VIII-2

K-BAND T/R-CONVERTER MODULES FOR THE IRIDIUM® SATELLITE PROGRAM*

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Abstract

The paper describes two K-band multi-chip modules developed for the satellites on the IRIDIUM® communication program*. The modules employ a wide range of low noise and power 0.25 um PHEMT MMICs to provide all K-band transmit/receive functions aboard the spacecraft. The modules include over 500 active and passive components including LNAs, power amplifiers, mixers, frequency doublers, and associated support circuitry. Descriptions are provided of the MMIC and module development programs, module producibility features, and the associated MMIC reliability test program. Also described is a novel K-band interface method which eliminates RF alignment.

Introduction

The IRIDIUM® satellite system* is a personal communication network with very aggressive production rates and cost allocations. In order to meet these difficult program goals, extensive usage of MMIC technology and commercial practices must be combined to form highly producible K-band hardware.

This paper describes the development of two space-based K-band multi-chip modules (MCM) developed at Motorola's Commercial Space Division in Chandler, AZ. Each module incorporates multiple low noise and power 0.25 um PHEMT MMICs and robust K-band interfaces which eliminate the need for RF alignment.

Since the reliability of these advanced monolithic processes is not well established, the associated reliability test program is also described.

It will be demonstrated that statistical design techniques played a key role in the development of the modules.

IRIDIUM® System Description*

With the exception of the subscriber-to-satellite link, all RF communications in the IRIDIUM® system* occur at K/Ka-band frequencies. Communication between satellites is accomplished using 23.3 GHz "crosslinks" while communication between the satellite and ground uses "gateway" feeder links operating at 19.5 downlink and 29.2 GHz uplink. Telemetry, tracking, and control functions are provided through a secondary link also operating at 19.5 GHz downlink and 29.2 GHz uplink. Each satellite features four crosslink and four gateway subsystems.

The K-band transmit/receive functions and up/down frequency conversion for these subsystems is performed by the modules whose block diagrams are shown in Figures 1 and 2. As is evident from the block diagrams, the gateway modules operate in a full duplex mode while the crosslink modules operate in a half-duplex mode. Except for the filters and ferrite devices, all elements in the diagrams denote multi-stage GaAs MMIC chips.

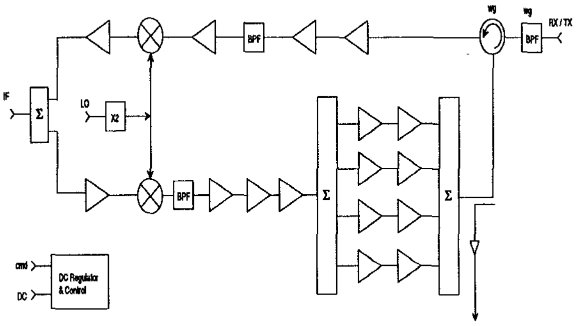

Figure 1. Crosslink T/R-Converter Block Diagram

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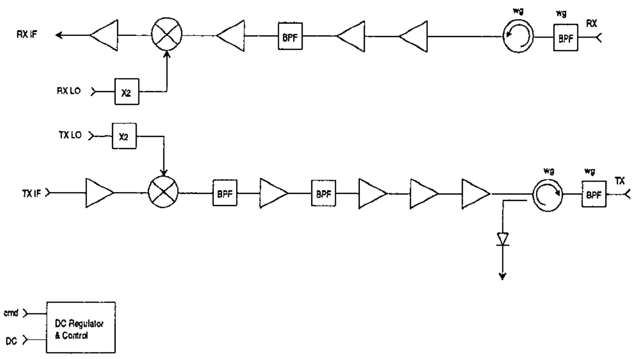

Figure 2. Gateway T/R-Converter Block Diagram

The resultant MMIC chip set consists of eleven low noise chip types and five power chip types. The low noise MMICs were designed by Motorola and fabricated by Microwave Signals, Inc. in Clarksburg, MD using their 0.25 um enhancement mode low noise PHEMT process. The power MMICs were designed by Motorola and fabricated at Raytheon's Advanced Device Center in Andover, MA using their 0.25 um double recess 06A power process. A total of 120 K-band GaAs MMICs are used on each space vehicle (S/V).

Key performance requirements of the modules are listed in Tables 1 and 2. The required build rate of four of each module type per week is required to support the extremely aggressive build rate of one S/V per week.

Parameter	Center Frequency (GHz)	Target Value	Measured Value	Delta (std dev)
Rx Noise Figure	23.3	4.8 dB	4.9 dB	+0.5
Rx Path Gain	23.3	38 0 dB	39.2 dB	+0.3
Tx Output Power	23.3	+35.0 dBm	+35.0 dBm	+0
Tx Path Gain	23.3	+60.0 dB	+59.0 dB	-0.2

Table 1. Crosslink T/R-Converter Performance

Parameter	Center Frequency (GHz)	Target Value	Measured Value	Delta (std dev)
Rx Noise Figure	29.2	4.8 dB	4.5 dB	-1.2
Rx Path Gain	29.2	38.0 dB	39.0 dB	+0.24
Tx Output Power	19.5	+28.0 dBm	+28.7 dBm	+2.4
Tx Path Gain	19.5	+45.0 dB	+47.3 dB	+0.6

Table 2. Gateway T/R-Converter Performance

Design Methodology

The program design approach was to systematically flow down all key technical requirements in statistical form. The method uses pooled variance techniques[1,2] to allocate both means and standard deviations to all lower level circuit functions. In this fashion each lower level circuit function receives an allocation from each system level specification to which it contributes variation. When each lower level circuit function meets its statistical allocation, statistical quality at the top level is guaranteed.

In addition to the statistical allocations, other key requirements imposed on the MMICs were unconditional stability, on-chip ESD protection, stress analysis, and full statistical yield analysis.

It is apparent from the table that pseudomorphic HEMT processes were required for both the low noise and power functions. A comprehensive foundry selection process was undertaken to select the optimum foundries for the program. Detailed questionnaires were sent to candidate foundries followed by on-site visits by design and reliability personnel. Final selections were then made and the detailed MMIC designs initiated.

The modules also required various filters to meet post-upconversion and image rejection specifications. A set of alumina filters was developed to meet very demanding requirements. The toughest requirements were those imposed on the post-upconvert filters which were required to provide 35 dB of transmitter LO rejection. This level of rejection at only 0.75 GHz from the K-band carrier would normally be performed by high Q cavity filters. But in order to maintain compatibility with an MCM environment, printed filters on drop-in microstrip substrates were developed.

A key technology developed on the program was a K-band wirebond interface which provides a low VSWR interconnection between the MMICs and the 50 ohm microstrip line. The associated performance of the interface is shown in Figure 3. This method uses wirebond processes typically suited to the lower microwave frequencies and applies them in novel fashion to generate an interface that is usable to 40 GHz. This interface method has completely eliminated RF tuning within the modules greatly enhancing MCM producibility. An added benefit of this interface is that it provides a bidirectional 50 ohm port impedance so that all MMICs may be tested at wafer probe stations and then installed into the module without having to account for parasitic input/output bondwire inductance.

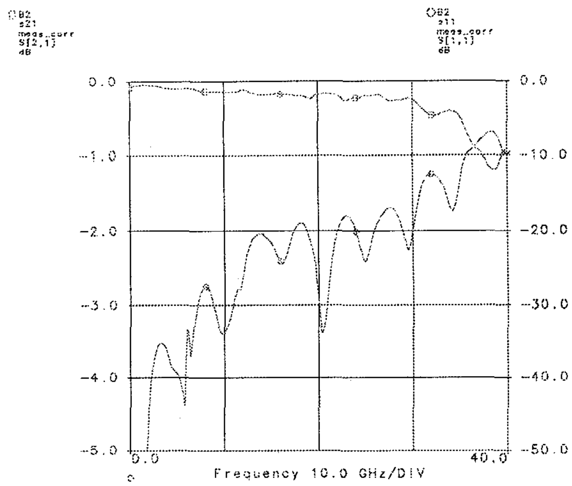

Figure 3. Wire Bond Interface Performance

Other functions provided in the MCMs include active bias for all MMICs, dual polarity linear regulators, independent TX and RX DC power strobing, DC sequencers, and module on/off control. Each module contains over 500 passive and active components and 500 wirebonds to satisfy these functions. Photographs of the two MCMs are shown in Figures 4 and 5.

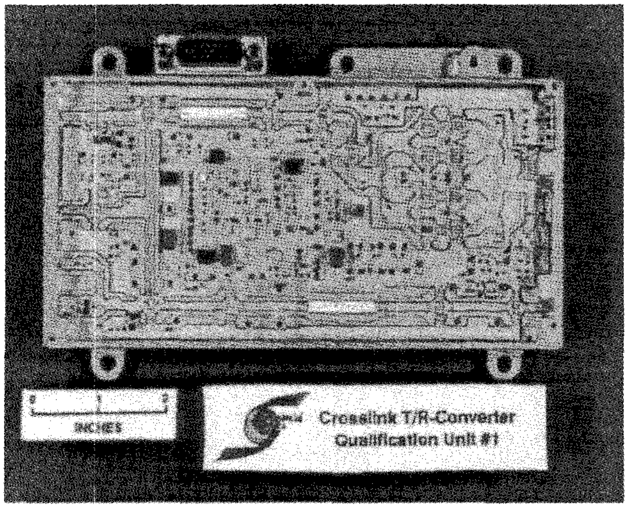

Figure 4. Crosslink T/R-Converter MCM

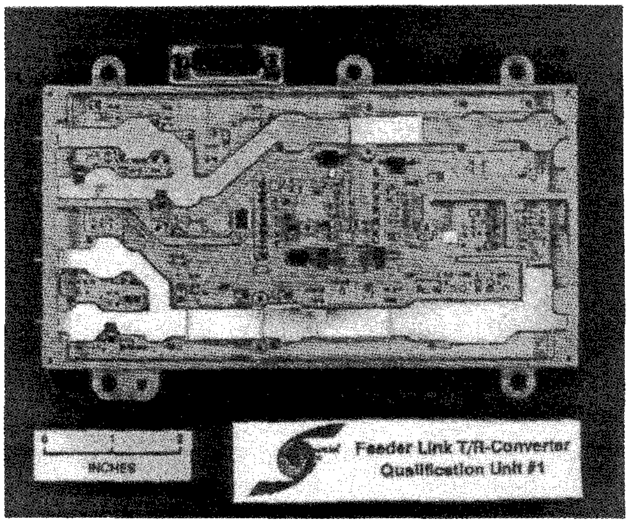

Figure 5. Gateway T/R-Converter MCM

The active bias circuits eliminate DC alignment of FET bias operating points, the linear regulators provide local regulation of power buses for improved supply filtering, and the DC strobing and on/off control preserve DC power when the K-band links are inactive.

Module Construction

The module housing is made from E20, a beryllium composite material featuring high thermal conductivity, low weight, and a thermal coefficient of expansion which closely matches that of GaAs. Internal walls are machined into the housing to provide cavity definition for the RF channels. All RF channels are set to 0.15 inch width which corresponds to a TE_{10} cutoff frequency of 38 GHz. This is sufficiently above the operating band of interest to prevent undesired waveguide moding. Solid covers are then attached over all RF channels to complete cavity definition. Figure 5 shows these RF channel covers installed.

The MMIC cavities are much wider than 0.15 inch so absorptive inserts are employed. The inserts suppress spurious modes and fill the gaps in the sidewalls through which DC bias to the MMICs is applied.

The housing is an H-frame which accommodates a single layer Duroid® 6002 RF board on the top side and a multi-layer polyimide DC distribution board on the bottom side. Both boards are laminated into the housing using conductive epoxy film. Since the housing is an H-frame, thermal bosses are employed on the underside of all power MMICs to provide good thermal contact to the mounting baseplate. Electrical connection between the top and bottom layers is then made through feedthroughs epoxied into the housing floor.

Manufacturing/Test

The module was designed for compatibility with automated assembly equipment. The assembly process calls for the automatic dispense of conductive epoxy followed by robotic pick and place of components and final automatic wire bonding. The RF side of the module is kept solder free so that a clean, flux-free environment may be maintained for the exposed wirebonds. The components on the DC side are attached using solder paste and convection oven reflow.

Automatic special test equipment (STE) capable of handling multiple modules simultaneously was developed to reduce test cycle time. The STE provides an automatic data tracking system so that statistical trends may be monitored and compared to the appropriate process limits. The test throughput time has been designed to support the 8 units per week MCM production rate.

Reliability

Since very little reliability data existed for 0.25 um GaAs PHEMT devices, an extensive reliability test program was conducted. Devices from both the low noise and power processes were subjected to unbiased accelerated life testing in order to evaluate diffusion related failure mechanisms. Using a failure criterion of 10% degradation in DC transconductance, all devices exhibited reliability on par with mature MESFET devices. The low noise devices exhibited an MTTF of 2500 years at Tch=100°C with an associated activation energy of 1.4 eV. The power devices exhibited an MTTF of 4000 years at Tch=120°C with an associated activation energy of 1.4 eV.

The power devices were then placed in an RF life test program whereby amplifiers were subjected to varying levels of gain compression, DC bias, and channel temperature. This testing produced excellent results after accumulating greater than 18 years of equivalent device life. Less than 10% RF gain and output power degradation was observed.

Maximum input power ratings have also been established for the low noise amplifiers. Burn-out testing shows that the low noise devices can withstand 2 minute exposures of +24 dBm with no associated degradation in noise figure or gain. The effects of longer exposure to RF overdrive is currently under investigation.

Module Performance

Resultant module performance is summarized in Tables 1 and 2 along with the statistical target values for the hardware and resultant sigma calculations. The tables include the differences between the target and measured values in standard deviations. Note that the numbers in the tables represent gains achieved after final selection of IF attenuators. IF gain trimming was employed to offset the large process variation build-up associated with multiple stage microwave hardware. As is evident from the tables, the measured performance is very close to the target values. This demonstrates the value of the statistical design approach. Also note that no RF tuning was required to provide the reported performance.

Conclusions

We have described the development of two highly producible K-band multi-chip modules for the satellites on the IRIDIUM® communication program*. The modules demonstrate that high frequency hardware can be produced using conventional automatic assembly equipment. Also demonstrated was the value of statistical design methods and the robustness of a new K-band interface technique.

The reliability of 0.25 um PHEMT monolithic processes was also established and shown to be capable of supporting extended space missions.

Acknowledgments

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