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Characterization of Two MMIC GaAs Switch Matrices at Microwave Frequencies

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CHARACTERIZATION OF TWO MMIC GaAs SWITCH MATRICES AT MICROWAVE FREQUENCIES

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ABSTRACT

Monolithic GaAs microwave switch matrices for use in satellite switched, time division multiple access (SS-TDMA) communication systems have been developed under contract* for the NASA Lewis Research Center, Cleveland, OH. Two monolithic GaAs MESFET switch matrices have been fabricated; one for switching operation at intermediate frequencies (IF), 3.5 - 6.0 GHz, and another for switching at radio frequencies (RF), 17.7 - 20.2 GHz. Key switch parameters have been measured for both switch matrices.

INTRODUCTION

NASA is actively involved in the 30/20 GHz market with the launch of the Advanced Communications Technology Satellite (ACTS) in 1992. Satellites similar to ACTS will require the use of a switch matrix to route time-division multiple access signals through a satellite transponder. As shown in figure 1, a switch matrix performs the synchronized routing of signals to and from several ground terminal destinations. A three-beam (A,B, and C) SS-TDMA network is illustrated. The on-board switch matrix is made up of rows and columns; when the crosspoint of one row and one column is activated, contact is made at the intersection. In figure 1, three different traffic patterns during time slots I, II, and III, and three switch states are shown in the lower right-hand corner. During time interval I, switch state I interconnects uplink beam A to downlink beam D, uplink beam B to downlink beam E, and uplink beam C to downlink beam F. Likewise, during time interval II, switch state II interconnects uplink beam A to downlink beam E, uplink beam B to downlink beam F, and uplink beam C to downlink beam D. The pattern will continue in this fashion to permit proper transmission of the data from uplink to downlink. Therefore, the high speed microwave switch matrix serves an important role in establishing efficient use of the SS-TDMA system.

Previous microwave switch matrix architectures have relied on mechanical, PIN diode, ferrite, and/or hybrid microwave integrated circuit (MIC) approaches. These approaches have been employed in various applications, such as automated test equipment, telemetry, and electronic countermeasures systems. For smaller switch matrix configurations, mechanical switches have been used and have proven to be very reliable. Of course, as the size of the matrix increases to 4-input by 4-output (4x4) or more, the matrix becomes increasingly complex. PIN diode approaches have reduced the size and have increased the speed, but problems still exist when assembling these switches to obtain the needed electrical performance. Monolithic microwave integrated circuits (MMICs) are now making a strong impact in the microwave and millimeter-wave switching market. Reliability, low cost, and size and power savings are some of the benefits gained by using an MMIC approach. In space applications, where weight and power are at a premium, the MMIC switch matrix has its advantages. The MMIC switch matrix designs are favorable for their low power consumption and reduced size and weight. Low cost can be expected for volume production of these MMIC switch matrix chips. NASA Lewis has developed two 3x3 MMIC switch matrices under contract for use in satellite communication systems. The IF switch matrix contract was completed in July 1987 and the RF switch matrix contract concluded in October 1988. The test results of measurements performed on these devices are presented.

MONOLITHIC IF SWITCH MATRIX

An approach was taken to develop state-of-the-art MMIC switch matrix technology which could equal or better the performance of hybrid MIC switch matrices from previous Lewis hardware development programs. An improvement over these switch matrices was addressed and a monolithic implementation of

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* This work is based on devices developed by Microwave Monolithics, Inc., Simi Valley, CA. under SBIR contracts NAS3-24252, NAS3-24895 for the NASA Lewis Research Center, Cleveland, OH.

the IF switch matrix was initiated. Theoretical predictions of switching FET performance was calculated using computer models and the designs were based upon these results. A modular design concept was introduced to allow the capability of forming larger switch matrix arrays from smaller individual switch matrix "building blocks". This "building block" approach is very common in the MMIC field, where cell libraries are often established to form a variety of products from a subset of working MMIC devices. Table 1 lists the key performance goals of the switch matrix program.

The 3x3 monolithic IF switch matrix (IFSM) was composed of nine individual crosspoints arranged in a matrix configuration. These individual crosspoints contain a number of switching GaAs MESFETs; each FET having a gate length of 1.5 microns. This gate length was chosen primarily to help increase the overall yield of the chips without sacrificing performance. The crosspoint area measured about 1.2 square millimeters. The total gate periphery of 36 millimeters is distributed between 144 FETs. The total chip size is 24.01 square millimeters, which also includes area for packaging and assembly. The prototype engineering model switch matrix was packaged in a 2.1 X 2.1 X 0.4 inch fixture, the size of which was determined by the minimum spacing required between the SMA connectors. The chip itself is much smaller than the test package, as seen in the photograph of figure 2. A key characteristic of the monolithic switch matrix approach is the high density of FETs restricted in a small area, while maintaining a high isolation requirement. Microstrip feed lines were employed for the RF and DC bias lines. The DC power and control lines were bonded to a bias board and connected to the switch matrix package with ribbon cables. The switch architecture used is a blocking type. This means that if one crosspoint is closed to connect an input port to a certain output port, no connection will be permitted from this input to any other outputs as long as the crosspoint remains closed.

MONOLITHIC RF SWITCH MATRIX

The development of a monolithic switch matrix operating at 20 GHz was addressed and it was determined that this device could possibly reduce spacecraft complexity by the elimination of one level of frequency conversion. Present 30/20 GHz satellite configurations, such as ACTS, will transmit uplink signals to the satellite at 30 GHz, where the satellite receiver will downconvert the signal to a 3 - 4 GHz IF band. The satellite switching would occur at the intermediate frequencies. The routed signal would then be upconverted back to 20 GHz where high power amplification occurs for downlink transmission. With the development of an RF switch matrix, signal routing may be accomplished at the 20 GHz band and eliminate the IF switching, while also reducing the IF signal processing required on the satellite.

The monolithic RF switch matrix (RFSM) design was aided greatly by the development of the IF switch matrix. The crosspoint used the basic FET structure as the IF switch matrix, but was operated in a resonant configuration to improve the isolation requirements at 20 GHz. The RF switch matrix also utilized the same test package developed under the IF switch matrix program, though several improvements were required to accomodate the higher frequencies. The addition of fully shielded microcoaxial transmission lines for the RF feed network aided in maintaining the high isolation requirements. The size of the 3x3 chip remained the same and much of the specifications and design goals were the same. However, the gate width of the switching FET was decreased to 200 microns to accomodate the resonator necessary for acceptable isolation. This decrease in gate width also increased the insertion loss, but helped the bandwidth for full coverage of 17.7 - 20.2 GHz. To obtain the zero insertion loss feature of the matrix, it was necessary to fabricate a set of buffer amplifiers, placed around the periphery of the chip. Under the assumption that each individual crosspoint is the same, a fixed gain amplifier can be placed for each path such that the insertion loss is zero throughout the array. Within the time frame of the contract however, amplifier devices were unable to be included on the same mask set due to the 0.7 micron gate lengths required and the additional problem of chip yield. Therefore, separate chips were built and packaged in single housings to provide the buffer amplification. Single or dual stage amplifiers were required dependent on the amount of gain required. A total of six amplifiers were built for the input/output of the RF switch matrix.

SWITCH MATRIX CHARACTERIZATION

A number of tests were conducted on the Hewlett-Packard 8510B automatic network analyzer to characterize both the IF and RF switch matrices. The rf tests performed included insertion loss/gain, isolation, group delay and SWR, among others. For clarity, definitions of the measured parameters are given below.

Insertion loss is defined as the power lost from transmission through the switch path, or the net power loss at the output port compared to the input port, with the switch crosspoint closed, or "on". Mismatch loss is included as part of the total insertion loss.

$$\text{INSERTION LOSS (dB)} = P_{out/on} - P_{in}$$

Isolation is defined here as the amount to which the switch matrix can reject an undesirable input. Isolation measurements are made by inserting a signal at a given input port and measuring the output level (dB) with the switch crosspoint open, or "off", for the signal path under test. All other switch crosspoints are in the open state during this measurement.

$$\text{ISOLATION (dB)} = P_{out/off} - P_{in}$$

On/off ratio in this context will be defined as:

$$\text{ON/OFF RATIO (dB)} = P_{out/on} - P_{out/off}$$

= Insertion Loss - Isolation

Group delay is the measurement of signal transit time through a device. It is defined as the derivative of the phase characteristic with respect to frequency:

$$\text{GROUP DELAY (sec)} = t_g = -d\phi/d\omega$$

This derivative is basically the instantaneous slope (rate of change of phase with respect to frequency), therefore a perfectly linear phase shift will result in a constant slope, or a constant group delay. The phase characteristic consists of both linear and higher order components. The linear component is attributed to the electrical length of the device and represents the average transit time, or the time required for a signal to pass through a circuit. Thus, if there were no amplitude distortion and $d\phi/d\omega$ is constant across the frequency band of the signal, the output signal would be an exact replica of the input, but displaced in time by t_g seconds. The higher order components of the signal are variations in the transit time for different frequencies and represents a source of signal distortion.

Return loss (RL) and standing wave ratio (SWR) are basic reflection measurements of the impedance match present at the ports of the device. From transmission line theory, a signal applied to a uniform, lossless line terminated in an impedance other than its characteristic impedance will produce both an incident and reflected traveling wave. These two traveling waves will interfere, producing a stationary standing wave along the transmission line. The equations for return loss and SWR are

$$\text{RETURN LOSS (dB)} = -20 \log \rho$$

$$\text{SWR} = (1+\rho)/(1-\rho)$$

where ρ is the magnitude of the reflection coefficient,

$$\rho = |E_{reflected}/E_{incident}|$$

For the switch matrix, the system impedance was kept at 50 ohms. The interconnection lines were of a higher impedance, resulting in an inductance which tuned out the parasitic capacitances associated with the switching elements. This technique allowed for a flatter insertion loss across the frequency band.

TEST RESULTS

For all of the network analyzer tests, a continuous-wave (cw) signal, with a power level of 0 dBm, was provided to each switch matrix. The tests were performed over 3.0 - 6.5 GHz for the IF switch matrix; 17.7 - 20.2 GHz for the RF switch matrix. Network analyzer measurements have been summarized at midband for both of the switch matrices tested. Test package losses are included in these measurements, since these losses could not be deembedded from the chip measurements during the network analyzer tests. To describe each path of the 3x3 switch matrix tested, a numbering of the ports is defined and is shown in figure 3. Note that for the 3x3 matrix, a different number of crosspoints are traversed dependent upon the path taken. For example, to connect input 3 to output A, only one crosspoint is used; likewise, to connect input 1 to output C, five crosspoints are traversed. Therefore, the total response will be dependent on each individual crosspoint response in the path. Selected crosspoints were tested for the IFSM and for the RFSM with and without buffer amplifiers. Insertion loss, isolation, on-off ratio, group delay and input SWR are given for the IFSM at midband, 4.75 GHz, in Table 2. Table 3 summarizes the amplitude variation for insertion loss and isolation over a 3.5 GHz bandwidth for the IFSM. Table 4 provides a summary of the measured test results for the RFSM at midband, 18.95 GHz. Table 5 lists the pertinent network analyzer results for the RFSM with added buffer amplifiers. Several other limited tests performed included 1-dB compression point and generation of 3rd-order intermodulation products.

The insertion loss was measured over the bandwidth goals for each switch matrix. Recall that the insertion loss for each switch path is related to the number of total switch crosspoints traversed from input to output. Figures 4a-7a show a representative sample of the insertion loss (s21) response for the IFSM and RFSM. The insertion loss tended to increase (up to 3 dB) as the upper edge of the bands were approached for most of the cases tested. The input/output buffer amplifiers for the RFSM crosspoint 3A provided a gain which varied from 7.6 dB to 12.2 dB throughout the band as shown in figure 6a. In this case, a constant gain of 7.5 dB would have been required to obtain the 0 dB insertion loss performance goal. Uniformity of the individual switch crosspoint losses will be necessary to achieve a 0 dB switch matrix. Mean crosspoint insertion loss for the IFSM was 4.15 dB at 4.75 GHz. Average amplitude variation over 3.5 to 6.0 GHz was 5.1 dB. The mean crosspoint insertion loss for the RFSM (without buffer amplifiers) was 4.21 dB at 18.75 GHz. Average amplitude variation (without buffer amplifiers) over 17.7 to 20.2 GHz was 2.7 dB.

Isolation responses for those crosspoints given above are shown in figures 4b-7b. Isolation in each path was generally better than 40 dB down across the full bandwidths of each switch matrix. For several single frequencies within band, the isolation was better than 60 dB. The isolation did not tend to be as good for the RF switch matrix as in the IF switch matrix, but this was expected due to the 20 GHz switching requirement. It is important to note that the addition of the buffer amplifiers to path 3A of the RFSM provided overall gain to the switch path, but the isolation also decreased by the same amount over the 2.5 GHz band. On/off ratio generally was unaffected by the addition of the amplifiers.

Group delay was typically below 1 nsec. for all frequencies for both the IF and RF switch matrices. A plot of the group delay for IFSM crosspoint 2A is shown in figure 8a. The values are about 0.5 - 0.6 nsec. over the band. Maximum peak-to-peak deviation over 3.0 - 6.5 GHz was 0.28 nsec. Figures 8b and 8c illustrates the group delay response for crosspoint 2A for the RFSM without and with buffer amplifiers, respectively. Without the buffer amplifiers, the group delay was about 0.3 - 0.4 nsec. over the 2.5 GHz band. Addition of the amplifiers increased the group delay to above 1.0 nsec. across the band. A narrow, negative group delay spike of nearly 1.5 nsec. was apparent at the upper edge of the frequency band for most of the RF switch matrix crosspoints. The cause of this distortion was unknown, however such spikes could have degrading effects on signal quality and should be eliminated if possible.

Input standing wave ratio was measured for the cases with the IF switch matrix crosspoint on and off. The SWR measured was better than 2:1 for the most IF crosspoints tested. The RF switch matrix exhibited some high SWR values for inputs 1,2 and 3 at 18.95 GHz, for the crosspoint both on and off. Better SWR values were measured for the top set of inputs (4,5,6) to the RFSM. The SWR for the RFSM ranged from 1.4 to 3.0 with the crosspoint on, and from 1.35 to 2.30 with the crosspoint off.

The input power handling of the IF switch matrix was performed on switch crosspoint 3A. A cw input signal was increased up to a level of +13 dBm with no sign of output power compression. The power level was not increased any further due to the risk of damaging the device. No change in on-off ratio was observed at the higher power levels. The switch matrix did not exhibit any change in performance when returned to lower input power levels. According to the contractor, the switch matrix should be able to handle up to +17 dBm before any power compression begins.

The 3rd order intermodulation (IM) products were measured for the IF switch matrix, crosspoint 3A. Figure 9 shows the results of the 3rd order IM tests. Two cw signals, f_1=4.725 GHz and f_2=4.775 GHz, spaced 50 MHz apart around the center frequency, were summed at the input to the switch matrix. The fundamental power level was set at 0 dBm. The third order intermodulation products formed at 4.675 GHz ($2f_1$-f_2) and 4.825 GHz ($2f_2$-f_1) were measured to be -66.0 dBm and -65.3 dBm, respectively. The 3rd-order intercept point was determined by graphical techniques to be approximately +32 dBm. This result is very encouraging and illustrates that the switch matrix should function well in applications such as frequency-division multiple access (FDMA), where multiple carriers are present and where channel spacing may be limited.

CONCLUSIONS

This new monolithic GaAs switch matrix technology will allow for the realization of advanced switching architectures for NASA programs, as well as provide for other communications systems applications. The development of a monolithic microwave switch matrix can significantly reduce the size, weight and power consumption of presently used switch matrices. Promising results have been obtained at both IF and RF, and should provide a firm basis for continuing advancement in MMIC switch matrix technology. Demonstration of a switch matrix with buffer amplification properly matched for each switch path has reinforced the idea that a zero insertion loss switch matrix is achievable. These results have indicated that further development of a 6x6 monolithic IF switch matrix subsystem (to be completed in 1991) will be a cornerstone in future switching applications.

ACKNOWLEDGEMENTS

The author would like to acknowledge the technical contributions of Dr. Daniel R. Ch'en, Dr. Wendell C. Petersen and the staff of Microwave Monolithics, Inc. for the development of the MMIC switch matrix devices and their support of this work. The author would also like to thank Mr. William D. Ivancic of NASA Lewis for the design of the switch matrix controller and his assistance throughout the testing phase.

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TABLE 1: KEY SWITCH MATRIX PERFORMANCE GOALS

SPECIFICATION	GOAL
Matrix Size	3x3
IF Band (GHz)	3.5 to 6.0
RF Band (GHz)	17.7 to 20.2
Crosspoint I.L (dB)	1.5
Crosspoint Isol. (dB)	60
Matrix I.L. w/ ampl. (dB)	0
Matrix Isolation (dB)	52
SWR	1.5
Input Signal Level (dBm)	0
Impedance (ohms)	50
Switch Configuration	Blocking

TABLE 2: SUMMARY OF ANA MEASUREMENTS FOR IFSM (f=4.75 GHz)

XPT PATH	INSERTION LOSS (dB)	ISOLATION (dB)	ON/OFF RATIO (dB)	GROUP DELAY (nsec)	INPUT SWR XPT on/off
1A	- 9.9	-39.5	29.6	0.32	1.65/1.45
1B	-13.4	-46.0	32.6	0.45	1.27/1.45
1C	-15.2	-57.0	41.8	0.27	1.55/1.45
2A	- 7.4	-46.4	39.0	0.38	1.40/1.06
2B	-10.9	-50.0	39.1	0.46	1.29/1.10
2C	-54.0	-49.3	**	3.00	1.49/1.06
3A	- 5.2	-36.8	31.6	0.41	2.12/1.54
3B	- 7.4	-52.5	45.1	0.38	1.75/1.54
3C	-25.0	-50.1	25.1	0.11	1.30/1.54
47	-10.2	-48.0	37.8	0.37	1.73/1.30
48	-21.8	-50.1	28.3	0.36	1.37/1.30
49	-16.6	-46.5	29.9	0.31	1.16/1.30

** Crosspoint path 2C inoperative.

TABLE 3: AMPLITUDE VARIATION FOR IFSM OVER 3.0 - 6.5 GHz

XPT PATH	INSERTION LOSS (dB)			ISOLATION (dB)		
	Min	Max	Δ	Min	Max	Δ
1A	- 8.9	-13.6	4.7	-34.5	-70.5	36.0
1B	-10.8	-15.8	5.0	-36.0	-63.5	27.5
1C	-13.8	-19.6	5.8	-39.0	-69.0	30.0
2A	- 7.1	-11.5	4.4	-38.8	-62.0	23.2
2B	- 8.9	-13.4	4.5	-38.2	-57.0	18.8
2C	-37.0	-67.0	30.0	-68.8	-66.0	27.2
3A	- 3.9	- 6.4	2.5	-35.5	-64.0	28.5
3B	- 6.6	-10.4	3.8	-34.0	-59.4	25.4
3C	-24.7	-32.0	7.3	-36.0	-70.0	34.0
47	- 9.3	-12.1	2.8	-40.9	-72.0	31.1
48	-20.6	-26.6	6.0	-48.0	-65.0	17.0
49	-15.0	-19.1	4.1	-44.0	-81.9	37.9
57	-30.5	-35.5	5.0	-42.0	-85.0	43.0
58	-37.5	-47.0	9.5	-44.0	-90.0	46.0
59	-32.8	-39.0	6.2	-41.0	-85.0	44.0
67	- 4.8	- 9.7	4.9	-38.0	-57.5	19.5
68	-22.6	-27.3	4.7	-35.6	-56.5	20.9
69	-50.0	-92.0	42.0	-44.0	-66.0	22.0

TABLE 4: SUMMARY OF ANA MEASUREMENTS FOR RFSM (f=18.95 GHz)

XPT PATH	INSERTION LOSS (dB)	ISOLATION (dB)	ON/OFF RATIO (dB)	GROUP DELAY (nsec)	INPUT SWR XPT on/off
1A	-13.5	-46.2	32.7	0.46	5.60/10.3
1B	-17.3	-41.0	23.7	0.30	9.81/10.2
1C	-36.6	-46.8	10.2	0.85	7.70/8.30
2A	- 8.8	-39.8	31.0	0.40	2.30/3.00
2B	-12.4	-41.3	28.9	0.44	3.50/3.10
2C	-16.2	-41.0	24.8	0.34	2.90/3.10
3A	- 7.9	-39.5	31.6	0.34	2.60/4.20
3B	-11.1	-37.0	25.9	0.28	5.00/4.20
3C	-15.0	-47.5	32.5	0.40	4.00/4.20
47	-11.3	-42.5	31.2	0.52	2.30/1.30
48	-13.9	-43.5	29.6	0.44	1.65/1.33
49	-17.2	-47.7	30.5	0.59	1.40/1.35
57	-10.0	-38.0	28.0	0.30	3.00/2.35
58	-12.1	-44.0	31.9	0.22	2.85/2.30
59	-15.0	-37.5	22.5	0.40	1.80/2.30
67	- 5.5	-39.2	33.7	0.37	2.15/1.70
68	- 8.0	-41.0	33.0	0.39	2.20/1.70
69	-11.0	-34.0	23.0	0.40	1.70/1.70

TABLE 5: SUMMARY OF ANA MEASUREMENTS FOR RFSM WITH BUFFER AMPS (f=18.95 GHz)

XPT PATH	INSERTION LOSS (dB)	ISOLATION (dB)	ON/OFF RATIO (dB)	GROUP DELAY (nsec)	INPUT SWR XPT on/off
1A	8.0	-22.5	30.5	1.63	4.32/4.30
1B	5.0	-21.0	26.0	1.55	4.30/4.32
1C	1.5	-26.5	28.0	1.58	3.30/4.30
2A	1.2	-30.8	32.0	1.25	3.60/3.60
2B	- 3.0	-33.0	30.0	1.15	3.65/3.60
2C	-13.0	-40.0	27.0	1.40	3.55/3.50
3A	4.0	-27.5	31.5	1.37	1.35/1.35
3B	- 1.5	-24.8	23.3	1.20	1.35/1.35
3C	- 1.2	-40.0	38.8	1.38	1.35/1.35

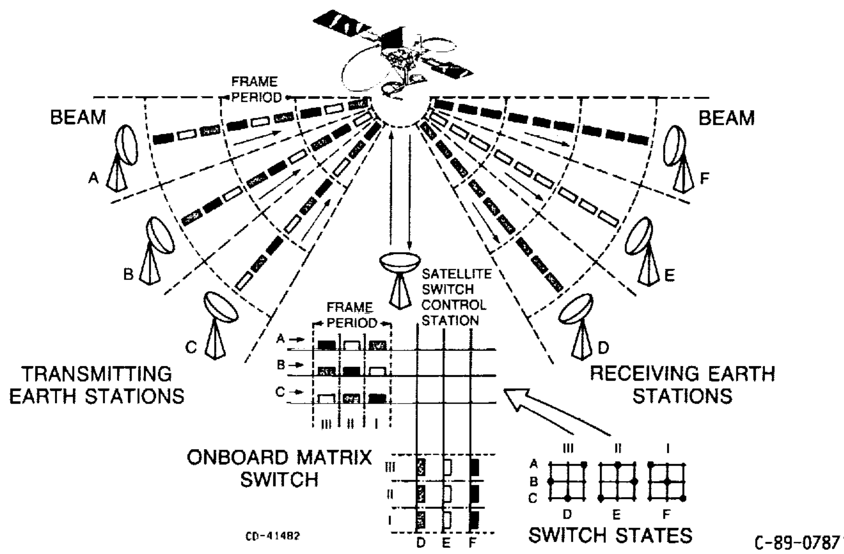

FIGURE 1. - SS-TDMA USING A MICROWAVE SWITCH MATRIX.

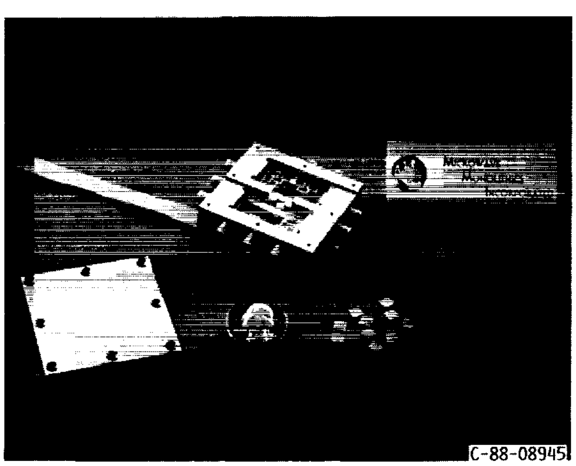

FIGURE 2. - PHOTOGRAPH OF TEST PACKAGE AND 3x3 SWITCH MATRIX CHIPS.

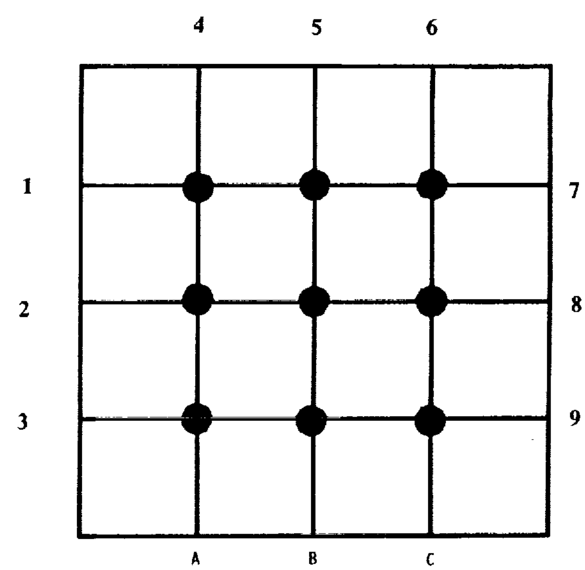

FIGURE 3. - NUMBERING OF INPUT/OUTPUT PORTS FOR 3x3 SWITCH MATRIX.

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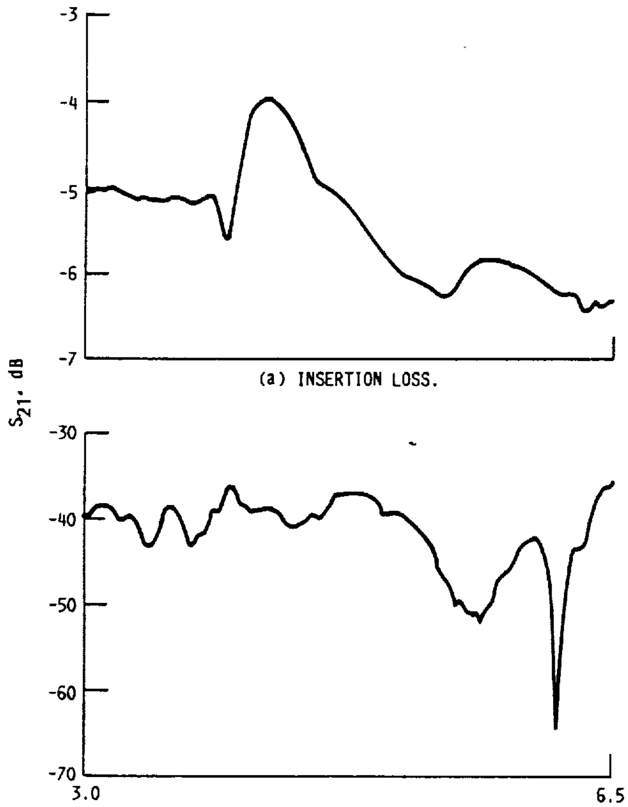
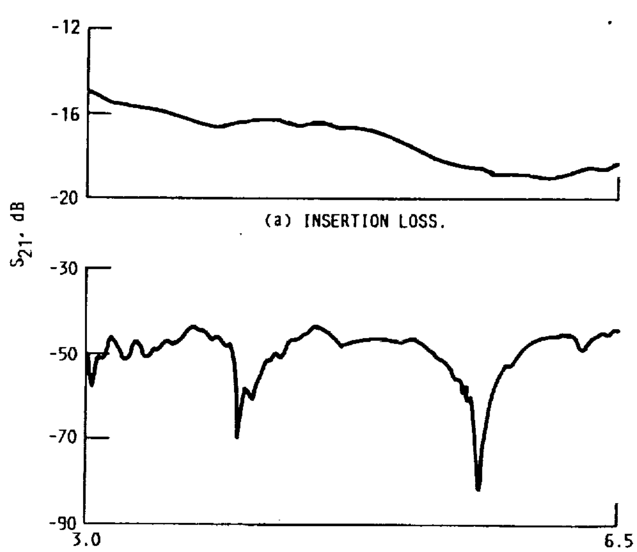
BLACK AND WHITE PHOTOGRAPH



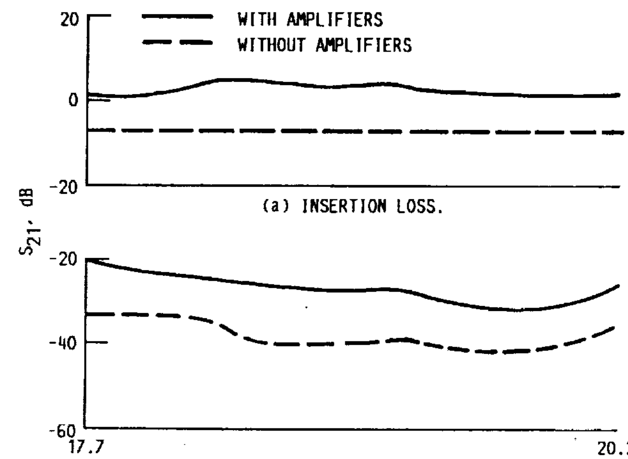
FREQUENCY, GHz
(b) ISOLATION.

FIGURE 4. - RESPONSE FOR IF SWITCH MATRIX, CROSSPOINT 3A.



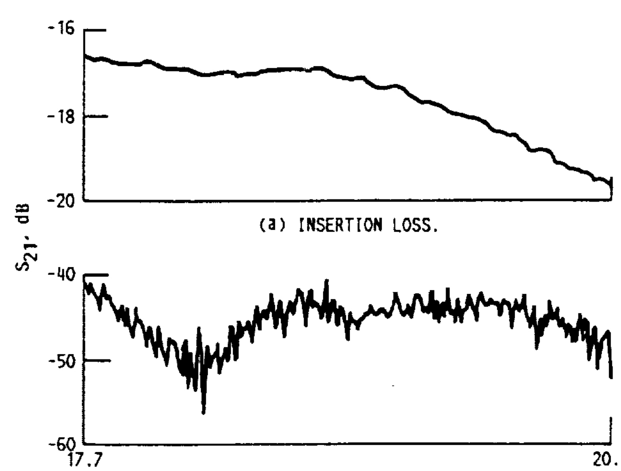
FREQUENCY, GHz
(b) ISOLATION.

FIGURE 5. - RESPONSE FOR IF SWITCH MATRIX, CROSSPOINT 49.



FREQUENCY, GHz
(b) ISOLATION.

FIGURE 6. - RESPONSE FOR IF SWITCH MATRIX, CROSSPOINT 3A.



FREQUENCY, GHz
(b) ISOLATION.

FIGURE 7. - RESPONSE FOR RF SWITCH MATRIX, CROSSPOINT 49.

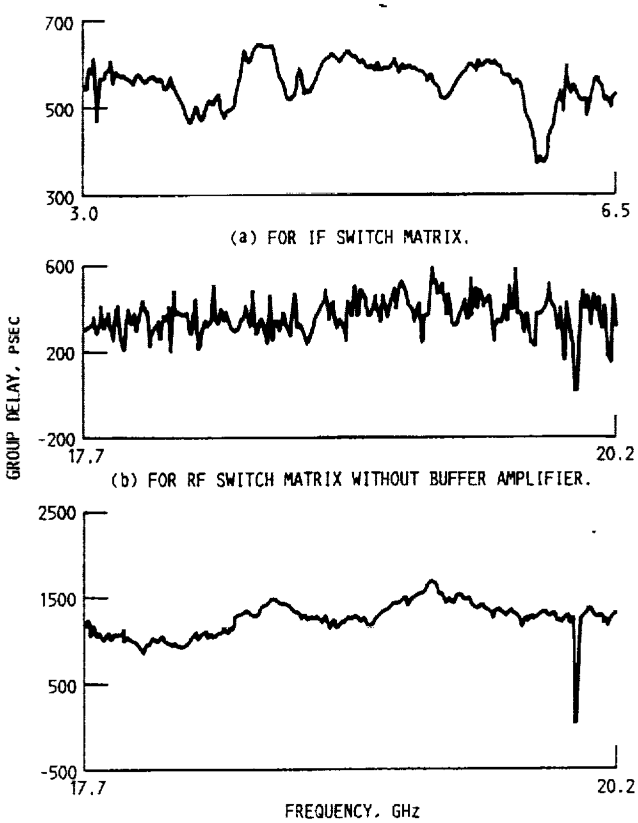


FIGURE 8. - GROUP DELAY RESPONSE. CROSSPOINT 2A.

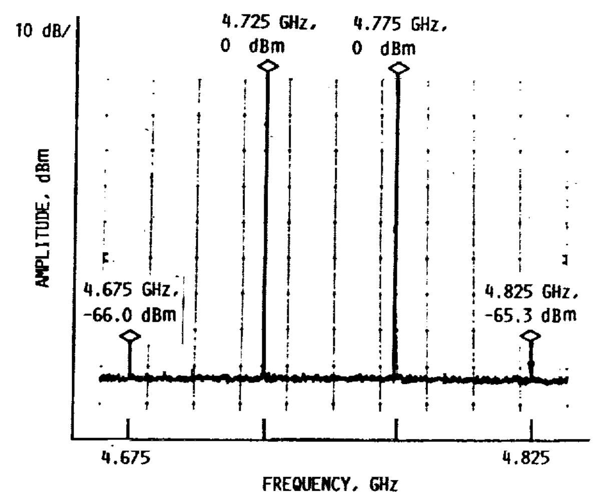


FIGURE 9. - THIRD ORDER IM PRODUCTS AT 4.675 GHz AND 4.825 GHz.

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Report Documentation Page

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16. Abstract

Monolithic GaAs microwave switch matrices for use in satellite switched, time division multiple access (SS-TDMA) communication systems have been developed under contract for the NASA Lewis Research Center, Cleveland, OH. Two monolithic GaAs MESFET switch matrices have been fabricated; one for switching operation at intermediate frequencies (IF), 3.5 to 6.0 GHz, and another for switching at radio frequencies (RF), 17.7 to 20.2 GHz. Key switch parameters have been measured for both switch matrices.

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