DEVELOPMENT OF A LOW COST X-BAND SOLID STATE TRANSMITTER FOR LOW VOLUME COMMERCIAL APPLICATIONS

J. Faulkner, E. Lee, J. Masti, M. Pingor

Westinghouse Electric Corporation
P.O. Box 746, MS 75
Baltimore, MD 21203

Abstract

A low cost X-Band solid state transmitter has been successfully demonstrated for low volume commercial applications. Advanced modeling techniques, novel circuit design, concurrent specification flowdown and automated processing technologies were utilized to develop a robust design which maximized yield and achieved the low cost goals required for solid state transmitter amplification in low volume commercial applications.

Introduction

Advantages of using solid state amplification for airborne applications are well documented. Smaller size, lighter weight and lower phase noise are a few advantages over the traditional TWT. FET based MMIC power amplifiers also have a well demonstrated reliability record, but to achieve commercial viability the system must also achieve the low cost targets. In particular, low volume commercial applications impose even tougher targets since economies of scale are not achievable. This requires a robust design with high yields that utilizes advanced modeling techniques and concurrent engineering as well as automated manufacturing and test methodologies.

System Application

In 1991, Westinghouse embarked on a new product line aimed at both the military and commercial markets. The need for this system, MODAR (MODular Avionics Radar), was developed from a commercial aviation hazard known as wind shear which has been known to cause damage to property, personal injury as well as loss of life. Prior to the Westinghouse entry into the wind shear detection market, technology could only warn that an aircraft was in a wind shear event. The Westinghouse system added the capability for prediction and early detection of a wind shear, allowing the aircraft to avoid this hazardous condition.

A family of wind shear detection radar systems was developed out of the design efforts. The MODAR-3000 was designed for the commercial market, while the MODAR-4000 was directed at the military tanker/transport market. Additional features in the MODAR-3000 system include ARINC-708 weather radar functions and basic ground map. The MODAR-4000 system included these functions in addition to high resolution ground map with precision update capability, airborne target detection and beacon detection. All of the systems included a highly reliable solid state transmitter. Since the production quantities were low and the cost goals aggressive, Westinghouse designers had to be innovative in the design approach in order to be successful in the new business area.

Design Approach

The key requirements for the X-Band weather mapping radar transmitter were a peak output power of 160 watts, a gain of 60 dB, an MTBF of 20,000 hours, and a cost commensurate with a high volume product within the first 180 systems. In addition, the transmitter was required to provide low phase noise and intrapulse amplitude weighting in order to support a mapping wave form that does not interfere with other radars. A trade among various transmitter architectures which utilize IMPATT oscillators, TWTs, and MESFET amplifiers was performed against these key performance parameters. This trade resulted in the selection of a MESFET amplifier as the building block for the transmitter.

The driver amplifier and the power module were the two key building blocks comprising the transmitter. These two amplifiers were two distinct physical packages each with 30 dB gain. This physical boundary was established to eliminate any potential instabilities associated with cavity mode feedback. Simple package geometries and microstrip routing of the RF were easily utilized with the limitation of 30 dB of gain per amplifier. The power module was further partitioned into two identical packages to limit parts count per assembly and enhance the yield of the overall transmitter. The block diagram for the transmitter is shown in Figure 1.

The two identical power modules which represents over 80 % of the overall transmitter cost, were the focus of the low cost design. The block diagram of the power module is shown in Figure 2.

CH3577-4/95/0000-0331$01.00

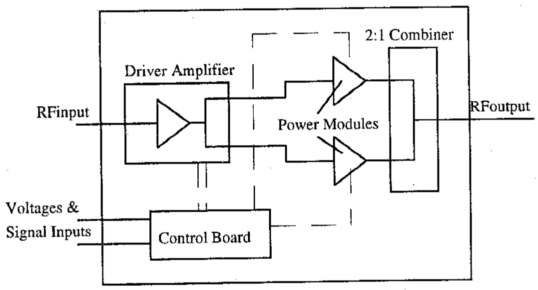

Figure 1. MODAR Transmitter Block Diagram

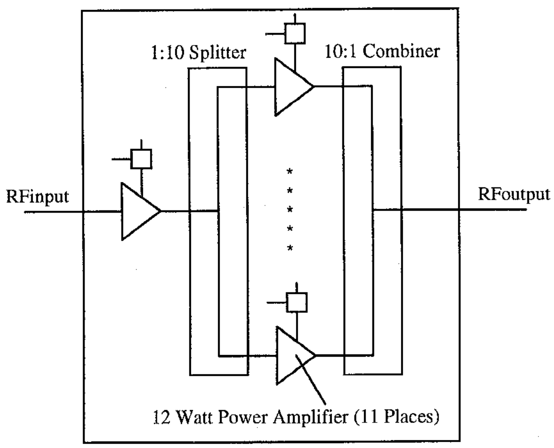

Figure 2. MODAR Power Module Block Diagram

The power module is comprised of eleven fully matched 12 watt GaAs amplifiers using MMICs developed at the Westinghouse Advanced Development Laboratory. Ten of these amplifiers were combined in parallel using a unique stripline based serial combiner to achieve 85 watts of RF power. The ten amplifiers were driven by another 12 watt amplifier and a 10 way splitter identical to the stripline combiner. The stripline nature of the splitter and combiner allowed the vertical integration of the DC bias circuitry on top of the stripline. The size impact of this bias circuitry, which included regulators, bias switching devices and energy storage capacitance, was minimized through the use of thick film multilayer construction stacked on top of the stripline. A picture of the MODAR power module is shown in Figure 3.

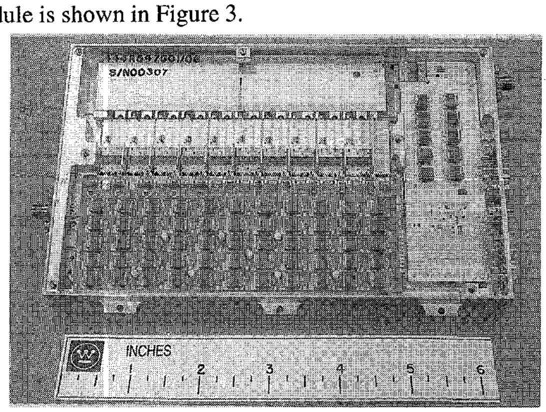

Figure 3. MODAR Power Module (85 Watts)

The 12 watt power amplifier building block is comprised of only eight parts including two thin film networks, four fully matched 4.0 watt MMICs, a Copper-Moly-Copper (CMC) carrier, and a solder preform. A picture of the MODAR power amplifier is shown in Figure 4. The 12 watt power amplifier represented over 75 % of the materials cost to the power module. This single most significant contributor to the transmitter cost was the focus of much of the attention in the design of the MODAR transmitter.

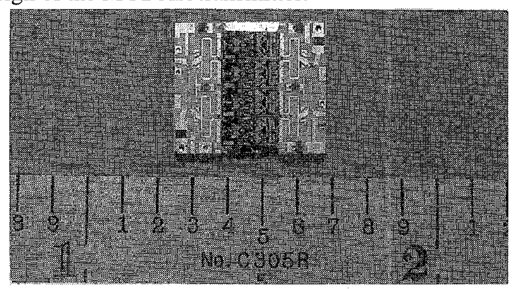

Figure 4. MODAR Power Amplifier (12 Watts)

The power amplifier combines four 4W MMICs in a balanced configuration. The divider/combiner network consists of a 3 dB Lange coupler feeding a pair of Wilkinson power dividers. The use of .015" thick alumina substrates with identical input and output substrates and integrated thin film resistors, air bridges, and ground vias, together with a minimized parts count supported a low cost producibility philosophy.

The four 4W MMICs used in each power amplifier are based on the Westinghouse baseline X-band power MESFET process which employs conventional GaAs processing techniques. The MESFETs employ a buried spike-dope Lo-Hi profile [1] for active-layer uniformity to maximize yield. Typical MESFET performance is 450-500 mW/mm saturated power out with > 45% P.A.E. for 9V drain operation. The process has been successfully demonstrated through MIMIC Phase 2 to maximize yield and is currently employed on production programs.

The MMICs were designed with on-chip matching to minimize assembly cost and to avoid tuning and phase variations that would result in a hybrid assembly. On-chip matching allows extensive wafer level screening to improve the power amplifier production yield. A compact size was required to meet the allocated module physical constraints and to maximize device yield. To achieve a compact device, an in-house thermal modeling program [2] was used to calculate maximum junction temperatures, and to set the device gate pitches at a reliable minimum of 18 um for the output FET. The chip input and output match was designed to partially compensate for the bond wire inductance which were predetermined by the assembly techniques of the production facility. Initial fabrication runs demonstrated that the FET gate voltage was uniform enough to fix the gate voltage and thereby further reduce the test and assembly cost. This data also demonstrated that an insertion phase uniformity of no worse than ±25° could be expected.

Copper-moly-copper (CMC) was selected as the carrier material of choice due to its favorable coefficient of thermal expansion, low cost, and inexpensive processing (stamped vs. machined). The use of compensating stubs in conjunction with proprietary automated assembly techniques were employed to allow the elimination of pedestals on the carriers. The power amplifier assembly has no additional chip resistors or capacitors, and incorporates ground-signal-ground test pads to be compatible with automated testing.

The DC bias to the power amplifiers was provided with a single gate regulator and eleven individual drain regulators and modulators. The drain regulators and modulators, which provided a gated drain bias to the 12 watt amplifiers, were collocated with the individual amplifiers. This gated bias was synchronized with the system PRF, which lowered both the average dissipation of the transmitter and the noise leakage into the receiver.

The individual drain bias circuits also provided a means to evaluate the performance of an individual 12 watt power amplifier in the power module subassembly. The health of a given 12 watt amplifier can be quickly evaluated by sequencing the drain bias of an individual amplifier to the on state and the drain bias of the other amplifiers to the off state. This technique also provides an efficient way to phase tune individual paths in the splitter combiner network. Intrapulse amplitude shaping was achieved by sequencing the bias to different numbers of MMIC amplifiers across the time frame of the RF pulse.

The resulting power amplifier successfully met all of the performance specifications. The uniformity of the batch MMIC processing also eliminated the need to bin chips for matched power, gain and DC current characteristics. Insertion phase uniformity of better than $\pm 25°$ has been demonstrated in both MMICs and power amplifiers which is necessary for efficient power combining at both the power amplifier and power module level.

Producibility

Recognizing the aggressive performance and cost targets led to the formation of a multifunction IR&D team consisting of the MMIC designer, power amplifier designer, transmitter designer, manufacturing engineer and test engineer. This team was responsible for the design of the transmitter, which incorporated the necessary design features required to achieve repeatable high performance in conjunction with a robust low cost producible package.

The items identified by the team as key elements for success were:

Associated with the transmitter:

1. Low cost materials
2. No post production tuning
3. Design compatible with automated production practices:
    a. Automated pick and place
    b. Automated vacuum/pressure solder reflow
    c. Automated bonding
    d. Automated testing

Associated with the power amplifier:

1. Mature, low risk MMIC process technology
2. Internally matched unconditionally stable MMIC
3. Identical TFNs for the input and output
4. No machined parts
5. Minimal additional chip components (resistors, capacitors, etc.)

A major cost driver in the development of the power amplifier was the handling of the power amplifier through the assembly and test cycle. A proprietary common carrier for processing eight amplifiers thus was used throughout the assembly and test cycles. The power amplifiers were not removed from the carrier until being packed for shipment.

The common carrier in conjunction with automated assembly techniques provided very accurate parts placement and consistent wire bond lengths for enhanced performance. Vacuum - pressure soldering was performed using a single AuSn solder preform under all the components. No epoxy attach is used. Automatic wirebonding reduced bonding time from 30 minutes to 2 minutes per power amplifier. After wirebonding, the power amplifiers are ready for test. An automated test system was developed using vision processing techniques to automatically place RF and DC probes for automated electrical testing. The elimination of conventional manual test fixtures, launchers, and test connections greatly improved yield and reduced test time by a factor of 20:1.

Results

The program successfully demonstrated the ability to use automated production techniques in conjunction with producing a high performance transmitter which required no tuning. The actual production costs accurately reflected the projections of the initial cost model. The transmitter met all of the system requirements and was inserted into the MODAR system without disruption. Additionally, the power amplifiers have successfully undergone in-module life testing for 171 days with over 25,000 cycles with no measurable degradation in performance.

To date, over 150 transmitters have been delivered to the MODAR program. These have been supported by the internal manufacture of 16,000 MMICs and 2,500 power amplifiers with an overall yield of 85 %.

The implementation of the flowdown distribution specifications assisted in meeting the yield goals. Figure 5, 6, and 7 show the distributions for the output power of the MMICs, power amplifiers and transmitters. These distributions highlight the relationship between the actual measured data and the specification. Yields for the MMICs and power amplifiers were 25 % and 85 % respectively.

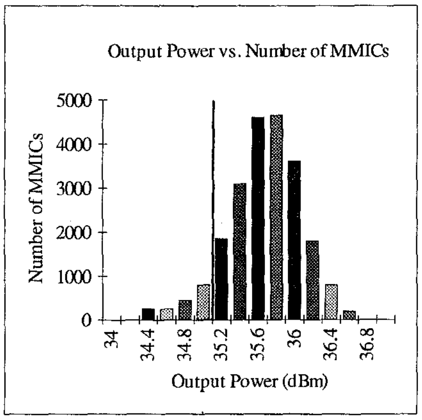

Figure 5. Histogram of the Output Power of MMICs

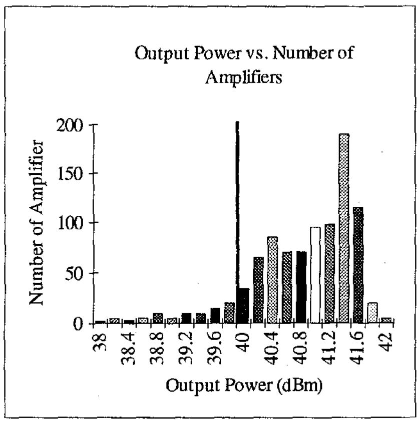

Figure 6. Histogram of the Output Power of Power Amplifiers

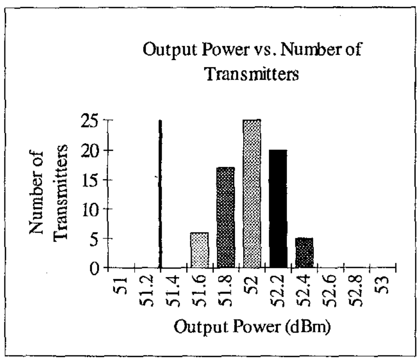

Figure 7. Histogram of the Output Power of Transmitters

Production testing was streamlined by the excellent phase consistency of the power amplifiers. The phase grouping was well within a 50 degree window, which allowed utilization of a passive microstrip loaded line phase trimmer to equalize the phase between amplifier channels. This supported a transmitter one time phase set philosophy which resulted in a 90% reduction in "tuning" time of the transmitter. Phase compensation from 10 degrees to 60 degrees in 5 degree increments is achievable by the selection of the appropriate wire bonds in the module. At the present time, only 20 % of the power modules require the phase compensation, a 10 minute operation.

Summary

Through the use of a multifunctional team, a low cost commercial X-Band solid state transmitter was successfully designed, developed and produced proving the viability of solid state power amplification for low volume commercial efforts. Distribution specifications assisted the team in meeting the imposed performance and yield goals. Presently, over 150 transmitters have been delivered and are operating in the Westinghouse MODAR wind shear detection system.

Acknowledgments

Authors would like to acknowledge the significant contributions of the team members who were instrumental to the overall success of the program. Ron Freitag, George Henry, John Lane, and Harry Salvo for the design, processing and testing of the GaAs MMICs. Paul Belt, Gerri-Ann Bell and Kenneth Hines for their work in the areas of automated testing and manufacturing.

References

[1] S. Sriram, R.C. Clarke, R.L. Messham, T.J. Smith and M.C. Driver, "High Voltage Operation in Class B GaAs X-Band Power MESFETs", Proceedings of the 1989 IEEE Cornell Conference on Advanced Concepts in High Speed Semiconductor Devices and Circuits, pp. 218-227.

[2] Dale E. Dawson, "Thermal Modeling, Measurements and Design Considerations of GaAs", 1994 IEEE GaAs IC Symposium Digest (to be published), 1994.