HIGH VOLUME MANUFACTURING OF A HIGH-EFFICIENCY X-BAND POWER MODULE FOR PHASED ARRAY APPLICATIONS

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ABSTRACT

This paper describes the production of a state-of-the-art microwave power module for use in active aperture phased-array radar transmit/receive (T/R) modules. More than 2000 modules have been manufactured to date at rates exceeding 100 modules per week. The production process will be described in detail with particular attention given to the issues relating to large volume manufacturing of microwave power circuits.

INTRODUCTION

The active aperture phased-array radar systems planned for the next generation high-performance aircraft will require thousands of transmit/receive (T/R) modules per platform. A key element in the T/R module is the power amplifier portion of the transmitter chain. This paper describes such a power amplifier module. The nominally 5-W, 30% efficient X-band module is presently being produced in large volume for a variety of customers. The details of the manufacturing process, which has resulted thus far in more than 2000 highly reproducible modules, are presented in this paper.

MODULE MANUFACTURING

The X-band power amplifier module has been described in detail elsewhere (1). Briefly, the module consists of a pair of two-stage amplifier chains combined in a balanced configuration. In each chain a 3.0mm GaAs FET is used to drive a 7.2mm FET. Figure 1 shows a photograph of the module. In addition to the four microwave devices, there are nine substrates (ranging from 15 mil thick Al_2O_3 to 3 mil thick $BaTiO_4$), 25 capacitors and five diodes in the assembly. The parts are eutectically bonded onto a 15 mil thick, multi-level CM-15 (Copper 85%, Moly 15%) composite metal machined carrier which has been gold plated. All of the module components, FETs, capacitors, diodes, substrates and the carrier are produced within Avantek.

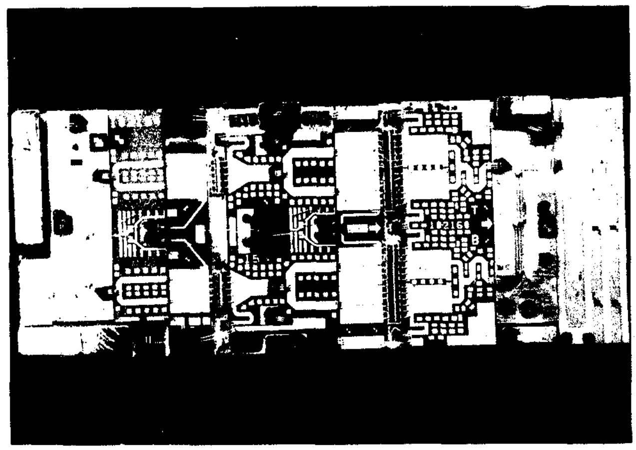

Figure 1. Two-Stage Balanced X-Band Power Amplifier Module

Key to successful manufacturing of the module was production of the large quantity of high-efficiency, X-band power FET's required. The FET's were fabricated on 2" wafers on which a special high-low-high doping profile (1) had been grown by molecular beam epitaxy. Wafer fabrication was our standard power FET production process described elsewhere(2).

After wafer sawing, the dice are sorted into as many as 10 separate plates each representing a different pinch-off voltage range. This sorting is for later matching of die pairs in each module for optimal performance. DC parameter maps generated by on wafer probing are used by the computer driven automated pick-and-place equipment which "bins" the die. Sample die from each bin are mounted onto pre-matched carrier assemblies and evaluated for power and power-added efficiency (PAE) at a single frequency (10.2 GHz). Die that meet minimum performance specifications (34.9 dBm and 37% PAE for the output FET's) qualify those particular bins from that wafer as candidates for use in production. Final qualification is done by producing a small quantity of modules from die selected from the candidate bin. If the modules pass the acceptance test criteria, the entire lot of die

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from that bin are released to the production line for assembly.

After assembly of the power amplifier module and prior to rf tuning, the module quiescent current (~1 A) is set by selectively bonding up thin-film resistor networks printed on two of the substrates. Since the module is operating in class A-B for maximum efficiency the operating current is determined by the rf drive level. No adjustment of the dc operating point is made during the tuning operation.

Tuning time is minimized during the production process by close interaction between assembly and technician personnel. Many commonly required bond wires can be added during the initial assembly steps as the tuning characteristics of the dice from each wafer are identified. To further increase throughput extensive use is made of subtractive tuning to minimize the labor associated with the tuning process. To further expedite tuning and testing a special test fixture (Figure 2) was designed. The fixture is fitted with a hinged cover containing spring-loaded dc and rf contacts to facilitate quick mount/dismount of the assembled carrier. A window like opening in the fixture cover allows easy access to the module top surface for tuning operations. The fixture also provides good mechanical stability and thermal contact during the testing process.

Liquid crystal measurements have verified that the thermal resistance between the FET channel and the test fixture is 6°C/watt greater than the thermal resistance between the channel and a heat sink to which the module has been soldered. This corresponds to an excess channel temperature rise of approximately 25°C. To simulate operation of a power module soldered into a T/R module being maintained at a 55°C base plate temperature, testing of power module performance was performed with the test fixture operating at room temperature.

A sophisticated, automated test set-up and associated software (3) aids the technician in rapidly switching between swept power, gain and VSWR measurements to allow simultaneous optimization of all three. The same software performs final acceptance testing for all module parameters.

PERFORMANCE DATA

Figure 3 shows the computer print-out of final acceptance data on a typical module. The acceptance criteria are checked automatically by the test software and any failures are noted on the print-out. Although the specified operating frequency of the module is from 9.2 to 10.2 GHz, data is standardly recorded every 100 MHz from 9.0 to 10.4 GHz.

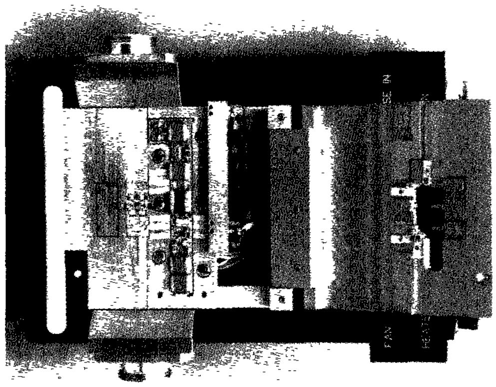

Figure 2. Photograph of The Special Test Fixture

27 Oct 1988 09:11:54
OPER: TONY SPROUL
WAFER# F94-017D F96-001A
WO# S501880105-59
DEVICE# Z1024

Gate Bias Voltages: M148: -1.70 M123: -2.00

Drain Bias:9V Gate Bias:-5V

INPUT POWER: 23 dBm Small Signal Ref Level: 15dBm

Frequ (GHz)	Pwr out (dBm)	Gain Comp. (dB)	Gain SSG (dB)	Gain LSG (dB)	Gate Curr (mA)	Drain Curr (Amps)	Efficiency (Pow add.) (%)	InVSWR (dB)	OutVSWR Dr off (dB)
9.0	37.5	4.1	18.7	14.6	9	1.88	32.3	-17.8	-15.9
9.1	37.4	3.7	18.2	14.5	9	1.85	32.0	-17.6	-16.5
9.2	37.2	3.2	17.6	14.4	9	1.82	31.1	-16.6	-17.8
9.3	37.3	2.6	17.1	14.5	9	1.80	32.1	-17.2	-19.7
9.4	37.5	2.1	16.8	14.7	9	1.81	33.0	-20.0	-22.4
9.5	37.6	1.7	16.5	14.8	10	1.81	34.3	-26.1	-25.7
9.6	37.5	1.7	16.4	14.7	10	1.80	33.5	-35.6	-29.7
9.7	37.6	1.6	16.4	14.8	10	1.79	34.1	-32.7	-33.5
9.8	37.2	2.0	16.5	14.5	10	1.78	31.8	-28.6	-30.1
9.9	37.2	2.4	16.7	14.3	10	1.72	32.4	-29.1	-26.0
10.0	37.2	2.6	17.0	14.4	10	1.68	33.4	-27.9	-23.0
10.1	37.3	2.7	17.2	14.5	10	1.67	34.6	-25.1	-20.9
10.2	37.2	2.6	17.0	14.4	10	1.64	34.1	-24.0	-19.5
10.3	37.0	2.3	16.5	14.2	10	1.61	33.7	-22.6	-18.2
10.4	36.6	1.5	15.2	13.7	10	1.58	30.7	-21.7	-16.9

Figure 3. Typical Module Final Acceptance Printout

In addition to the major parameters of power and efficiency, many other module characteristics are measured and recorded including large- and small-signal gain, gain compression, gain and power flatness, gate and drain operating currents, maximum input VSWR and maximum output VSWR (with the drain bias off). All data are recorded under cw conditions at a fixed input drive of 23 dBm (approximately 2 dB into compression). Because the power modules are destined for phased-array systems, average performance characteristics and module-to-module variations are as important as individual minimum performance specifications. For example, certain parameters like power and drain current have ensemble minimum, maximum and/or standard deviation specifications which must be met. For this reason all performance data is collected into a centralized computer data base using a commercial software package for later analysis.

Figure 4 shows the average output power vs. frequency for the entire ensemble of modules. The plot also shows the plus/minus one sigma range for each data point. The average power across most of the band varies less than 0.1 dB. A reduction in the minimum specified power (from 37 to 36.5 dBm) above 10 GHz accounts for the roll-off in power at the high end of the operational band. The standard deviation of power at all frequencies is less than 0.28 dB. The tight control of the module output power is shown another way in Figure 5. This plot is a histogram of the number of modules falling into each 0.05 dBm window in module power (averaged over the 9.2-10.2 GHz band). The distribution shows a clear Gaussian shape with some 69% of the modules falling within +/- 0.18 dB (one sigma) of the population mean.

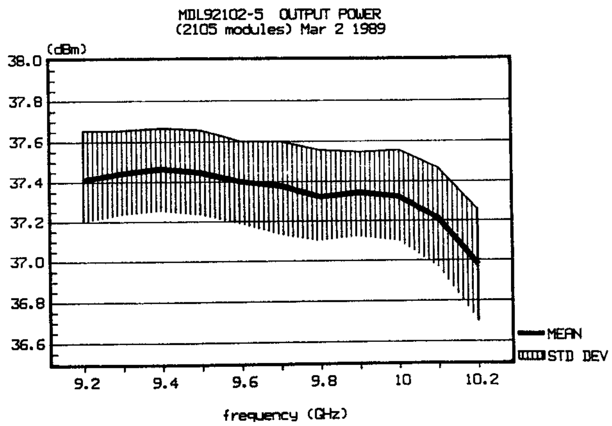

Figure 4. Ensemble Output Power vs. Frequency

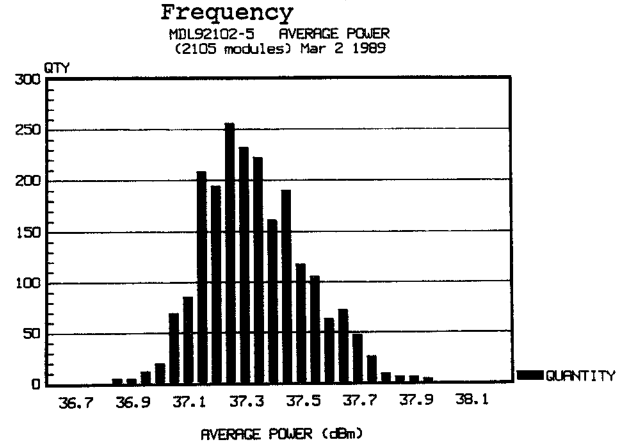

Figure 5. Histogram of Average Module Power

Figure 6 shows a performance vs. frequency plot of module PAE. Note that the average module efficiency is greater than 32% at all frequencies in the band. Again, as one would expect for a normal distribution, 66% of the modules fall within one sigma (1.9 percentage points) of the overall population average PAE of 33.2%.

An important parameter for the designer is the total current consumption of the T/R modules in the array. While the maximum current for any module at a given frequency could be as high as 2.2 A, the maximum <u>average</u> current at each frequency was specified as less than 1.9 A (under rf drive conditions) so that the overall array current consumption could be predicted. The data presented in Figure 7 demonstrates that the module ensemble meets this requirement.

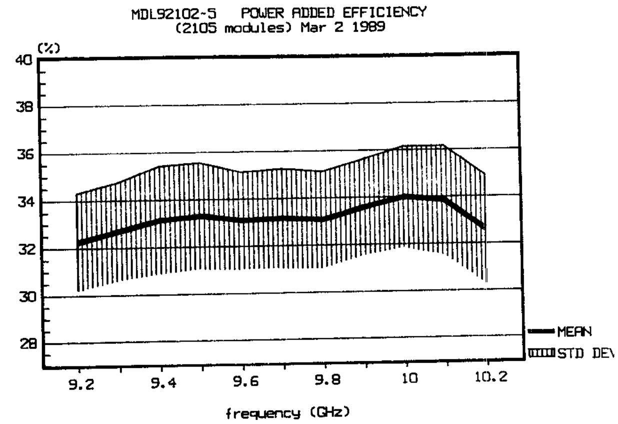

Figure 6. Ensemble Power-Added Efficiency vs. Frequency

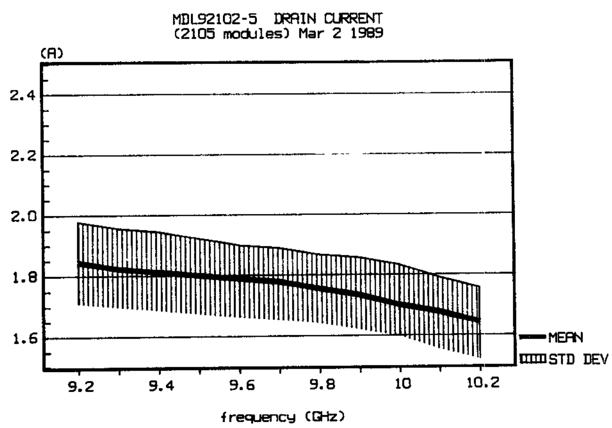

Figure 7. Ensemble Drain Current vs. Frequency

MANUFACTURING HISTORY

Initial development of the module design was begun in mid-1987. Design of a final production version was completed in early 1988 and small quantity pilot production of the power modules to verify manufacturability of the design was started in the spring. The transfer of responsibility from the development group to the manufacturing organization began in the summer of that year. Peak production in excess of 100 modules per week was achieved by early 1989. The weekly shipment rate beginning with the start-up of the production operation is shown in Figure 8.

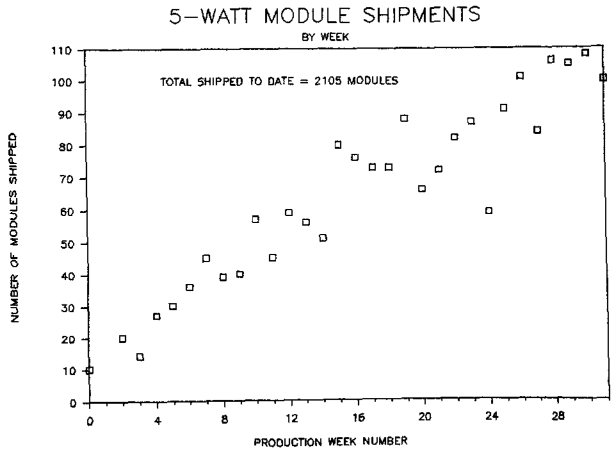

Figure 8. Weekly Module Shipments for Program To Date

Throughout the production run the average performance of major module parameters has been monitored to detect significant systematic changes (either improvement or degradation). Only negligible amounts of systematic change in any of the major module parameters have been detected. For example, average module efficiency has increased only 2.3% over that period (Figure 9). Such consistency over time is key to successful long-term manufacture of phased-array components.

CONCLUSION

The manufacturing processes used in producing state-of-the-art X-band power modules for use in phased-array radar systems have been presented. Large volume production with consistent, reproducible performance has been demonstrated. Because of the extensive qualification of dice for production and the careful control maintained during the assembly process on such critical factors as die attach and component bonding, we have achieved the excellent module-to-module uniformity necessary in phased-array radar applications.

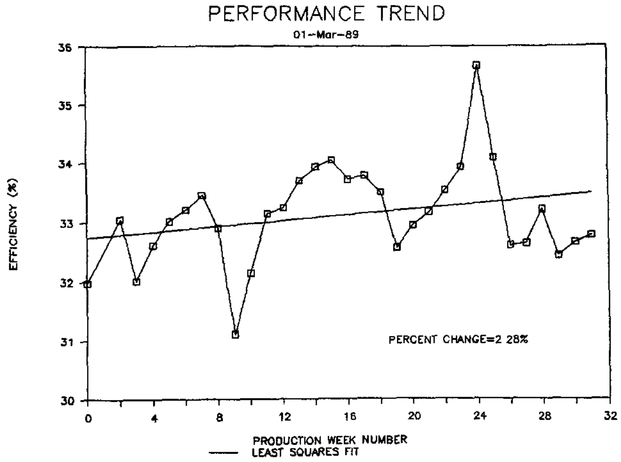

Figure 9. Change in Average Module Efficiency for Program To Date

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(2) M. Avasarala, D. S. Day, "2.5-Watt and 5-Watt Internally Matched GaAs FETs for 10.7-11.7 and 14-14.5 GHz Bands," 1986 IEEE MTT-S International Microwave Symposium Digest, pp. 455-458.

(3) D. Glajchen, "Characterize Power Amplifiers Automatically," Microwaves & RF, Vol.27, No.8, pp. 103-114.