INTRODUCTION TO THE MPM: WHAT IT IS AND WHERE IT MIGHT FIT

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Abstract

The Microwave Power Module (MPM) is introduced and described. The synergistic combination of technologies -- MIMIC driver, vacuum power booster, and integrated electronic power conditioning -- has a multitude of advantages for system applications. The MPM is capable of achieving performance not attainable with either solid-state or vacuum-electronics technology alone. Power, efficiency, and noise performance in the 6- to 18-GHz band in a compact lightweight package -- to be available in the first-generation MPM by June 1994 -- will be suitable for selected radar and EW applications. The second-generation MPM will be even more capable and suitable for insertion in a wider range of systems.

The background of the MPM Program is detailed; MPM programmatics are presented. To ensure that next-generation MPMs will be even more advantageous to the military and civil system designer, technical challenges that must be met in a variety of technical areas are identified.

Introduction

Severe demands are placed on the characteristics of microwave power delivered to the radiating elements of next-generation radar and electronic warfare phased-array antennas. Peak and average power, bandwidth, modulation noise and spectral purity, phase and amplitude control, and other mission-related performance requirements tax the capabilities of current RF amplifier technology in advanced-system contexts. Additional constraints on the power sources -- such as size, weight, efficiency, maximum operating temperature, and thermal management -- are critical to the implementation of systems in advanced platforms, such as aircraft, where space and weight are at a premium. For such next-generation systems, RF power source technology cost and reliability will be extraordinarily important factors bearing on final system architecture choices.

The microwave power module (MPM), a "supercomponent" combining a wideband MIMIC driver, a highly-efficient miniaturized vacuum power booster, and integrated power conditioning, all in a small lightweight package, is a revolutionary device that creatively links solid-state and vacuum-electronics RF power amplification technologies to meet these demanding challenges.

Soon, MPM performance will exceed, by many measures, that possible by either solid-state or vacuum-electronics technology alone. The inherent efficiency of the TWT in the output stage of the module combined with the low-noise performance of the solid-state MIMIC produces a unit with the breakthrough performance and packaging required for many critical system designs, in which enhanced efficiency, reduced size and weight, and lower cost are foremost concerns. By enabling a new flexibility in system architecture, the MPM is expected to benefit diverse military systems, and impact RF power generation in commercial markets, as well.

In the near-term, the microwave power module will synergistically combine iterative improvements in vacuum electronics (helix and coupled-cavity TWTs) and MIMIC source technologies to enhance total device performance. More speculatively, the new field of RF vacuum microelectronics, which combines the advantages of electron transport in vacuum with gated emission structures derived from solid-state microfabication, may have a strong impact on RF source technology. Both recent advances and new opportunities are indicative of a growth potential that has re-established RF vacuum electronics as a viable competitive technology capable of responding to the challenges of the future.

Background

(1988) Special Technology Area Review. At the annual S&T review in June 1987, the Advisory Group on Electron Devices (AGED) Working Group A (Microwaves) reported to OUSD(A) on the status of the microwave power tube technology base. The most dramatic observation was that the vitality of the industrial technology base -- and its ability to respond to future military needs -- was at risk due to exceedingly low Exploratory Development (6.2) investments. These observations echoed earlier warnings of a similar nature. [1,2] The difference was that by 1987 more than a decade of stagnant and eventually declining R&D investment in the power tube technology base had undermined the strength of the industry.

In response to the deteriorating situation, AGED Main Group requested Working Group A to conduct a Special Technology Area Review (STAR) on the topic of microwave (and millimeter-wave) power tube R&D; the review was held in October 1988. The STAR highlighted R&D needs from both industry and Service perspectives, identified tube and solid-state needs for airborne radar and electronic warfare systems, tube requirements for the surface Navy, and the status of tube technology overseas.

(1989) Microwave Power Module Panel. The requirement for a broadband medium-power phased-array module surfaced at the October 1988 STAR. Dr. John Mendel, STAR Chairman, formed a panel as a STAR adjunct to investigate the power module concept in greater detail. The Microwave Power Module Panel (Dr. Mendel, Chairman, and Mr. Lynwood Cosby, Deputy Chairman) was chartered to explore the potential of an integrated vacuum-electronic/MIMIC device that could be broadly applied in next-generation microwave systems, including EW, radar, and communications. This Panel activity, supported by the Naval Research Laboratory, brought Government and industry experts from the systems and device areas together to define the optimum power module. Representatives from the systems, vacuum-electronics, MIMIC, and power conditioning communities developed realistic near- and long-term projected performance characteristics that were matched closely to evolving and projected system requirements.

The Microwave Power Module Panel concluded that the combination of solid-state and vacuum-electronics technologies in a single device or "supercomponent" would leverage the performance advantages inherent to each type of technology. The MPM was conceived as an unit of moderate power level, integrating a solid-state driver, a vacuum-electronics power booster, and power conditioning, (See Figure 1.), each module capable of powering one or more radiating elements in an array. In the most constrained system envisioned -- a fully-distributed-amplifier phased array -- the cross-section of each MPM channel would be limited to approximately one-half-inch square; the depth to several inches. However, it was agreed that a near-term MPM only width- or height-constrained would benefit either line arrays, partially-distributed arrays, or single-module applications.

By integrating improved solid-state power amplifier and power conditioning technologies, the MPM would enable the development of flexible and affordable radar and EW phased-array architectures. Clearly, specific military missions would dictate the phased-array system architecture. Radar applications require both power-aperture product and resolution; electronic warfare requires higher ERP. A higher-power MPM feeding several radiating elements in a close-packed array may be suitable for radar, for example, whereas electronic warfare applications may favor a lower-power MPM that is fully-distributed across the array (one module per radiating element). Preliminary point design specifications were developed by the Microwave Power Module Panel for each application area.

Economies of scale never before achieved in the history of military electronic device applications could result from broad application of an optimized high-performance MPM common to radar, EW (both on-board and expendables), and other systems, such as communications. The Panel noted that substantial savings and improved reliability would be realized by volume production of a multi-purpose MPM serving as a building block for many systems. A common MPM serving advanced radar and EW applications could reach production quantities in excess of several millions ***if only a fraction*** of the targeted planned systems were to reach maturity and production. This approach would also support the long-sought goal of microwave amplifier standardization.

(1990) AGED Report. Concurrently with Panel deliberations, AGED Working Group A published a report [3] in which microwave power tubes were identified as a critical national defense technology in need of expanded funding over a period sufficient to rejuvenate the technology infrastructure. In the report, AGED noted that "the depth and vigor of the vacuum electronics technology base have been severely weakened by a long-term decline of R&D investments" and that "the trend must be reversed through well-structured, vigorous, and sustained funding." The primary recommendation was to "implement a unified program based on tri-Service needs to take advantage of existing technical opportunities. Evidence was presented to suggest that the appropriate level of funding was in the range of $25 million to $30 million per year over a program life of 5 to 10 years.

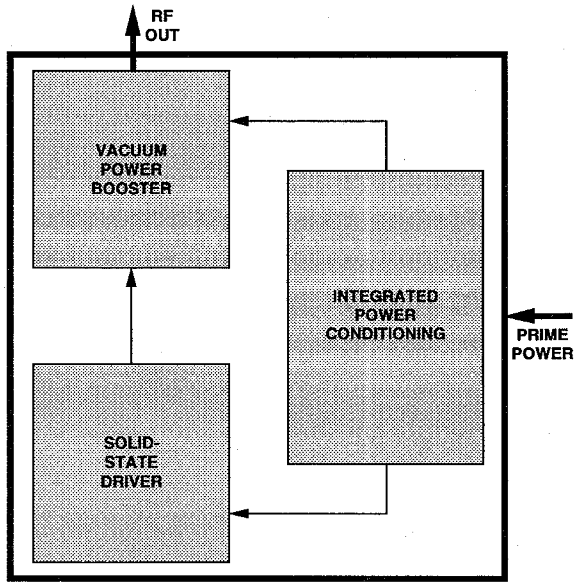

Figure 1. MPM Block Diagram

AGED identified five high-impact opportunities for focussed investment, and recommended sustained funding above the current Service investments for 6.2 and 6.3A programs. Five vacuum-electronics technology areas were identified as candidates for enhanced high-leverage 6.2 investments, including "Microwave Power Module "Supercomponent" Development that integrates solid-state drivers, vacuum electronics power boosters, and power conditioning to support shared-aperture array applications at affordable costs."

(1990/91) Tri-Service/DARPA Vacuum Electronics Initiative. The DoD-wide response to the AGED findings and recommendations was three-fold [4]:

- DARPA/DSO implemented a Vacuum Electronics Initiative ($3 million in FY91) centered on the two high-risk high-payoff investment areas recommended in the AGED report, viz., wideband RF amplifiers based on vacuum microelectronics and second-generation fast-wave amplifiers for millimeter-wave radar.

- An additional $15 million, mandated for microwave power tube R&D by Congress during its consideration of the FY91 defense budget, was directed to DARPA/DSO ($5 million) and the Naval Research Laboratory ($10 million) for implementation of an expanded microwave power tube R&D program. The Navy funds established the tri-Service Vacuum Electronics Program, a technology core program focussed on tri-Service issues with high impact. DARPA's enhanced assets funded a single-year expansion of the DARPA/DSO Vacuum Electronics Initiative and inaugurated, jointly with the tri-Service Vacuum Electronics Program, the initial year of MPM development.

- Finally, to sustain the tri-Service Vacuum Electronics Program in the out-years, DoD decision PBD-208 recommended placement of additional funds (FY-92 through FY-97) in the Navy Exploratory Develoment budget, stipulating that these additional funds complement, rather than supplement, the funds already programmed by the three Services for RF vacuum electronics.

The integrated DoD 6.2 and 6.3A program in RF vacuum electronics now includes the DARPA/DSO Vacuum Electronics Initiative, the tri-Service Vacuum Electronics Program, and all system-specific investments by the individual Services. These actions have substantially increased DoD investment in vacuum electronics R&D (6.2 and 6.3A).

Microwave Power Module Program

Before the establishment of the Vacuum Electronics Program described above, the Naval Research Laboratory funded two industrial contracts to examine radar and electronic warfare MPM applications to determine whether major obstacles existed to implementing a full-fledged development effort. The Electron Dynamics Division of Hughes Aircraft Company and Teledyne MEC, examined the basic issues in radar and electronic warfare, respectively. Neither investigation identified any major obstacles to further development of the MPM concept.

Phase I of the MPM program was initiated in March 1991 with a briefing to industry on program structure and proposal requirements. Proposals from industry were evaluated; contract monitoring responsibilities were assigned (contracting activity was supported by Army , Air Force, and Navy laboratories); and a FY92 start date for the program was selected by the end of April. The program, with a 5-year two-phase structure, was formally initiated in November 1991. Phase I of 2-1/2 years duration will result in a demonstration of a linear array of MPM modules; Phase II will drive the technology even further with the goal of demonstrating MPMs capable of powering a two-dimensional phased array.

The MIMIC Program has provided substantial support to the MPM program under Phase II of the Raytheon/TI Joint Venture in the "Micro-TWT Driver Module Demonstrator Development" task. Target specifications for the MPM MIMIC driver were developed in December 1991.

MPM Phase I program objectives were based on the point designs developed by the Microwave Power Module Panel. The Phase I MPM program objective is to develop a module addressing the goal of radar and EW commonality in the 6- to 18-GHz frequency range at ~ 100 watts CW in a 5/16 in x 4 in x 6 in (0.8 cm x 10 cm x 15 cm) package by June 1994. The overall module efficiency is to be greater than 35%. Meeting the $\lambda/2$ requirement at the upper-band-edge frequency of 18 GHz will support the demonstration of a one-dimensional array at the conclusion of Phase I. Overall MPM performance was stated as a set of "goals," as presented in Table 1, rather than specifications, with considerable latitude being given to individual corporate approaches to the MPM, e.g., in cooling, power supply topology, and vacuum power booster design.

TABLE 1
PHASE I MPM PRIMARY PERFORMANCE GOALS

RADAR	REQUIREMENT	EW
7 to 11 GHz	Frequency Range	6 to 18 GHz
100 watts	Output Power	50 - 100 watts
~ 50%	Duty	CW

In Phase IA of the MPM program, hardware was developed at Hughes, Northrop, Raytheon, Teledyne MEC, and Varian. As detailed in Paper D-2 of this session, diverse systems expected to benefit from the MPM include jammers, decoys (both towed and expendable), active missile seekers, and phased-array radars. Paper D-3, a paper co-authored by industrial MPM participants, gives a sense of the industry's achievements to date.

In August 1992, at the conclusion of Phase IA, vendor hardware was demonstrated that ranged from a 655-cm^3, full performance (100 W, CW) device to a 123-cm^3, limited performance (100 W, 1% duty) device across 6- to 18-GHz. The former package represents a four-fold reduction, the latter a twenty-fold reduction in amplifier volume at that power level. Moreover, the potential for bandwidth extension to three octaves (2 - 18 GHz) at these moderate powers was indicated. Most importantly, the demonstrated devices uncovered no major roadblocks to final package size reduction.

Based on Phase IA of MPM development, projections indicate a five-fold improvement in efficiency over MIMIC alone. As demonstrated, the MPM represents a significant enhancement in amplifier specific power (watts per unit weight); as projected, the size reduction will be even more impressive. In addition to enhanced specific power, the superior efficiency and low noise offered by the MPM offer an option not available from solid-state or vacuum-electronics technology alone. Recently revised targets for MPM development are shown in Figure 2.

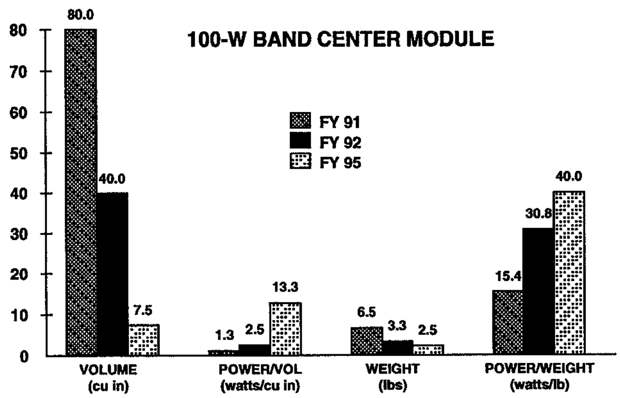

Figure 2. MPM Reduced Weight and Size Goals

MPM Payoff

The major payoff of the MPM as conceived is the provision of flexibility in phased-array architectures that would otherwise tax the capability of either solid-state or vacuum electronics power source technology alone. The MPM is also expected to achieve widespread application through the deployment of phased-array architectures enabled by MPM affordability. A brief, and probably incomplete, list of MPM synergy benefits includes:

- Enhanced overall efficiencies, and a reduced thermal management burden, derived from the use of a vacuum power booster capable of efficient operation at high ambient temperatures.
- Higher reliability, as compared to tube approaches, brought about by the partitioning of total gain between MIMIC driver and the vacuum power booster.
- Higher power-aperture products provided by the vacuum power booster.

- Relaxation of power supply requirements, as compared to tube approaches, due to the dynamic gain partitioning possible between driver and booster, leading to reduced weight.

- Reduced acquisition costs brought about by volume manufacture of standardized units, with further cost reductions realized through the development of a multi-purpose or standardized MPMs serving a variety of needs.

- Improved gain and phase-matching/control, as compared to tube approaches, by use of MIMIC elements in the proposed gain blocks.

Technology Challenges

Clearly, the concept of an efficient low-cost MPM will require the development or innovative application of specific technologies. Note also that the program will require MANTECH funds in addition to RDT&E funds to properly integrate new approaches and processes that will evolve in vacuum electronics, solid-state, materials, and passive component technology areas to achieve a fully-integrated MPM meeting performance, affordability, and reliability goals.

Challenges to fill the gaps in current technology include:

- Improved magnetics capable of supporting high-quality high-perveance electron beams within module cross-section and weight constraints.

- Improved depressed-collector designs to enhance power booster efficiencies within the size constraints imposed by array element spacing.

- Innovative waste heat removal designs for the dimensionally-constrained Phase II MPM.

- Improved MIMIC performance at high-junction temperatures.

- Novel power conditioning schemes to provide spectral purity in radar applications.

- Development of low-loss passive components and devices to minimize overall system losses.

- Improved power conditioning components such as high voltage diodes and capacitors suitable for high-density power conversion.

- Low-cost three-dimensional fully-electromagnetic computer modelling.

- Low-cost MPM manufacturing techniques.

Although of a more speculative nature in future MPM plans, RF vacuum microelectronics, using gated emission structures derived from solid-state microfabrication, will have a strong impact on RF source technology. [5] Vacuum microelectronics is based on solid-state fabrication techniques to improve the emission of electrons into a vacuum, effectively substituting the transport medium of a vacuum for that of a solid. New classes of density-modulated RF sources derived from vacuum microelectronics will include large-scale devices related to established power tube types, as well as on-chip, integrable micro-devices.

Based on today's vacuum microelectronics technology, a range of amplifier options appears possible, from the triode to the inductive output amplifier. One obvious focus for insertion of a vacuum microelectronic amplifier is the MPM, with its needs for compact efficient operation. [6] A key advantage of vacuum microelectronics in this application is that the MPM power booster need only be a low-to-moderate gain device which also must feature high efficiency and specific power. By inserting a density-modulated vacuum-microelectronic-based amplifier, it should be possible to enhance efficiency by increasing the single-pass interaction efficiency and depressed collector operation. For those applications where small enhancements are critical, as in space-based operations, the absence of a heater for the emitter is attractive. In addition to the enhanced efficiencies possible, an amplifier based on density modulation will be shorter, which may have attractive benefits for applications in which not only real estate but also skin depth is critical. After the 1-GHz benchmark is surpassed, the push to higher frequencies and broader bandwidths will be the focus for the next phase of technology development in this area.

Acknowledgments

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