High Performance Microwave Power Modules for Military and Commercial Systems

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Abstract — **The desirable attributes of solid state and vacuum electronics have been combined in Microwave Power Module (MPM) technology to create miniaturized amplifiers for high power transmitter applications in the 2-40 GHz range. These modules have demonstrated an order of magnitude increase in RF output power per unit weight when compared to conventional traveling wave tube amplifiers (TWTAs) and solid state power amplifiers (SSPAs). In this paper, the recent performance improvements of MPMs developed by Northrop Grumman will be described. These improvements include power booster efficiencies that have reached in excess of 60%, and bandwidths that have reached almost three octaves.**

I. INTRODUCTION

High power microwave transmitters are key elements in a wide variety of military and commercial systems. The development of the Microwave Power Module (MPM) is the result of the need for an efficient compact lightweight microwave power amplifier which possesses both high power, high gain, and low noise characteristics. Northrop Grumman Corporation (NGC) has developed MPMs [1] that provide microwave power at various power levels, frequencies, and bandwidths for a variety of applications including radar, electronic countermeasure (ECM), and airborne or ground-based communications. High power radar applications include synthetic aperture radar for remote sensing, long-range surveillance, and tracking. There is also interest in using an array of active elements such as MPMs to replace a single high power RF source that requires subsequent power splitting and phase shifting. The combined power of such an array could exceed megawatt power levels.

The MPM combines an integrated power conditioner (IPC), solid state amplifier (SSA), and a vacuum power booster traveling wave tube (TWT) within a single module resulting in a small, lightweight device for efficient DC-to-RF energy conversion. This unique combination of both solid state and vacuum electronic technologies results in significant reduction in size and weight over conventional amplifiers as well as increasing overall efficiency, decreasing thermal dissipation and prime power requirements, and reducing noise. NGC has developed a family of MPMs operating from 2-40 GHz based on common circuits, materials and processes, leading to a low risk, low cycle time, cost effective transmitter solution. World-class performance has been demonstrated by NGC narrowband and broadband MPMs, which all share a common architecture. Design flexibility has been established such that the Ultra-Band MPM operating from 4.5-18 GHz for ECM applications was easily modified for a narrow X-Band SATCOM communication application with minimal impact on manufacturing flow or cost. The same level of design flexibility is possible for the broadband MPM operating from 2 to 6 GHz and narrower band communication and radar band variants. MPMs can be used individually for low to moderate output power (i.e., 100 to 300 watts) requirements or they can be power combined (i.e., through the use of power combiners or optical power combining techniques) for significantly higher power.

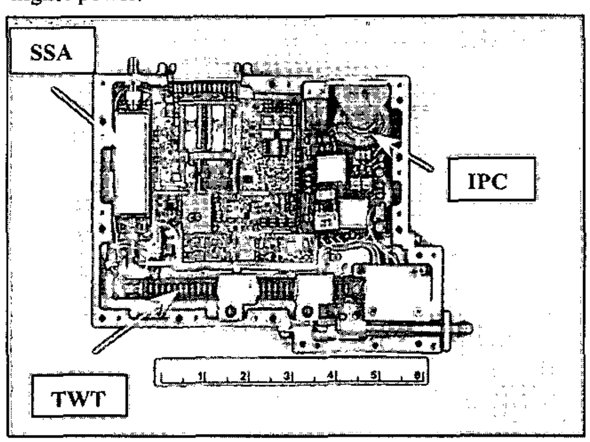

Figure 1 – C-Band MPM

A photograph of an early version of a C-Band MPM is shown in Fig. 1. The RF chain for all MPMs starts at the RF input followed by the SSA which provides typically 25-35 dB gain. The SSA incorporates MMIC technology

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and includes internal temperature compensation in addition to other features (i.e., phase shifter, digital attenuators, built-in-test) upon request. The SSA output feeds the TWT, which amplifies the power by 20-35 dB at saturation. TWT fabrication uses high temperature precision brazed metal and ceramic parts. The Pierce electron gun uses a focus electrode designed to provide beam cutoff at approximately 1-1.3 kV. MPM TWTs employ moderate 0.5-1.0 μP perveance to produce a 130-250 mA beam at 4.0-5.0 kV using an M-type dispenser cathode with a current density of about 1 A/cm^2. All Northrop Grumman MPM TWTs utilize four stage graphite depressed collectors for high total efficiency under saturated conditions and low thermal dissipation under low drive conditions. The power for both the TWT and SSA is provided by the IPC powered by a 270 VDC input voltage. The IPC conversion efficiency is in excess of 90%. The measured noise figure of most MPMs is < 10 dB and the TWT beam-gated-off noise is typically <-170 dBm/Hz. The total DC-to-RF conversion efficiency of the C-Band MPM is in excess of 50%, with the TWT efficiency exceeding 60%.

As a result of the small size and weight of the MPM, the system designer can now envision new transmitter concepts previously not realizable. Physically small transmitters can be located directly behind the radiating aperture, eliminating RF losses due to cabling. This reduces the RF output requirements of the transmitter, which in turn, reduces the prime power and cooling required from the system. At NGC, MPMs have been used in a multitude of transmitter applications ranging from single MPMs driving a single aperture to multiple MPMs being power combined. For example, a transmitter has been built that combines the power of four Ultra-Band MPMs to provide RF output powers between 300 to 600 watts across the 6 to 18 GHz operating frequency band (bandwidth limited by the power combiner and not the MPMs). The compact size of an MPM also makes possible a towed decoy configuration for ECM applications. This off-board ECM approach provides natural angle of deception to target tracking radars and missile seekers which translates into increased miss distance and probability of survival for the host platform. Towed decoys have proven to be extremely effective in defeating radar guided munitions as well as overcome several shortcomings of present on-board ECM systems. Using a fiber optic link between the platform and the decoy increases overall signal processing capability and enables the use of aircraft receiver and technique generator jamming techniques.

In order to achieve enhanced effective radiated power on platforms with limited space, prime power, and cooling, the need to focus radiated energy has long been recognized. Since there are practical limits to the amount of power that can be generated in a limited volume, not to mention applied to a single focusing element, arrays of elements are used to focus radiated RF energy. The key conflicting requirements for ECM RF arrays are effective radiated power (ERP) versus beamwidth. As radiating elements are added to increase ERP, the resulting increase in aperture size reduces the beamwidth. As beamwidth decreases, beam steering to keep maximum ERP on the one or more threats becomes complicated, resulting in higher system costs. Ideally, the solutions to these varying system requirements should have common hardware components, optimized to address the broadest possible range of applications, while at the same time keeping unit cost low. For microwave power amplifiers, this implies maximum power over the broadest possible frequency range, while maintaining small size and high efficiency. Maximizing module power means that even small arrays can provide ERP one to two orders of magnitude higher than a conventional TWT coupled to a single antenna. Maximizing frequency coverage allows the same amplifier to be used for multiple missions across multiple platforms. Economies of scale can be realized through commonality of assemblies across multiple customers and applications. Small size and high efficiency are absolutely necessary to be compatible with volume, weight, prime power, and cooling limitations of small and medium-sized platforms.

II. Wideband Operation

The inherent nature of ECM requires that transmitters be able to address new and existing threats over very wide operating frequency bandwidths. As a result of this requirement, increasing the MPM bandwidth has been an important goal for the NG's MPM product line. NGC is actively developing a 2-18 GHz, 125W Ultra-Wide-Band (UWB) MPM for applications that require multi-band frequency coverage. The basic design approach of the UWB-MPM employs a stand-alone 3-18 GHz miniaturized vacuum power booster TWT. Harmonic injection and signal conditioner circuitry are integrated within the MPM architecture in order to meet the full performance objective of 125 W of fundamental power over 3^+ octaves of bandwidth.

The TWT development effort builds on the proven success of the Northrop Grumman 4.5-18 GHz, 125 W CW Ultra-Band MPM TWT. Table 1 shows the goal specifications for the UWB TWT. The vacuum envelope is approximately 8.5 inches in length and 0.75 by 0.5 inches in cross-section, representing a growth of 1.0 inch in length over the existing Ultra-Band TWT. Figure 2 shows a photograph of the prototype Ultra-Wide Band TWT in a high-duty package. Low-end bandwidth extension is realized through internal harmonic suppression using the dispersion of the TWT. Beam intercept is controlled over the extended bandwidth range through optimization of beam laminarity and magnetic confinement. Stability to BWO and other oscillation scenarios is achieved through adequate gain partitioning between the SSA and TWT, between the TWT input and output circuits, and through the use of multiple circuit sections. Figure 3 shows the fundamental power of a prototype TWT from 3-18 GHz. The fundamental power is 51 dBm or better from 3.2-18 GHz and 50.0 dBm or better from 2.7-3.2 GHz at full CW duty.

Table 1. TWT Parameters for the UWB MPM

Parameter	Ultra-Wide-Band MPM TWT
Frequency	3 to 18 GHz
Power Output (Watts)	> 125 W min. / 260 W max.
Minimum Efficiency (%)	> 27 %
Beam Voltage (V)	4640 V
Beam Current (mA)	260 mA
Saturated Gain (dB)	28 dB min. / 48 dB max.
Input RF Drive (dBm)	6 dBm min. / 23 dBm max.
TWT Width (inch)	0.75 inches (nominal)
TWT Length (inch)	8.5 inches (nominal)

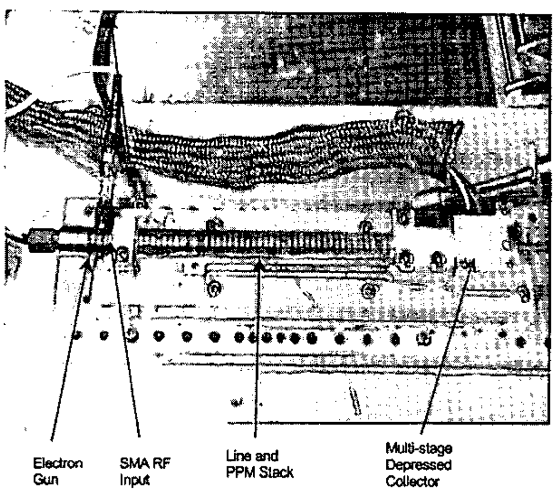

Figure 2 - Photograph of the prototype UWB TWT in a high duty package.

A number of TWT design tools developed by the Naval Research Laboratory, including the CHRISTINE [2] and CTLSS codes, have been utilized in the TWT design effort. Additionally, a simulated annealing routine for global optimization of power-bandwidth performance has been incorporated in the 1-D CHRISTINE code. The development of these power-bandwidth optimization routines was an important factor for deriving the original prototype design.

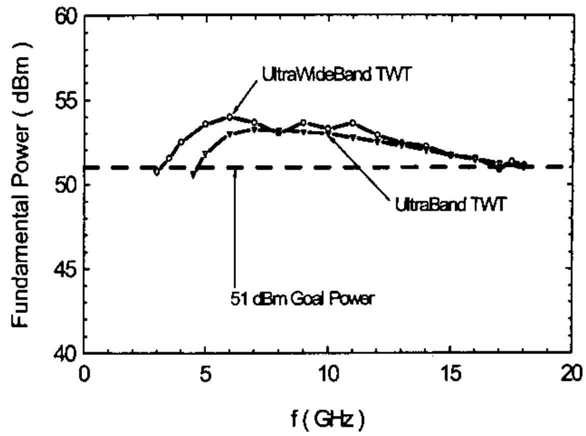

Figure 3 - Fundamental power performance for the UltraWide Band TWT.

III. EFFICIENCY ENHANCEMENTS

Although high RF conversion efficiencies are important in all microwave systems, they are particularly important in airborne and space-based applications due to limitations on size and weight of available system power supplies. The MPM subcomponent that primarily limits the overall efficiency is the miniaturized TWT that serves as the vacuum power booster (VPB). As requirements for these VPBs become more and more difficult to achieve in practice, accurate modeling of the device is required as well as effective design and testing optimization methods. Several advances have been realized in methodology, modeling, and testing, which have substantially improved VPB performance while maintaining the original miniature size and light weight. The resulting VPBs, and the MPMs incorporating them, are the smallest and lightest of their kind operating at such efficiency and power levels.

The miniaturized vacuum power booster performance has been increased substantially during a recent C-Band efficiency enhancement program. During the duration of the C-Band program, multiple VPBs were designed and tested, and the progression of the VPB efficiency during the program is shown in Figure 4. The total efficiency of the device is seen to increase from approximately 40% at the start of the program to over 60% at present. Advances include accurate modeling and optimization of the VPB magnetic field structure and beam entrance conditions, enhanced accuracy of design codes, new hybrid circuit design methodology for high efficiency interaction including harmonic power growth, electron gun perveance reduction, and development of a real-time automated system for parameter optimization.

IV. Millimeter-Wave MPM

Although much of the MPM development at NGC has focused on the 2-18 GHz band, there is growing interest in developing sources above 18 GHz for emerging communication and ECM needs. Operating at higher frequencies does require a corresponding decrease in the helix circuit size, and as a result special fixturing is necessary and thermal management becomes more demanding. An early TWT prototype tested at NGC did demonstrate 100 watts of RF power from 18-35 GHz, but was only able to generate 18 watts at 40 GHz. The TWT has been redesigned using CHRISTINE 3D large signal modeling, and a new prototype will be ready for tests in early 2002. The RF power goal is 80 watts cw over most of the 18-40 GHz band, with at least 40 watts at 40 GHz. Other TWT goals include 40% efficiency at mid-band, and a saturated gain of 30-35 dB. The TWT package measures 8 x 2.5 x 1 inches.

V. Conclusion

The performance of MPMs has improved dramatically since their introduction almost a decade ago as part of the Tri-Service vacuum electronic initiatives. Recent improvements include power booster efficiencies in excess of 60%, and bandwidths that have reached almost three octaves. The work being performed by Northrop Grumman in the area of MPM-based transmitter development promises to maintain its leadership in high power RF transmitters for military ECM applications. Our goal is to exploit the high degree of MPM design commonality in order to address new applications in commercial and military communication, and radar.

Acknowledgement

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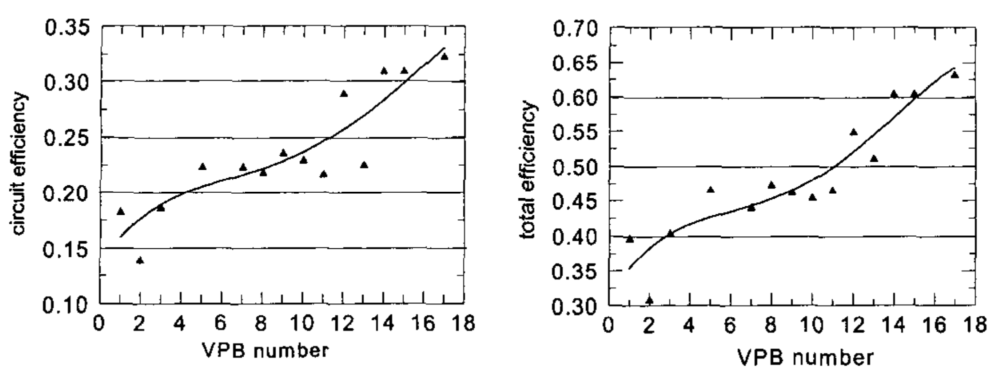

Figure 4 - Evolution of C-Band VPB circuit and total efficiency.