

Microwave Power Modules

Miniature Microwave Amplifiers for UAVs

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Abstract

While UAVs have proved to be invaluable over the past decade in monitoring and observing situations in dangerous locations, their potential capabilities are just now being recognized. New UAVs will have expanded roles. In many cases, power microwave systems will be required to fulfill these roles. In order for such systems to be practical for UAVs, size, weight, and cost need to be significantly reduced. Since power microwave transmitters contribute significantly to these critical parameters, transmitter improvements are vital.

Over the last several years, miniature transmitters have been developed for UAV communication systems, as the need to transmit real-time video is primary for UAVs. The transmitters for the Predator and Global Hawk UAVs use Microwave Power Modules (MPMs) for satellite and line-of-site communication links. MPMs are miniature microwave amplifiers, recently developed devices that offer significant advantages over traditional high power amplifiers. MPMs are available from manufacturers in Europe, the USA, and Japan.

MPMs take advantage of the best features of both solid state and traveling wave tube (TWT) technology. A solid state driver within the MPM provides low noise drive power drive to a TWT, which provides high output power with high electrical efficiency. The two components combine to form a low noise, high gain, high power, and high efficiency microwave chain. By integrating them into a single package with a multiple-output power supply that powers and controls the solid state driver and TWT, the MPM offers the following performance advantages relative to typical high power amplifiers:

- 5:1 reduction in size
- 5:1 reduction in weight
- 100:1 reduction in noise
- 50% improvement in efficiency

MPMs not only allow for use of a small antenna and reduce the volume required by the power amplifier, the high efficiency of the MPM results in a smaller prime power source and cooling system.

The desire to incorporate SAR/MTI capability onto existing and future UAVs creates a need for a miniature microwave power amplifier, and again system developers are turning to the MPM. Both new SAR/MTI systems and upgrades to existing systems are employing MPMs to reduce the system size, weight, and cost. In response to the need for higher peak power levels required by radars, pulse MPMs are being developed to augment the line of CW communication MPMs available today.

Communication MPMs typically provide 50 to 100 watts of output power over the C, X, and Ku frequency bands in a single amplifier, and therefore can be used for single and multiband applications. These MPMs are less than 770 cc in volume and 1.75 kg of mass. X band radar MPMs are being developed with a tenfold increase in peak output power, with little increase in prime power or cooling requirements. These MPMs will allow the SAR/MTI systems to use antennas small enough for a wide range of UAVs. Moreover, with MPMs available in millimeter wave bands, radars with extremely high resolution are possible.

EW protection systems for UAVs have been under discussion but to date have not been significantly



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deployed. The primary use has been self-protection for higher-cost vehicles, such as the Global Hawk. Standoff jamming has also been contemplated. In either case, the driving factors are the same: size, weight, and cost. Sensor payloads are considered more important for UAVs than EW protection, but with the miniaturized radars being developed, use of miniature EW protection systems becomes practical. The wide bandwidth, high output power, and small size and weight of the MPM make it the ideal choice as the output amplifier for such applications.

Clearly, over the next several years there will be great advancement in the capabilities of UAVs. Many of these advancements will be achieved with the use of new SAR/MTI systems, improved communication systems, and new EW systems. The MPM enables the realization of these miniature microwave and millimeter wave systems suitable for UAVs.

Introduction

UAVs have been used with great success for a variety of missions and in a variety of environments. From information-gathering in Kosovo, to targeting in Afghanistan, to peace-monitoring in the Solomon Islands, there are numerous examples of UAVs performing missions that would otherwise put lives at risk or would be much more difficult and/or expensive with piloted aircraft. This level of success, often with missions not commonly envisioned for UAVs, has led to a multitude of new UAV developments.

These developments include UAVs designed for application-specific and/or environmental-specific requirements. The system requirements for these

UAVs are generally more demanding than that of previous UAVs, particularly with size and weight but not necessarily with technical performance.

In addition to more demanding system requirements, there are also requirements for different types of systems. Existing UAVs are primarily dedicated to information, surveillance, and reconnaissance (ISR) missions and are therefore configured with video, IR thermal imaging, and communication links. New UAVs may include these capabilities plus SAR/MTI, ESM, EW, weapons, and other systems.

The systems presently installed on UAVs are typically derivatives of avionics systems. While they have generally performed admirably and have been responsible for many of the successes achieved by UAVs, they were not specifically designed for UAVs and therefore compromises were inevitable. However, the system requirements for new UAVs and the forecast for increased quantities of UAVs has created a climate where both the need and the potential business level justifies development of systems specifically designed for UAVs.

New UAV System Requirements

Many new UAV systems, including communication links, radar systems, and EW systems, require high power microwaves. Communication links to satellites, and in some cases line-of-sight links, require high power microwave transmission in order to transmit high data rate signals, such as real time video and radar data, with an acceptable signal to noise ratio. Radar systems require high power microwave transmission in order to obtain high quality radar images at medium range and under all



weather conditions. EW systems require high power microwave transmission in order to effectively jam or deceive enemy radar signals.

Communication links are standard on almost all larger UAVs. These include satellite and line-of-sight communication links. The satellite links are generally in Ku band, with the line-of-sight links primarily in L and C band at low power levels, and X band at higher power for longer distances. [1] In the future, millimeter wave satellite communication links are anticipated, including secure transmission links to military satellites. As more sensor payloads are installed on UAVs, there will be a need for higher data rates and for transmission of multiple signals. Higher power communication links, in both Ku and Ka band, will be required for these applications.

A few UAVs, such as the Predator, now carry radars. There is considerable development activity with SAR/MTI systems for UAVs, and it seems clear that these systems will become standard payloads for medium and high altitude, long endurance (MALE/HALE) vehicles. The typical frequency for such systems is X band, with Ka band requirements expected in the future for very high-resolution images.

EW systems are generally not installed on existing UAVs. The size, weight, and power required for such systems is valuable and instead used for sensor payloads. It is possible that some UAVs will employ passive EW systems. For the larger and higher cost UAVs, such as the Global Hawk, active EW systems are anticipated.

Microwave Power Amplifiers for UAVs

A primary factor in the size, weight, and cost of a power microwave system is the transmitter. Transmitters include a high power microwave amplifier, a regulated power source for the amplifier including the control electronics, and the associated cooling. The transmitter and antenna subsystems can account for most of the weight and power consumption of a power microwave system. The power consumption affects the system size and weight directly and indirectly. The size and weight of the transmitter cooling depends on the power consumption, efficiency, and environmental factors. The power consumption also affects the size and weight of the UAV prime power source.

As Figure 1 depicts, there is a tradeoff between the output power of the amplifier and the size of the antenna. The transmitter output power and the antenna gain determine the effective radiated power (ERP). For a given amount of ERP, system designers must determine the optimum configuration that meets the system requirements, including size and weight. With some limitations, the antenna size can be reduced by increasing the transmitter output power.

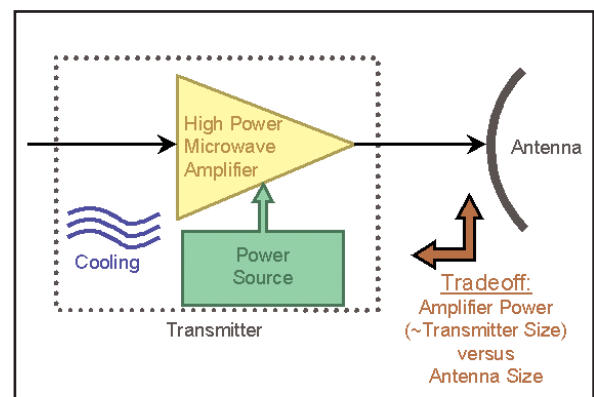


Figure 1 – Tradeoff of Amplifier Power/Size versus Antenna Size



For UAVs, size and weight are paramount. Therefore, it is desirable to have a very small and lightweight transmitter containing a microwave amplifier with relatively high output power, allowing the antenna size and weight to be reasonable for a given ERP level. It is also important for the amplifier to have high efficiency in order to keep the UAV prime power source, the regulated power source for the amplifier, and the transmitter cooling as small and light as possible. These requirements apply to all power microwave amplifiers used on UAVs; in addition, there are many of application-specific requirements that may apply for individual applications, such as pulsed power, low noise, low signal distortion, etc. The primary requirements for power microwave amplifiers used for UAVs are summarized below:

- High Power
- Availability in a Variety of Frequency Bands
- High Efficiency
- Small Size
- Other Application-Specific Requirements

Microwave Power Modules (MPMs)

Microwave power modules provide the solution for the UAV system designer: a small, lightweight, and highly efficient power microwave amplifier. These unique devices combine the advantages of both solid state and vacuum electronics technology in a single unit. [2] MPMs meet the general requirements for UAV microwave amplifiers identified above:

- High power
 - Now: 20 to 170 watts CW (depending on band)
 - Future: Up to 250 watts CW, 2kW pulsed
- Multiple frequency bands
 - Narrow Band: S, C, X, Ku, Ka Q

- Wide band: 2-8, 4.5-18, 6-18, 18-40, 40-46 GHz
- 25 - 30% typical, up to 50%
- Small size and lightweight
 - 100 watts in 770 cc. (47 in³), 1.75 kg. (3.85 lbs)

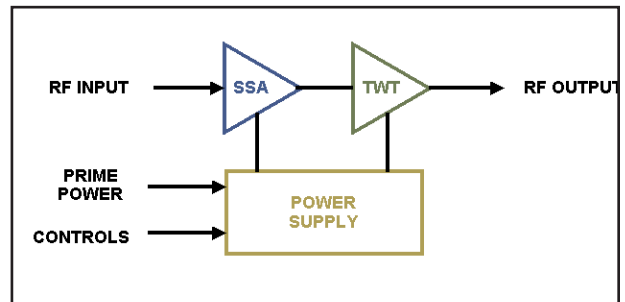


Figure 2 . MPM Block Diagram

MPM Description

MPMs are microwave amplifiers that include a helix miniature traveling wave tube (mini-TWT), a solid state driver amplifier (SSA), and a high-density power supply. All three components are housed in a small, compact, lightweight package. Figure 2 is a block diagram of a MPM.

The mini-TWT provides the high power RF output, with the gain split equally between the TWT and SSA. The SSA receives the RF input and amplifies it to provide sufficient RF drive to saturate the TWT. The power supply accepts the input voltage,

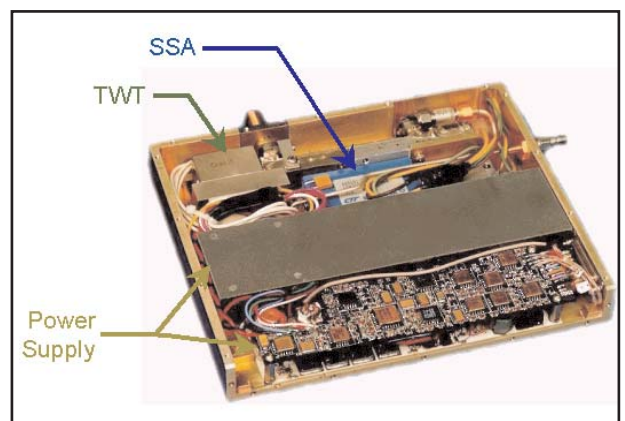


Figure 3 – MPM Internal View



generates the required voltages to the SSA and TWT, and provides module protection and controls. Figure 3 is a photograph of the internal view of a typical MPM.

SSA Description

As mentioned above, the SSA amplifies the MPM RF input power to a level sufficient to saturate the TWT. Generally, the SSAs used in MPMs are standard devices available from a number of manufacturers. Sometimes temperature compensation is added to maintain constant MPM gain over temperature. For wideband MPMs, an equalizer is sometimes used for gain compensation as a function of frequency, thereby allowing constant RF input drive to be used over the frequency band. Equalizers can be internal or external to the SSA.

For communications applications, multiple signal transmission is often required. The intermodulation (IM) products generated by amplifiers with multiple

input signals and the generation of nonlinear distortion have been extensively documented. [3, 4] In order to maintain an acceptable signal to noise (S/N) ratio, amplifiers must usually be operated below saturation, quantified by the output power back off (OPBO). However, this reduction in output power often results in an unacceptable link margin. To compensate for this, higher power amplifiers can be used, but this requires extra size, weight, and prime power and is therefore undesirable for UAV applications. Another solution is the use of a linearizer. Linearizers compensate for the nonlinear characteristics of amplifiers operated near saturation, and allow operation at higher power levels with acceptable S/N ratios. Using a linearizer with a MPM has been shown to result in up to four dB more output power at the typical signal quality required by most satellite operators. [5] Linearizers can be incorporated internal to MPMs, either as part of the SSA module or separately, or can be mounted externally.

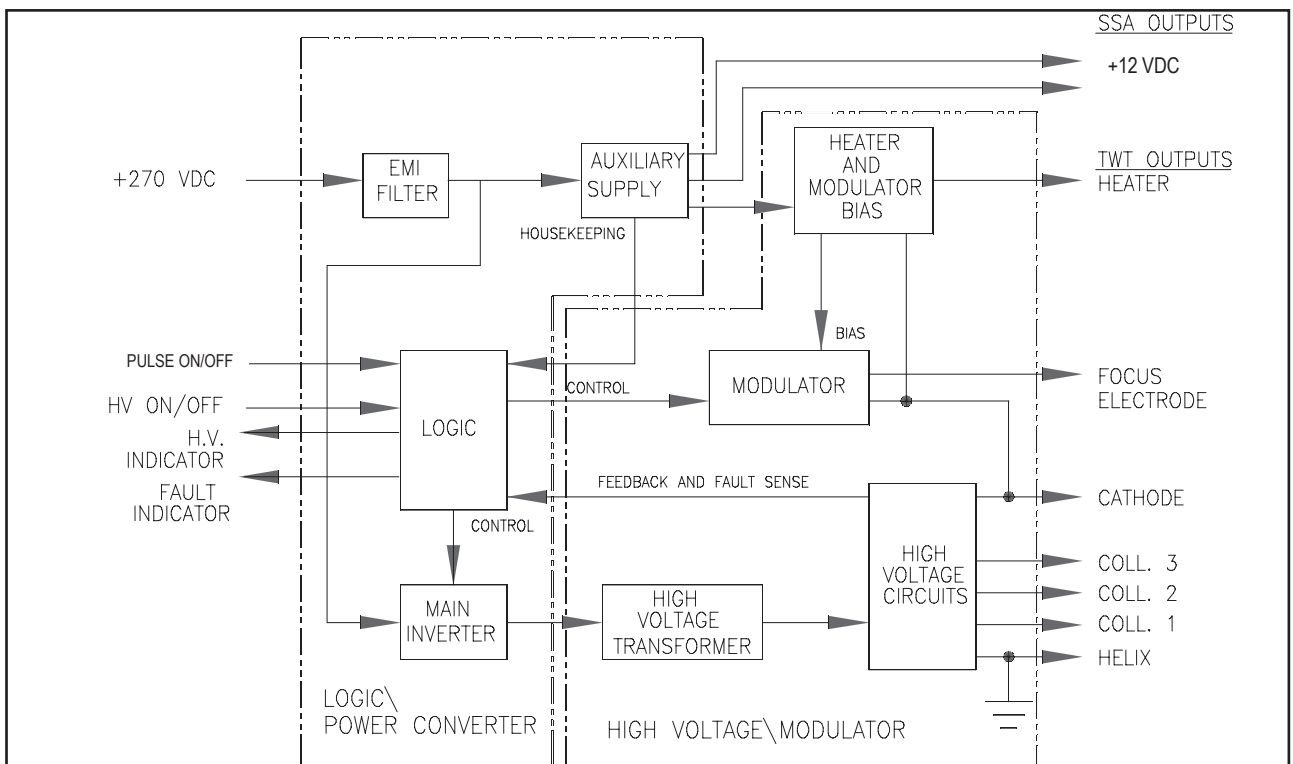


Figure 4 – Power Supply



Power Supply Description

A block diagram of a typical power supply is shown in Figure 4. The prime power input is shown on the left, as are the control and monitor signals. The outputs for the SSA and the TWT are shown on the right.

There are various prime power options for MPMs. Military MPMs generally operate from 270 VDC, 28

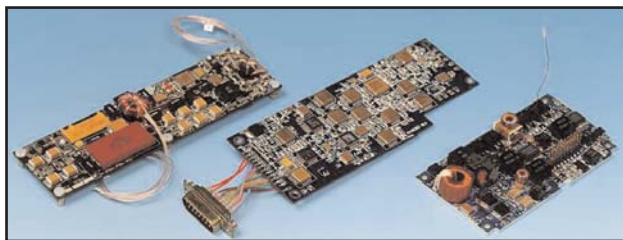


Figure 5 – Power Supply Circuit Boards

VDC, or 115 VAC 3-phase, 400 Hz prime power sources. Extensive use of surface-mount power electronic components, novel planar transformers, high frequency switching, and innovative circuit and packaging techniques have resulted in MPM power supplies that are approximately one-tenth the size and weight of previous generation power supplies. A photograph of MPM power supply circuit boards is shown in Figure 5.



Figure 6 – Photo of a TWT used in MPMs

TWT Description

TWTs are vacuum electronic devices that transfer kinetic energy from an electron beam to a RF signal, thereby providing amplification. [6] They are manufactured using high-temperature precision-brazed metal and ceramic parts. TWTs provide high microwave and millimeter wave output power at

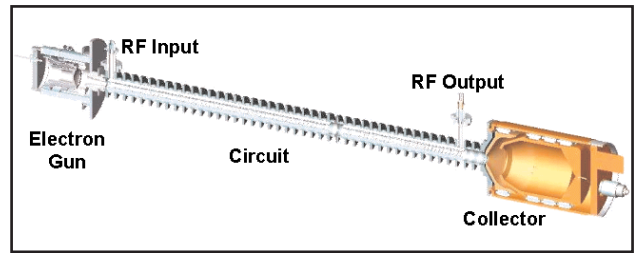


Figure 7 – Cross-Section View of a TWT

levels unattainable with solid state technology. The vast majority of high power microwave and millimeter wave systems in military use throughout the world use vacuum electron devices for the final amplifier stage, and many of these devices are TWTs. A photo of a TWT used in MPMs is shown in Figure 6. TWTs contains an electron gun, RF circuit slow-wave structure, and a multi-stage collector, as shown in the Figure 7.

The electron gun consists of a cathode, cathode heater, focus electrode, and anode. The cathode is the source of the electron beam. The heater warms the cathode to a temperature sufficient to liberate electrons. The anode, at positive potential with respect to the cathode, attracts electrons from the cathode and they gain kinetic energy as they travel towards the anode. The focus electrode compresses the beam, reducing the beam diameter so it can pass through the opening in the anode and into the circuit. The current available from any given cathode is limited; hence, beam compression represents a means of increasing the current density of the beam within the circuit.

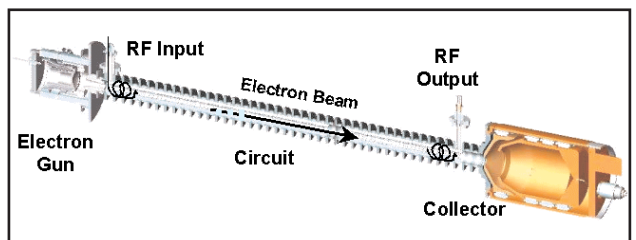


Figure 8 – TWT Electron Beam and RF Signal



Magnets about the circuit keep the electron beam focused as it travels from the electron gun to the collector. The input RF signal is introduced into the circuit at the RF input port and travels in a helical pattern towards the RF output as shown in Figure 8. This helical pattern gives name to the helix TWT, and slows the wave to allow for interaction between the electron beam and the RF signal spiraling about it. The electron beam interacts with fields along the circuit and kinetic energy from the beam is transferred to RF circuit power. This power is extracted from the circuit at the output port.

After RF power is extracted from the electron beam, much of the remaining beam energy is recovered in a multi-stage depressed collector. The residual energy is dissipated as heat. Multi-stage, or multi-potential, collectors greatly increase overall efficiency and are standard for MPM TWTs.

MPM Evolution

The MPM concept surfaced at the 1988 US DoD Special Technology Area Review of microwave tubes. [7] A MPM panel, supported by the Naval Research Laboratory, was formed in 1989. This panel brought together government and industry experts in systems and components, and developed performance goals based upon the requirements of new and future systems. Specification goals were developed for both EW and radar applications, with the EW requirements generally more difficult. [8, 9, 10] These goals are listed below in Table 1.

Phase 1 of the development effort was funded by the Tri-Service Vacuum Electronics Program established by the Naval Research Laboratory and the Vacuum Electronics Initiative established by the Defense

Parameter	Goal
Frequency (GHz)	6 to 18
RF Output Power (Watts)	50 to 100
Gain (dB)	50
Duty Cycle	0% to C
Efficiency	33%
Noise Power Density (dBm/Mhz)	-45
Noise Figure (dB)	10
Volume (cubic in./ cc)	7.5 / 123
Thickness (in. / cm)	0.31 / 0.79

Table 1

Advanced Research Projects Agency (DARPA). [11] Five industry teams participated in this development, initiated in 1991:

- Hughes EDD (now Boeing EDD)
- Lockheed Sanders/Teledyne Electronic Systems (now BAE Systems North America/Teledyne MEC/Teledyne Wireless)
- Northrop (now Northrop Grumman)
- Raytheon (power tube group now part of L-3 Communications EDD)
- Westinghouse/Varian (now Northrop Grumman/CPI)

These teams individually developed their version of the MPM, with each team taking a unique approach to satisfying the performance requirements. Various levels of specification compliance were achieved in 1992 and 1993. Northrop came very close to meeting all of the requirements of Table 1 [11], but each team demonstrated significant advancements against the existing state of the art.

This initial success was followed by refinements to the MPM subassemblies, and then a demonstration of a linear subarray of MPMs in 1994 [11]. Through the Tri-Service Vacuum Electronics Program, other DoD programs, and investment by MPM manufacturers, the MPM concept was expanded to other frequency ranges and power levels. This includes development efforts towards the following:



- 2 – 8 GHz MPMs
- High Efficiency C Band MPMs [12]
- 6 – 18 GHz MPMs (original MPM development)
- 4.5 – 18 GHz MPMs
- 2 – 18 GHz MPMs
- 18 – 40 GHz MMPMs (Millimeter wave Power Modules)
- 40 – 46 GHz MMPMs

MPMs have received three separate Top 100 Awards from R&D Magazine, awarded annually to the 100 most technologically significant new products and process of the year. Northrop Grumman's 6 – 18 GHz MPM received the award in 1994, their C Band MPM in 1997, and their 2 – 18 GHz MPM in 1998. [11]

MPMs are now available as standard devices. Although primarily used in military applications, a few companies have developed a line of MPMs for commercial use, primarily satellite communication applications. [13] Several companies have

developed MPMs, including L-3 Communications, Triton, Northrop, and CPI in the USA, Thales in France, and NEC in Japan.

MPM Capabilities and Advantages

The frequency and power capabilities of MPMs are shown below in Figure 9. This figure also shows the frequency/power range where solid-state devices are generally used, and the same for vacuum devices. MPMs fill much of the gap where neither technology is clearly superior.

MPMs are available in a variety of frequency bands and output power levels. The graphs shown in Figures 10 – 12 depict the output power and frequency range of L-3 Communications Electron Devices Division's low band, high band, and millimeter wave band MPMs. [14]

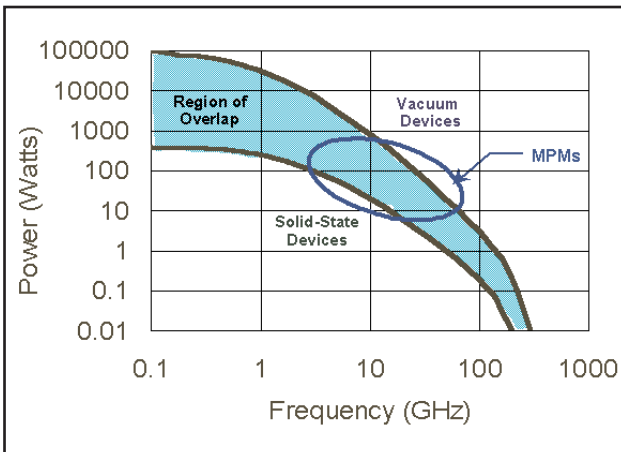


Figure 9 – MPM Output Power versus Frequency

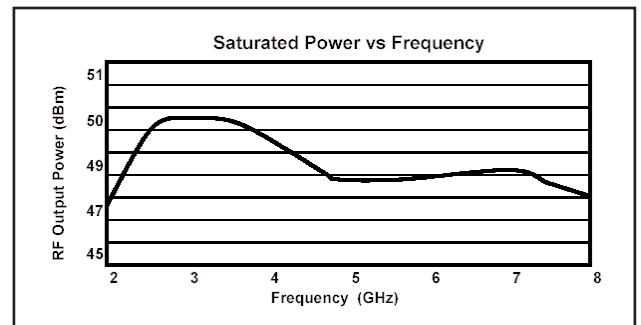


Figure 10 – L-3's Low Band MPM Power Output versus Frequency

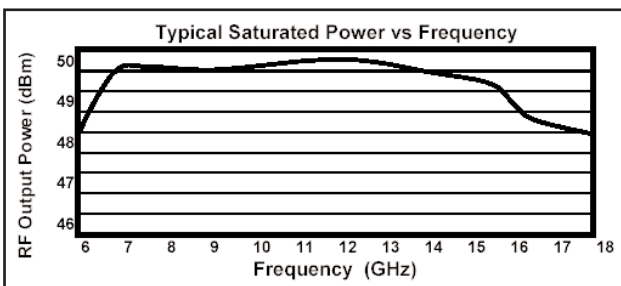


Figure 11 - L-3's High Band MPM Power Output versus Frequency

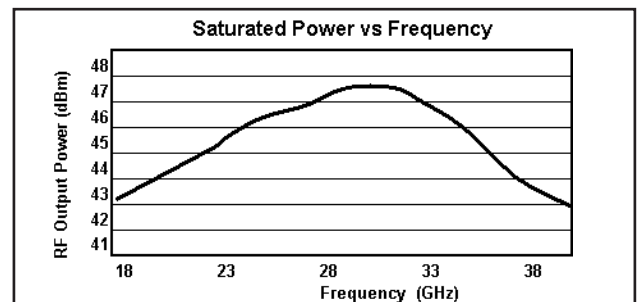


Figure 12 - L-3's High Band MPM Power Output versus Frequency



Figure 13 – Pictures of Various MPMs

Figure 13 displays several different MPMs. The MPM in the upper left is a wideband 18 – 40 GHz unit. The MPM on the upper right is a narrow band unit with integral air-cooling. In the lower right is a wideband 6 – 18 GHz MPM. The picture in the lower left is of an MPM subsystem covering 2 – 18 GHz, with two MPMs (one 2 – 7 GHz, the other 7 – 18 GHz) mounted back-to-back on a finned heatsink, with an external EMI filter.

There are several advantages of MPMs compared to traditional amplifiers employing only solid state or vacuum electronics. The primary advantages for UAV applications are size, weight, and efficiency. These advantages are not incremental in comparison to traditional amplifiers; they are revolutionary. In addition to the size, weight, and efficiency advantages, the MPM also has low noise and is typically lower in cost than traditional amplifiers. Figure 14 illustrates the advantages of MPMs relative to traveling wave tube amplifiers (TWTAs) and SSPAs, using a 100 watt Ku band amplifier as an example.

The size advantage of the MPM is shown pictorially in Figure 15 with a traditional TWTA shown on the left

Typical MPM Advantages compared to Traditional TWTAs and SSPAs (100 watt Ku band example)		
	<u>MPMs vs. TWTAs</u>	<u>MPMs vs. SSPAs</u>
Size*	5:1 reduction	8:1 reduction
Weight*	5:1 reduction	8:1 reduction
Noise	100:1 reduction	~2 dB degradation
Efficiency	50% improvement	3:1 improvement

*Includes Power Supply and Cooling

Figure 14 – MPM Advantages versus TWTAs and SSPAs and a comparable MPM shown on the right. The MPM size advantage to a comparable SSPA is even greater.

MPMs in UAVs

MPMs are presently being used in UAVs with great success. Both the Predator and Global Hawk UAVs contain satellite communication links employing MPMs manufactured by L-3 Communications. In addition, the SAR radar on the Predator uses MPMs.



Figure 15 – The MPM Size Advantage



MPMs have proven to be enabling technology for UAVs. The 1997 Annual United States Defense Report notes the following:

“Because of the UAV size, weight, and power constraints, installing both a surveillance radar and a satellite communications link in the Predator would not have been feasible without advanced Microwave Power Module technology developed by the Navy. This technology provides a factor of 30 increase in power density and a factor of 10 reduction in volume. Because it operates over a broad frequency range, it offers new opportunities for integrating communications, radar, and electronic combat systems.”

MPMs for UAV SAR/MTI Systems

Perhaps the most active area of development for UAV payloads is with miniature SAR/MTI systems. Numerous manufacturers are developing such systems. Amplifiers for radar applications differ from those for communication applications in several ways; most prominent is the need for higher peak pulsed power. Although existing MPMs can be pulsed, their peak output power is limited to approximately 250 watts. Modern SAR/MTI systems operating from medium and high altitudes require higher peak power in order to obtain acceptable image clarity with an antenna of reasonable size.

In response to this need, pulsed MPMs are being developed. This represents a significant engineering challenge, requiring a new TWT and a new power supply. The TWT will operate in X band. The power supply will have low phase noise, droop, and ripple, all extremely important characteristics for SAR/MTI

systems. These pulsed MPMs will enable a new class of miniature airborne radars.

MPMs for UAV EW Systems

Eventually, EW systems will likely be installed on some UAVs. EW systems can be pulsed or CW, and often have both capabilities. MPMs are presently used in some new miniature CW airborne EW systems, and these systems can be adapted for UAV use with little compromise.

For pulsed EW applications, the only high power options presently available are systems based on traditional TWTAs. These systems are large and heavy, impractical for UAVs. However, the pulsed radar MPM design approach could be adapted for pulsed EW applications. The X band pulsed TWT would have to be converted to a 6 – 18 GHz TWT, but the power supply remains essentially the same. Such a pulsed MPM would enable a new class of miniature airborne EW systems.

Summary

The success of UAVs has resulted in a multitude of new UAV developments. Most of these new UAVs require systems that are smaller and lighter than traditional avionics systems, and many require new types of payloads. Many of these payloads are microwave systems, and this results in the need for microwave amplifiers in a variety of frequency bands with high power, high efficiency, and very small size.

The MPM, a unique component that combines the advantages of solid state and vacuum electronics, provides an amplifier solution for the designer of microwave systems for UAVs. MPMs contain a SSA, a TWT, and a power supply in a single miniature



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package. MPMs are available in a variety of bands, from 2 to 46 GHz, from several manufacturers. MPMs are much smaller than traditional amplifiers, enabling the development of systems with size and weight limits previously unattainable.

MPMs are presently used successfully in UAV communication links, and on at least one UAV radar system. In the future, higher power and higher frequency MPMs are anticipated for use in new UAV communication links. Pulsed MPMs are being developed for new UAV radar systems to be used on the next generation of UAVs. EW requirements for UAVs are in the discussion stage, and use of both CW and pulsed MPMs will be critical for such systems. MPMs clearly represent enabling technology for these new classes of microwave systems.

Acknowledgements

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References

- [1] Shephard, "Unmanned Vehicles Handbook 2003", The Shephard Press; Burnham, UK; 2003
- [2] Robert K. Parker and Richard H. Abrams, "The Navy's Role in the Vacuum Tube Electronics Program", Microwave Journal, March 1992
- [3] L. Sivan, "Microwave Tube Transmitters", Chapman and Hall, London, 1994
- [4] A. Bruce Carlton, "Communication Systems", McGraw-Hill, 1975
- [5] Dr. Alan Katz and Robert Gray, "The Linearized Microwave Power Module", 2003 IEEE MTT-S International Microwave Symposium Digest
- [6] A.S. Gilmour, Jr., "Principles of Traveling Wave Tubes", Artech House, Boston, 1994
- [7] R.H. Abrams, Jr. and R.K. Parker, "Introduction to the MPM: What it is and Where it Might Fit", 1993 IEEE MTT-S International Microwave Symposium Digest
- [8] J.A. Christensen and et al, "MPM Technology Developments: An Industry Perspective", 1993 IEEE MTT-S International Microwave Symposium Digest
- [9] Lynwood Cosby, "MPM Applications: A Forecast of Near and Long Term Applications", 1993 IEEE MTT-S International Microwave Symposium Digest
- [10] A. Brees and et al, "Miniaturized Microwave and Millimeter-Wave Transmitters", Journal of Electronic Defense, June 1993
- [11] Carl R. Smith, Carter M. Armstrong, and Joseph Duthie, "The Microwave Power Module: A Versatile RF Building Block for High-Power Transmitters", Proceedings of the IEEE, Vol. 87, No. 5, May 1999
- [12] D.R. Whaley, C. M. Armstrong, and et al, "Sixty-Percent-Efficient Miniature C-Band Vacuum Power Booster for the Microwave Power Module", IEEE Transactions on Plasma Science, Vol. 26, No. 3, June 1998
- [13] Tom Ninnis and Philip Ballagh, "Development of the Microwave Power Module (MPM) and it's Potential for Use in Wireless Applications", Wireless Conference, September 1995, New York
- [14] L-3 Communications Corporation Electron Devices Division Web Site, see http://www-edd.tw.l-3com.com/edd/html/products_microwave_power.htm
- [15] Robert K. Parker, Richard H. Abrams, Jr., Bruce G. Danly, and Baruch Levush, "Vacuum Electronics", IEEE Transactions on Microwave Theory and Techniques, Vol. 50, No. 3, March 2002
- [16] Mark Basten and et al, "High Performance Microwave Power Modules for Military and Commercial Systems", 1992 IEEE MTT-S International Microwave Symposium Digest
- [17] Richard H. Abrams, Jr., "The Microwave Power Module: A 'Supercomponent' for Radar Transmitters", Proceedings of 1994 IEEE National Radar Conference
- [18] A. Brees and et al, "Microwave Power Module (MPM) Development and Results", 1993 IEEE International Electron Devices Meeting
- [19] EE. Foreman and M.C. Smith, "A Comparison of High Power Solid State GaAs FETs versus Microwave Power Modules from a User's Perspective: The Cooperative Engagement Capability Program", 1999 IEEE MTT-S International Microwave Symposium Digest