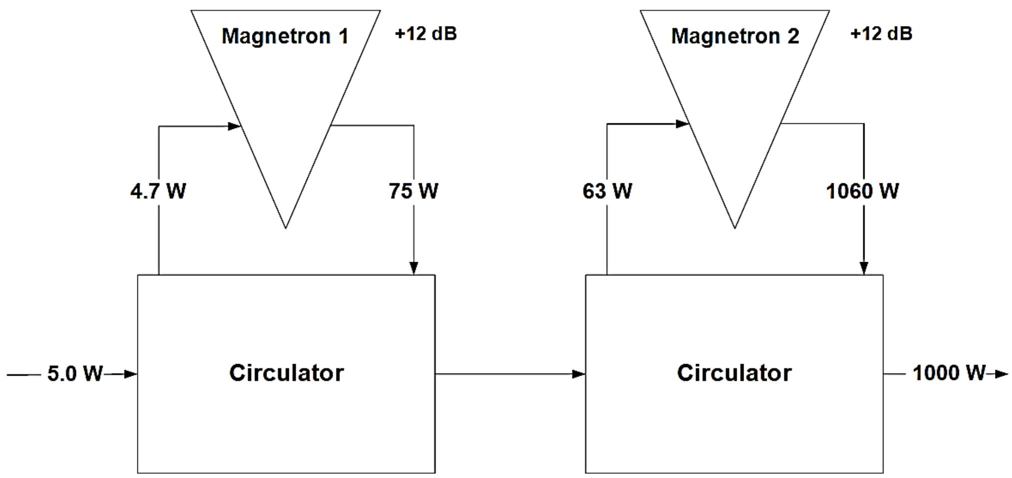


Fig. 1. Magnetron injection locked pair circuit.

Fig. 2. *L4110/L4111 Ku-band injection locked magnetron set (each magnetron is 4 x 2 x 1 in, not including circulator). The separation distance between magnetrons is 1 in. RF input and output ports are SMA, with an isodaptor at the input and a W/G to coax transition at the output.*

The need to cascade individual magnetrons for increased gain has been mitigated recently with the availability of efficient, high-power solid-state driver amplifiers. A solid-state amplifier feeding an injection locked magnetron can provide an attractive solution for compact missile seeker RF output chains, capitalizing on the low noise and high gain of solid state with the power, efficiency and compact size of the magnetron. The synergistic benefit of combining solid state and vacuum electronics is highlighted throughout this report. As Stellant Systems has both vacuum electronics and high-power solid state amplifier technology within its corporate domain it can provide an optimized solution for high power phase-locked radar transmitters.

Another member of the magnetron family used in radar is the frequency agile (FA) magnetron. As the name implies, the operating frequency of an FA magnetron can be varied during radar operation, typically achieved through active electromechanical control of the magnetron circuit. Frequency agility is attractive for missile seeker use due to the radar improvement it provides in target detection, as well as for increased protection against electronic countermeasures. An example of a FA magnetron for missile seeker use is the L4649 shown in Fig. 3. This device operates in Ku-band with a peak power more than 35 kW min over a 200 MHz tuning range. It employs a hot-shot thermionic dispenser cathode for quick turn-on of 2 seconds.

Fig.3. *L4649 High power Ku-band frequency agile magnetron. Nominal operating parameters: 14 kV, 10A (pulsed), 85 kW peak power, 225 MHz frequency tuning range (min), max duty 0.0006.*

b. Crossed-field amplifiers

While magnetrons are oscillators, the amplifier member of the crossed-field device family is the aptly named crossed-field amplifier (CFA). Crossed-field amplifiers are high power density devices providing high peak power with high efficiency (50%). Due to the fact that crossed-field devices convert potential energy into RF, they have excellent phase linearity with frequency, typically around ten degrees deviation (pk-pk). CFAs have found extensive use in high power radar systems. As they have moderate gain and bandwidth, CFA's primary use in radar transmitters has been as an output stage power booster. An example of a surveillance radar CFA manufactured by Stellant is shown in Fig. 4. The L4764 provides a peak power of 0.5 MW in X-band (9.5 – 10 GHz) with a gain of 16 dB and an efficiency of 50%.

Fig. 4. L4764 X-band radar crossed-field amplifier (0.5 MW, 9.5 -10 GHz, 0.001 duty). Dimensions are approximately 8.5 x 12 x 5.75 in (height, length, width). Nominal operating voltage is 35 kV.

i. Mini-CFA

While high power CFAs have been developed for air, sea and ground radars, they can be designed for missile seeker use as well. Indeed, Stellant (then Litton Electron Devices) developed a prototype compact CFA for just such application. The Mini CFA, as it is called, is designed to operate in X-band with a peak power of around 1 kW and a gain of 20 dB over a 2-4% frequency band. It is designed for high duty operation of 30%. Due to its relatively low peak power its operating voltage is quite low at around 2 kV. The low voltage operation of the CFA (a trait shared with magnetrons) simplifies the transmitter power supply design, reducing its size, mass and complexity.

The mini-CFA's low voltage and low peak power translates into a small, lightweight form factor (Fig. 5). A few engineering models were successfully built and tested at Stellant with good performance achieved:

Output Power	750 W
Frequency	9.2 – 9.8 GHz (instantaneous)
Gain	16 dB
Harmonic/Spurious	-40 dBc
Voltage	2.2 kV
Current	1.5 A

The efficiency of the early engineering models was around 20%. Higher efficiency is possible through design refinement.

Fig. 5. X-band Mini-CFA (5 x 4.25 x 2.75 in, incl. WR-90 W/G output flange and SMA input connector).

The Mini-CFA requires a drive power of around 20 W for rated power, easily provided by a solid-state driver. While reentrant CFAs, such as the mini-CFA, are known to have higher noise power spectral density than linear beam devices (such as TWTs), the use of gain partitioning, with a low noise, high gain solid state amplifier driving a low gain CFA power booster, provides an attractive solution for the missile seeker radar system designer. An example reenforcing this point is illustrative. Assume an overall RF transmitter gain of 50 dB is required. For an RF chain comprised entirely of CFAs, with representative noise figures of 41 dB, an output noise power spectral density of -83 dBm/Hz results. Now configuring the amplifier chain to be comprised of a 30 dB SSA frontend, with noise figure of 5 dB, and a mini-CFA output power booster, with 20 dB gain and 41 dB noise figure, an output noise power spectral density of -112 dBm/Hz results – a significant operational improvement.

While Stellant work on the Mini-CFA ceased at the turn of the century, the concept retains considerable merit for modern, low-cost seeker needs and should be revisited.

II. Linear Beam Devices

a. Helix TWTS

Stellant has a long and distinguished history of manufacturing traveling wave tubes (TWTs) for missile seekers. A crucial component of any vacuum device intended for missile applications (whether it be a linear device or crossed field) is the fast turn-on cathode. Stellant is a world leader in the technology with experience in both thermionic fast warm-up cathodes and cold cathode emitters. The I/J-band missile seeker helix TWT shown in Fig. 6 uses a proprietary fast warm up thermionic cathode. It has been in continuous production at Stellant since the 1980s.

Another key device attribute essential for missile use is the ability to reliably function after an extended storage period. Again, Stellant seeker products excel in this area with demonstrated shelf-lives more than 15 years achieved through the combination of rigorous vacuum processing and incorporation of internal getters.

Fig. 6. *I/J-band Seeker TWT.*

Helix TWT’s are known for their wide instantaneous bandwidths with TWTs developed for electronic warfare having bandwidths of 2 octaves, or greater. Assuming suitable antennas can be developed, a wideband helix TWT could be used to power a multi-frequency-mode seeker. And with the use of a multi-stage depressed collector a true multi-power/multi-frequency-mode seeker TWT is possible. These exciting TWT capabilities remain to be fully exploited in advanced seekers.

b. Coupled cavity TWTs

While helix TWT technology is ideal for producing high peak power at microwave frequencies its power generating capability begins to suffer in the millimeter wave frequency bands due to the thermal power handling limitations of its dielectric-supported helix interaction circuit and the small cross-sectional size of the circuit. For high power generation at millimeter wave an all-metallic variant of the traveling wave tube is required – the coupled cavity TWT (CCTWT), an example of which is shown in Fig. 7. This device operates in Ka-band and has a peak power in the kW-range. Designed for missile seeker use it employs a fast warm-up cathode with a gridded electron gun for high pulse repetition rate capability. Due to their robust all-metallic design CCTWTs can operate in demanding environments. Coupled cavity TWTs typically work at higher voltages than helix tubes due to their circuit's physical characteristics. The TWT shown operates at a voltage of around 20 kV. Higher power versions are possible.

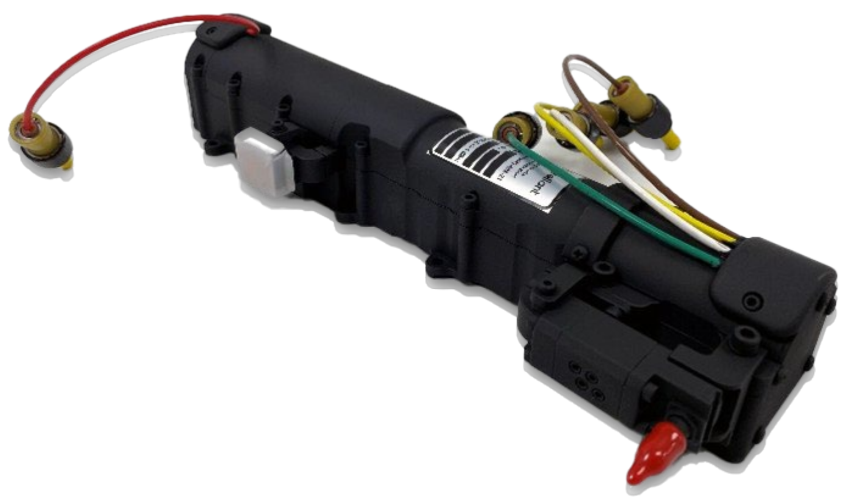


Fig. 7. *Ka-band missile seeker TWT.*

c. Serpentine waveguide mm-wave TWTs

Recent advancements in missile technology in speed, size, and maneuverability have made seeker targeting more challenging than ever. First and foremost, to intercept (i.e. kinetic kill) a hypersonic missile the interceptor must be traveling faster than the target. This can result in extremely fast closing speeds. Short pulse, high repetition rate radar operation is required. Further complicating matters, hypersonic missiles traveling through the atmosphere can generate extremely high temperatures on their surfaces creating plasmas. These plasmas can make traditional RF radar interrogation of the target problematic due to their dispersive, absorptive, reflective and emissive properties. In addition, offensive missiles are regularly deployed in swarms, including clever decoys. A high-resolution radiation scanning beam with sufficient power to overcome two-way atmospheric propagation loss and reduced signal to noise radar return, while providing sufficient dwell energy on targets (real and decoy), is essential for discrimination and terminal homing. The recently developed Stellant L6146 TWT addresses this need (Fig. 8).

Fig. 8. *L6146 W-band TWT, 100W (pk), 94 GHz +/ 2 GHz, 30% duty.*

Initially developed for airborne high-resolution radar/imaging in degraded visual environments, the L6146 W-band TWT provides 100W, min (pk) over a 4 GHz instantaneous bandwidth from 92 to 96 GHz. The device operates at 20 kV. The circuit used in the L6146 TWT is a derivative of the coupled cavity design known as a serpentine waveguide. Due to its integral all-metallic design the serpentine waveguide circuit can be mass manufactured with features appropriate for operation in the upper millimeter wave frequency spectral range (>75 GHz). Indeed, Stellant has successfully developed a serpentine waveguide TWT for a high-resolution imaging radar operating at 235 GHz.

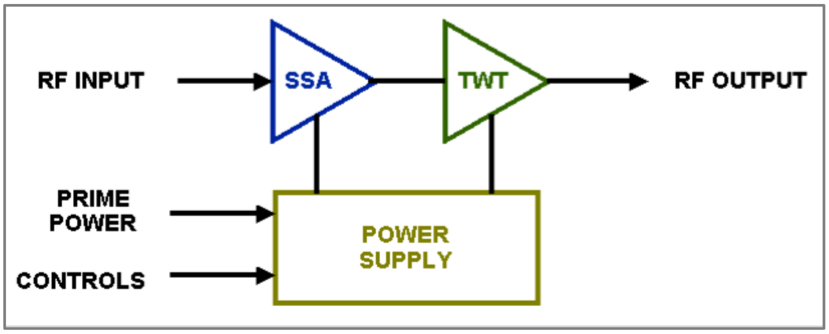
The L6146 W-band TWT has a large signal gain of 30 dB and employs a severed circuit to decouple reflections between the input and output. Designed for airborne use the L6146 has an isolated focus electrode for electron beam pulsed modulation, with a mod-anode for beam current control. The TWT employs a single stage depressed collector, suitable for operation at 30% duty. TWT efficiency is 10% minimum across the band with band-center efficiency more than 15%. A multi-stage collector is optional for higher efficiency, as well as for high duty operation to 50%.

The electron gun in the L6146 has been operated at a pulse repetition rate of 50 kHz with a high-speed high voltage modulator. For radar use requiring higher duty (>100 kHz) a gridded electron gun can be substituted. The electron emitter is a conventional, indirectly heated dispenser cathode. Similarly, for missile seeker use it can be replaced with a fast warm-up design providing turn-on times of under 3 s. With the aforementioned changes to the baseline design, the TWT designation is the L4095.

The L6146 TWT has been integrated with a compact 20 kV electronic power conditioner in a microwave power module (MPM) amplifier configuration, designated the M2839.

III. Microwave Power Modules (MPMs)

The microwave power module concept is based on gain-partitioning between solid state and vacuum electronics (Fig. 9). The basic idea is to use solid state RF technology to do what it does best – low noise signal amplification/signal conditioning and let vacuum electronics do what it does best – efficiently generate output power. When coupled with a miniaturized electronic power conditioner (EPC) a compact power amplifier results; one with best-in-class performance in power, efficiency and SWaP.



Legend:
- SSA: solid state amplifier/signal conditioner
- TWT: vacuum power booster traveling wave tube
- Power Supply: miniature electronic power conditioner (EPC)

Fig. 9. *Microwave Power Module concept.*

Stellant is the only merchant supplier of vacuum electronics products with both vacuum electronics and power supply capability under one roof. This unique capability makes Stellant perfectly suited to develop and manufacture state-of-the-art microwave power modules. Indeed, Stellant is a world leader in MPMs having produced over 4000 for use in communication, electronic warfare and radar. For pulsed radar use special power supply circuit techniques are employed for low phase noise and high on/off isolation. All Stellant MPM EPCs include high speed pulse modulators to gate the TWT on and off, as well as EMI circuitry for noise and spurious signal mitigation. Examples of Stellant MPMs used for radar are shown in Fig. 10. They include the M2835 100W Ku-band MPM, M1270 1 kW X-band MPM, M1871 40W Ka-band NanoMPM®, M2839 100W W-band MPM and the M2840 30W EHF MPM.

M2835: 6-18 GHz, 80W

M2840: 231.5-235 GHz, 32W (split-package MPM)

M1270: X-band, 1 kW pulsed

M1871: Ka-band NanoMPM®, 40W

M2939: W-band, 92-96 GHz, 100W

Fig. 10. *Stellant Pulsed-mode MPMs.*

An important advantage of the compact size of the MPM is that it can be placed near the radiating aperture, thereby eliminating the high RF transmission feed loss of conventional remote power amplifier installation. This allows for the design of extremely compact radar sensors, critical for platforms with constrained available physical space. A perfect example of compact sensor packaging is the Ku MiniSAR radar developed by Sandia Laboratories (Albuquerque, NM). As seen in Fig. 11, the Stellant MPM resides behind the radar's slotted waveguide radiating aperture. [It should be noted that the Sandia MiniSAR was not developed for missile seeker use.]

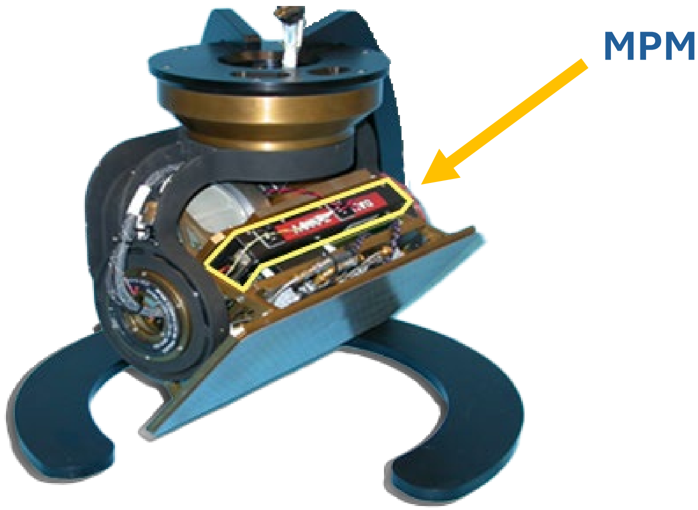


Fig. 11. *Sandia Laboratories Mini-SAR (Stellant Ku MPM identified by red label).*

While a traditional MPM has the SSA, TWT and EPC assemblies integrated in a single housing, this doesn't necessarily have to be the case. For some platforms a split package architecture consisting of separate RF and power conditioning modules is better suited for the system layout, while in other configurations the driver SSA/signal conditioning circuitry may reside external to the TWT. No matter the layout, as long as the gain-partitioning approach between solid state and vacuum electronics is employed the configuration functions as an MPM.

An example of a split package MPM is the M2840 (Fig. 10, upper right), developed under the DARPA ViSAR program. VISAR is DARPA's acronym for video-frame-rate synthetic aperture radar. This extremely high frequency (EHF) MPM (231.5-235 GHz) was successfully operated in an airborne developmental radar and high-resolution imagery obtained under visually degraded conditions.

For MPM use in missile seekers component packaging is crucial due to constraints on space and mass distribution. A split package configuration is thereby warranted. A custom layout is more likely preferred. Stellant is ideally suited to address the need for package customization owing to the modular design of the MPM electronic power conditioner. All the main EPC subassemblies including EMI/line filter, low voltage inverter, logic, high speed modulator and HV output are configurable. A notional example is shown schematically in Fig. 12 where the components of a W-Band MPM are rearranged to fit in an EO/IR ball. Stellant MPM EPCs have been designed for operation with 28 VDC or 270 VDC bus voltage providing another layer of flexibility for system interfacing.

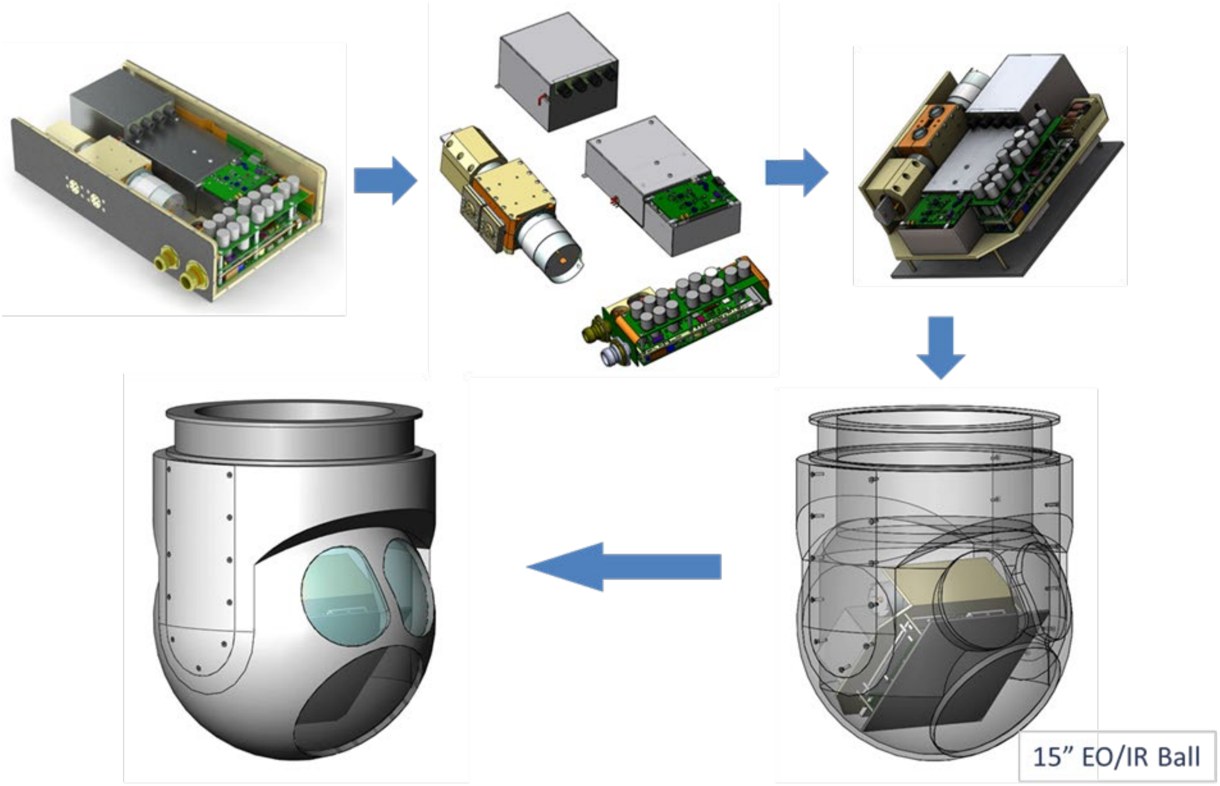


Fig. 12: *Example of flexible MPM packaging.*

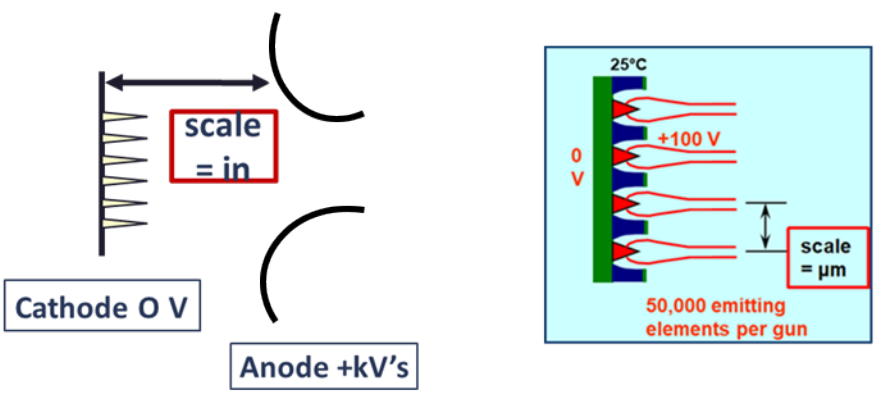
IV. On the horizon

While Stellant’s RF power toolbox is stacked when it comes to providing solutions for missile seeker radars there is much more to come. Research and development at Stellant on revolutionary technologies is lighting the path for breakthroughs in system capability. One advance already mentioned, the development of manufacturable serpentine waveguide TWTs/MPMs is poised to open up the extremely high frequency EM spectrum for exploitation, bringing with it radar system advantages of small antenna size and high resolution.

a. Cold cathode vacuum devices

Another key supporting technology area for advanced vacuum device capability is non-thermionic electron emitters. These include both electrically controlled and optically controlled emission sources. Parochially known as cold cathodes, these electron sources provide essentially “instant-on” operation, with no ancillary heater supply required. Furthermore, in advanced adaptations they can provide the capability to modulate (gate) the electron emission directly at the cathode at microwave frequencies, thereby pointing the way to extremely compact, highly efficient devices.

Field emission cold cathodes, where electron emission occurs through quantum-mechanical tunneling through the material/vacuum barrier due to the imposition of a high electric field at the cathode surface, can be delineated into two general configurations: bulk (macroscopically) gated and individually gated (Fig 13). The macroscopically gated field emitter configuration can be viewed as akin to an aperture grid thermionic cathode electron gun design where the emitting surface experiences the macroscopic field produced by the biased cathode/anode electrodes, as well as that of any intervening gun electrodes. The field in the cathode/anode gap is enhanced at the cathode field emission sites due to sharp geometric factors, reaching the levels required for high field emission. Due to the macroscopic distances between the cathode and intervening gun electrodes a high voltage difference is typically required between the electrodes to reach the field required at the cathode to "gate" emission. This potentially limits the pulse repetition rate to tens of kHz for continuous operation. Burst-mode operation however can be higher.



a.) b.)

Fig. 13. Classes of field emission cathodes. a.) bulk-gated field emitter, b.) individually gated field emitter.

In contrast to a bulk gated cold cathode, an individually gated field emitter cathode has the extraction field controlled at each emission site. It can be thought of as the analog of a shadow grid thermionic gun. But now the control grid is only hundreds of nanometers above the emitters, with each emitter aligned within its own grid opening! Sounding like science fiction individually gated field emitting cathodes do exist, with the leading practitioner being SRI (Menlo Park, CA). Sometime known as field emitter array cathodes, or Spindt cathodes (after one of its inventors, Charles Spindt, SRI), they are made using nanofabrication semiconductor processing technology.

A field emitter array cathode having an area of around a square millimeter can contain up to 50,000 individual molybdenum field emitter cones, each 1-2 um high with a tip radius of 50 nm (Fig.14). The emitters are grown in a patterned dielectric SiO2 substrate, with the metallized top of the substrate serving as the "gate electrode."

As the emitter tip to gate distance is sub-micron, field emission can be achieved at low voltages of a few hundred volts. This low gating voltage means compatibility with high PRF operation. Indeed, through proper geometric design and biasing, emission can be directly modulated at microwave frequencies, with experiments in the literature reporting on operation in X-band. It must be stated, of course, that while the gating voltage may be low, conventional high voltage electron gun electrodes are still required for beam extraction, acceleration and focusing to function in a TWT.

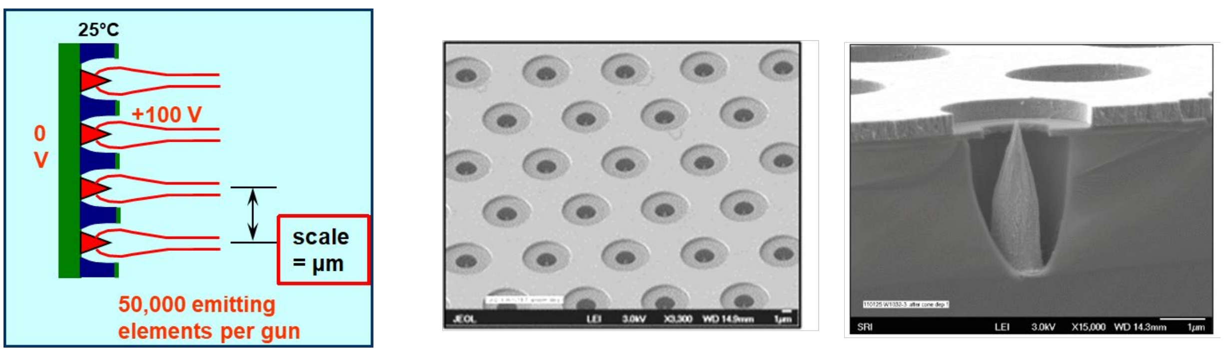


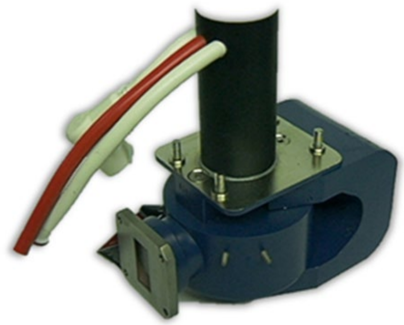
Fig. 14. *Low voltage gated field emitter cathode.*

Stellant (former L3 Electron Devices) is a world leader in the integration of field emission cold cathodes in crossed-field and linear beam vacuum devices.

i. Cold Cathode Magnetron

Annular, knife-edge macroscopic field emitter cathodes have been successfully operated in high power pulsed magnetrons at Stellant (Fig. 15). The advantages of the cold cathode magnetron are substantial. Since no heat source is required, they are instant on devices from the very first high voltage pulse. There is no need for a forced "hot shot" cathode warmup time, which can reduce magnetron lifetime and reliability. Similarly, the absence of heater chain failures of transformers, switches, relays mean greater radar system reliability and extended lifetime. Regarding signal fidelity, the absence of heater current eliminates the stray electromagnetic fields associated with it and the deleterious electron stream modulation and spurious RF signals it generates.

a.)



b.)

Fig. 15. *Cold cathode magnetron. a.) knife-edge field emitter cathode, b.) 65 kW X-band test magnetron. Cathode operated at 0.001 duty for 18,000 hrs.*

Advances at the system level brought about by cold cathode operation include instant changing of radar modes, with repeated changes of duty cycles as much as 100 times or more. The use of a cold cathode magnetron simplifies the system design, bringing with it reduced mass and volume with subsequent cost savings.

As a point of clarification, the descriptor of 'cold cathode magnetron' deserves some expansion as the defining role of the field emission cathode in this device application is to serve as the initial electron source during pulse start-up. The magnetron cathode, as in other recirculating crossed-field devices, is continuously bombarded by electrons from the electron sheath that forms above the cathode surface. This bombardment can result in thermal electron emission from the surface, due to self-heating, as well as secondary emission, depending on the choice of cathode material and the cathode operating parameters.

The baseline specifications for a cold cathode magnetron intended for missile seeker radar use are:

Output Power	35 kW
Duty	0.0006
Pulse Width	0.1 μsec
Frequency	Ku band center +/- 130 MHz dithered frequency
Voltage	14 kV
Current	10 A

ii. Cold Cathode TWT

An example of a linear beam adaptation of an individually gated field emission cathode is the Stellant C-band cold-cathode TWT (Fig. 16a). This helix mini-TWT used a field emitter array cathode manufactured by SRI. The TWT produced an output power of 100 W (pulsed) at 5 GHz. It was operated for over a hundred hours of pulsed operation at progressively increasing duty, running at rated power for over 2 hours. The gate voltage required for emission was under 100 V.

Moving up in frequency, the Stellant X/Ku-band cold-cathode TWT (Fig. 16b) produced over 25 W at 10 GHz, and 10 W at 18 GHz. It also employed an SRI field emitter cathode. Both the C-band and X/Ku-band results are world records for performance of cold cathode TWTs.

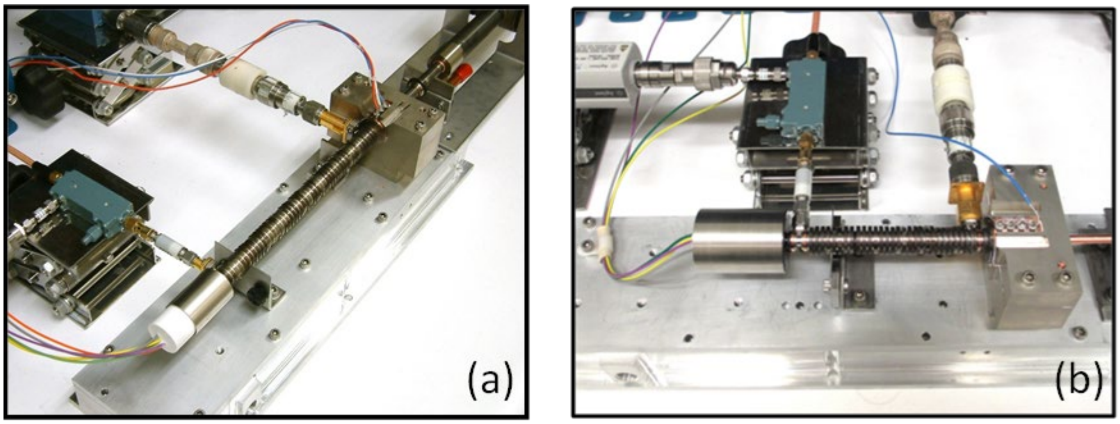


Fig. 16. *Photographs of operating C-band and X/Ku-band cold cathode TWTs.*

In summary, while work is required to improve cathode operating life in a vacuum tube environment, including measures to mitigate tip blunting from back ion bombardment, cold cathode vacuum devices employing field emission cathodes, macroscopic or individually gated, are considered suitable for the short mission durations representative of missile seeker use. Processing techniques and design modifications exist to ensure long storage life.

V. Closing

It is hoped that this survey on vacuum electronics solutions for missile seeker radar is beneficial to system designers. Stellant Systems is committed to this important application and looks forward to engaging with customers and interested parties alike with questions or seeking additional information.