A MICROWAVE SWITCH MATRIX USING MMICs FOR SATELLITE APPLICATIONS*

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ABSTRACT

This paper presents the design, packaging, and measured performance of a lightweight crossbar 4 x 4 Microwave Switch Matrix (MSM) for communications satellite applications. Miniaturization of the MSM has been achieved by integrating GaAs monolithic (MMIC) broadband switch elements with hybrid power dividers and combiners and driver/control circuits in a lightweight MSM package. The on-state insertion loss and on-to-off isolation for all MSM paths are measured to be 6.25 dB (maximum) and 50 dB (minimum), respectively, over 3.5- to 6.5-GHz frequency range. The corresponding path-to-path insertion loss and phase variations are within ±0.5 dB and ±10°.

INTRODUCTION

The use of microwave switch matrices (MSMs) on-board communications satellites enhances satellite capacity by providing full and flexible interconnectivity between signals of up- and down-link beams (1). The frequency reuses resulting from the introduction of microwave switching for satellite switched time division multiple access (SS-TDMA) operation significantly enhance the satellite utilization efficiency. A block diagram of the SS-TDMA transponder is shown in Fig. 1, in which the crossbar MSM provides high-speed dynamic interconnections between the RF input ports (receivers) and the RF output ports (transmitters). In INTELSAT VI satellites launched in October 1989, MSMs are being used in two channels for sixfold frequency reuse at C-band (2). Similarly, the NASA 30-20 GHz Advanced Communications Technology Satellite (ACTS), to be launched in 1992, employs IF switch matrices for routing of TDMA signals. For these and other programs (1)-(4), MSMs have been developed by using hybrid or MIC technology, which requires several manual wire-bonds internal to each switch element.

In this paper, we present the design and performance of a miniaturized, broadband (3.5- to 6.5-GHz), crossbar 4 x 4 MSM (Fig. 2) for on-board satellite applications. This MSM features significant performance improvements over the INTELSAT-VI MSM technology (2) with estimated reduction in equivalent mass volume and DC power consumption of more than 50 percent. In addition, the use of monolithic microwave integrated circuit (MMIC) dual-gate FET switch elements has resulted in improvements in switching speed and insertion loss. The 3-GHz bandwidth of the MSM provides a single design for all the channels in communications satellite 6-GHz up-link or 4-GHz down-link bands. Sixteen MMIC switches have been integrated in the MSM with 8 MIC power dividers/combiners, 16 RF feed-throughs, a driver/control circuit and a number of bias and control wires in a lightweight package with overall dimensions of 2 x 2 x 1 in. More than 50 dB of on-to-off isolation has been achieved over the 3.5- to 6.5-GHz frequency band. Previous MSM designs using MMIC technology for on-board satellite applications were implemented at 1-GHz IF to minimize on-chip coupling (5) and achieve high on-to-off isolation.

4 x 4 MSM DESIGN

Each transmission path of the 4 x 4 MSM (Fig. 2) consists of an MMIC switch element, input and output distribution networks, and a feed-through. Four-way Wilkinson dividers and MMIC switch elements are assembled on the top surface of a metal ground plane and Wilkinson combiners are mounted on the bottom surface. Sixteen feed-through interconnections are used to provide RF signal transmission paths from the MMIC switch outputs to the combiner inputs. The 4 x 4 MSM package is designed using Kovar because its thermal coefficient of expansion is nearly the same as that of alumina substrates (6). The GaAs MMIC switch element, which forms the key building block of the 4 x 4 MSM, is mounted on a separate carrier to facilitate its testing and assembly.

The MMIC switch element consists of two dual-gate FETs with nominal gate lengths and device widths of 0.5 μm and 300 μm, respectively (7). A two-stage design was considered necessary in order to achieve the desired 50-dB on-to-off ratio. Reactive matching with resistive loading resulted in small circuit size, made the circuit design relatively insensitive to device parameter variations, and resulted in excellent stability. Furthermore, a broad bandwidth match was obtained with very small changes in return loss in two states of the switch element. To minimize chip

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size, lumped-element metal-insulator-metal (MIM) capacitors, resistors, and spiral inductors were used in the matching networks. To improve on-to-off isolation, the input, interstage, and output matching networks were separated by ground planes. The chip (Fig. 3) is fabricated on a 12.5-mil (0.3-mm) GaAs substrate with overall chip dimensions of 1.5 x 2.5 mm (60 x 100 mils). The switch has a gain of approximately 10 dB and on-to-off isolation greater than 50 dB over the 3.5- to 6.5-GHz frequency range. The rise and fall times of the dual-gate FET switch element are less than 10 ns (Fig. 4).

Compact and broadband RF power distribution networks have been designed and fabricated on 10-mil-thick alumina substrate. For a design bandwidth of 3 GHz over the 3.5- to 6.5-GHz frequency range, multistep cascaded line lengths were used. To make the physical layout compact, space between the lines was kept to a minimum. Additional 50-ohm lines were added to get the desired spacing dictated by the MSM mechanical configuration. The broadband Wilkinson dividers/combiners are modular, so that the same networks may be used at the input and output of the MSM. Measured results show an amplitude balance of ±0.2 dB and phase balance of ±1.5° over the complete 3.5- to 6.5-GHz frequency band. A miniature feedthrough was custom designed which showed good performance up to 15-GHz frequency.

MSM CONTROLLER DESIGN

A distributed control architecture has been designed in which a number of on-board satellite units can be controlled by a single executive controller. The control architecture can be divided into four levels - the executive control unit (ECU), the data distribution and timing unit (DDTU), the local control module (LCM), and the driver unit. This partitioning provides a highly flexible and modular controller architecture for high speed satellite switching applications. The digital controller is used to download switch state data to microwave switches, upload telemetry verifying the correct state, and provides timing signals for synchronous switching.

The ECU, which generates the switch state data and verifies the telemetry data, is the highest level of control. The next level of control is the DDTU. This onboard unit provides the common timing signals for the lower level control units. A 944-kHz clock defines the switch state timings, a 500-Hz frame clock defines the TDMA frame timing, and a 0.06-Hz master frame clock is used for synchronous switchover of control data patterns. These clock timings correspond to the INTELSAT VI on-board SS-TDMA subsystem timings. The DDTU is also used to route data from the ECU to lower levels of control. The LCM stores an entire TDMA frame of MSM switch state data locally in RAM. The data for each switch state is serially downloaded to the driver units prior to switching to the next state. The download time is less than 4 µs, which is the minimum state dwell time. Telemetry can also be uploaded from the driver units. The LCM also stores an offline frame of data. The switchover from the online frame to the offline frame is controlled by the master frame clock. Each LCM can control up to sixteen 4 x 4 MSMs, and up to 16 LCMs can be connected to each DDTU.

The driver unit is the lowest level control component of the distributed control architecture, and its design is application specific. A block diagram of the driver board for the 4 x 4 MSM is shown in Fig. 5. It has three control inputs, two bidirectional data inputs, and 16 outputs to drive the 16 switches of the MSM. Sixteen bits are serially shifted into the shift-register over the two data lines at the rising edge of the clock signal. These 16 bits are then latched with the strobe signal. Telemetry can be serially shifted back to the LCM from the shift register by means of the direction signal. Level shift circuits are placed at the LCM interface instead of the MSM interface in order to minimize the overall circuit size. With this approach 6 level shift circuits are needed instead of 16. The latch output drives the MSM switches directly, with +1.5 V for an on state, and -3.5 V for an off state. The driver unit has been implemented on a 10-mil-thick 1- x 1.35-in. alumina substrate and has been assembled inside the MSM cover. Commercially available CMOS integrated circuit chips, which are available in radiation-hardened versions, have been used.

MSM PERFORMANCE

Key performance characteristics of the miniaturized MSM are summarized in Table 1. The MSM provides any N inputs to any or all M outputs including broadcast mode for synchronization. Measured transmission loss performance for all 16 paths (Fig. 6) shows on-state insertion loss of less than 6.25 dB and path-to-path insertion loss variation of less than ±0.5 dB over 3.5- to 6.5-GHz frequency. The on-to-off isolation is greater than 50 dB. Over the 3.7- to 4.2-GHz satellite down-link band, the amplitude variations are less than ±0.3 dB and the on-to-off isolation is greater than 60 dB. The phase balance for all 16 paths is better than ±8°. The return losses at all input and output ports are measured to be better than 15 dB over the 3-GHz bandwidth of the MSM (Fig. 7). The carrier to third-order

Table 1. MSM Performance Characteristics

Array Size	4 x 4
Connectivity	Any N to any M
Bandwidth (instantaneous)	3.5 to 6.5 GHz
Insertion Loss of any On-Path	6.25 dB (max.)
Path-to-Path Insertion Loss Variation	±0.5 dB
On-to-Off Isolation	50 dB (min.)
Input/Output Return Loss	15 dB (min.)
Amplitude Linearity (C/I) for two-tones (Pout < -10 dBm)	>45 dB
Differential Delay	±0.5 ns
Frame Period	2 mS
Frame Units/Frame	1888
Length of Frame Unit	1.06 µs
Rise or Fall Time	< 10 ns
MSM Mass	130 g
MSM Volume	2 x 2 x 1 in.
Power Consumption	<1.25 W

intermodulation distortion ratio is greater than 45 dB for two-tone output signal level of -10 dBm. Temperature tests over 0°C to 70°C show a maximum MSM path insertion loss variation of 1.2 dB at 4 GHz and 1.7 dB at 6 GHz (Fig. 8).

CONCLUSIONS

Design of a miniaturized, broadband 4 x 4 MSM has been presented demonstrating MMIC insertion in MSM arrays for on-board satellite applications. A distributed control architecture has been developed for dynamic control of MSM arrays. High density packaging of MMICs has been realized with the MSM driver/control circuits while achieving high on-to-off isolation, enhanced reliability, lower production costs and reduced weight and volume.

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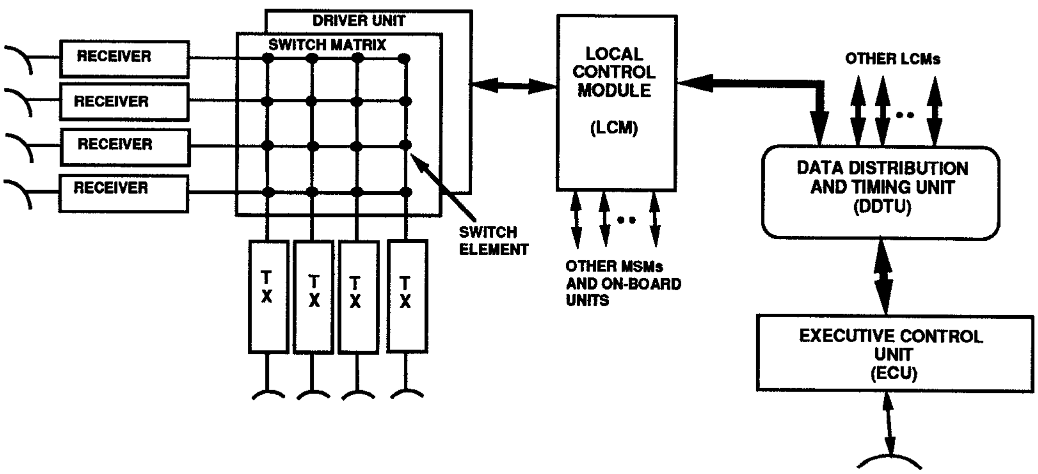

Figure 1. A Simplified Block Diagram of SS-TDMA Satellite Transponder

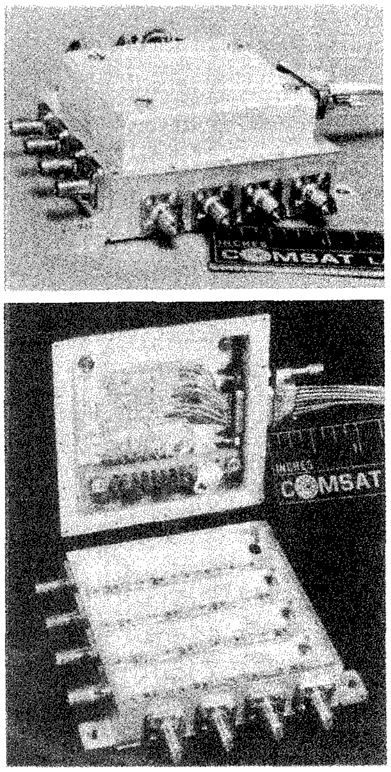

Figure 2. Fully Integrated Miniaturized 4 x 4 Microwave Switch Matrix (MSM)

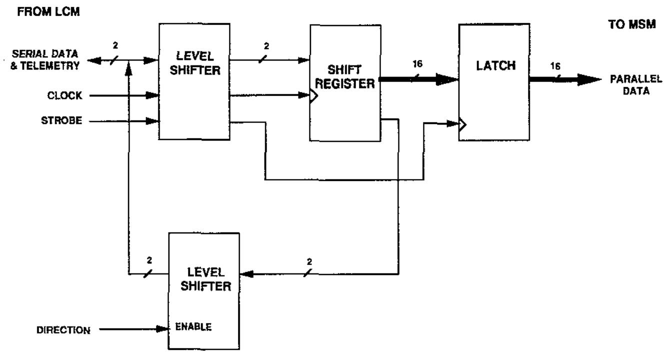

Figure 5. Block Diagram of the Driver Unit

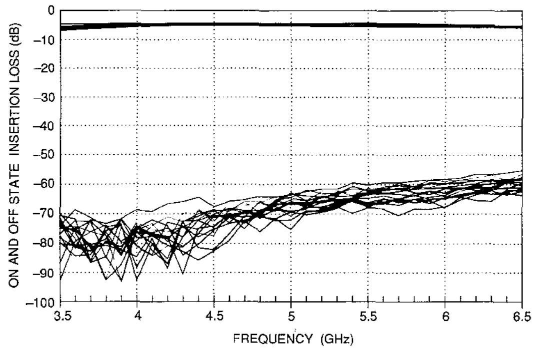

Figure 6. Measured On-state and Off-state Transmission Loss for All Sixteen Paths of the 4 x 4 MSM

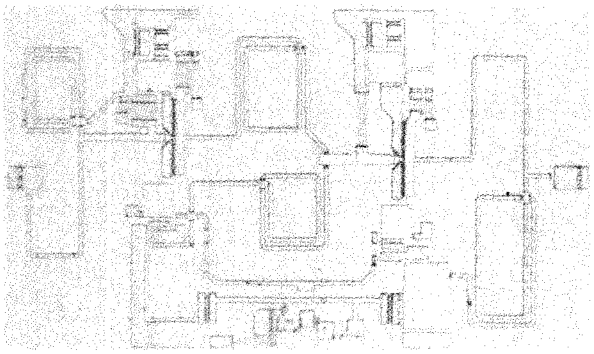

Figure 3. Two-Stage MMIC Dual-Gate FET Switch Element (Dimensions: 2.5 x 1.5 mm)

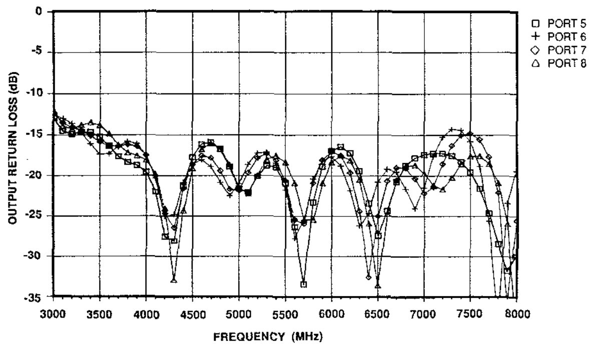

Figure 7. Output Return Loss of the MSM

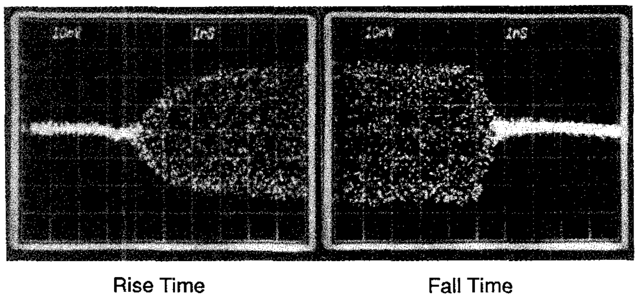

Figure 4. Rise- and Fall-times of the MMIC Switch Element

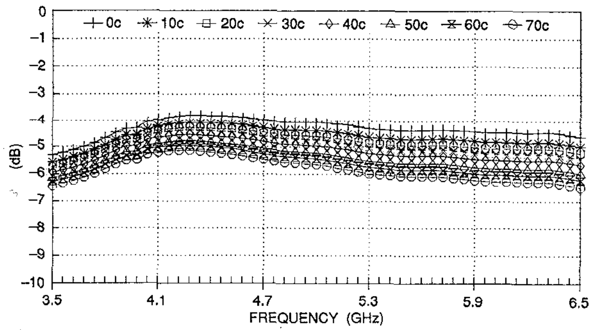

Figure 8. Insertion Loss of an MSM Path Over Different Temperatures