MMICs INSERTION IN A K_u-BAND ACTIVE PHASED ARRAY FOR COMMUNICATIONS SATELLITES*

J. R. Potukuchi, R. C. Mott, A. I. Zaghloul, R. K. Gupta, F. T. Assal, and R. M. Sorbello

COMSAT Laboratories, Clarksburg, MD 20871-9475

Abstract

Active elements consisting of 5-bit digital phase shifters, 5-bit digital attenuators, and amplifiers have been developed for insertion in a 64-element K_u-band active-transmit phased array antenna for communications satellite applications. To minimize the unit-to-unit amplitude and phase variations, the phase shifters, attenuators, and amplifiers have been implemented using MMIC technology.

In this paper, the performance characteristics of the 64 active elements integrated in the array, i.e., including the 64-way power distribution circuitry and the orthomode transducers are presented. Measured radiation patterns are also presented, and they show good agreement with the predictions.

INTRODUCTION

Future communications satellite systems may require the use of active phased arrays to achieve high capacity through frequency reuse with multiple spatially isolated narrow pencil beams. As narrow pencil beams focus the available power to produce higher effective isotropic radiated powers (e.i.r.p.s), communications via satellites with low-cost customer-premises earth stations are possible (1). This, in turn, reduces the overall service costs.

To demonstrate the feasibility of active phased array antennas for communication satellite applications, an active K_u-band, 64-element dual-polarized phased array antenna has been developed. The array performance has been successfully verified by producing a number of shaped and scanned beams and by comparing the measured antenna pattern and spatial isolation results with the predictions (2).

ACTIVE ANTENNA

A photograph of the 64-element active array and an active element is shown in Figure 1. A functional block diagram of the active element is shown in Figure 2. Each active element includes a 5-bit digital phase shifter and a 5-bit digital attenuator (for beam scanning, beam shaping and sidelobe control), amplifiers, a microstrip-to-waveguide transition, an orthomode transducer (OMT), a radiating horn, and element control circuitry with the required spacecraft interfaces.

The active antennas for broadband communications applications require a phase shifter in which the phase varies linearly with frequency (i.e., provide a constant group delay in the band of interest). For this application, a 5-bit phase shifter with a step size of 11.25° and a range of 360° at the band center (12.2 GHz) has been developed.

To shape the beam for the required coverage and to reduce the sidelobes to acceptable levels, an array taper is necessary. Therefore, a 5-bit digital attenuator with a 0.5-dB step size and 15.5-dB dynamic range has been included in each active element.

A buffer amplifier is inserted to provide isolation between the phase shifter and the attenuator. An MMIC driver amplifier is also included to provide compensation for the digital phase shifter and digital attenuator insertion losses, and appropriate power levels to a high-power amplifier.

Digital Phase Shifter

The 5-bit digital phase shifter design consists of 11.25°, 22.5°, 45°, 90°, and 180° bits in cascade, resulting in a 360° range and 11.25° resolution. Each phase-shift bit uses a pair of single-pole double throw (SPDT) switches to route the signal to either of the two paths, the reference path, or the phase shift path. The phase shift of a "bit" is given by the phase difference between these paths (3). To reduce the overall chip size, the phase shifts have been realized using low pass filters.

The statistical performances of the 64 phase shifters at 12.2 GHz are shown in Table 1 and Figure 3, respectively. Table 1 shows the mean

*This paper is based on work performed at COMSAT Laboratories under the joint sponsorship of the Communications Satellite Corporation and the International Telecommunications Satellite Organization (INTELSAT). Views expressed are not necessarily those of INTELSAT.

values and standard deviations for each of the five bits.

Table 1. Statistical Performance Parameters of 64 Phase Shifter Modules

Phase Expected (deg)	Mean Measured (deg)	Standard Deviation	Coefficient of Variation (SD/Mean)*100
11.25	10.4	0.48	4.6
22.5	20.9	0.65	3.1
45	45	0.87	1.9
90	90	1.1	1.2
180	200.2	2.46	1.2

Figure 3 presents a histogram of the measured characteristics of 64 phase shifters at 12.2 GHz. The abscissa shows several phase shifter performance windows around the mean for each bit, and the table displays the percent of phase shifters whose measured values are within those windows. Using the 90° bit as an example, the table indicates that the performance characteristics of 25-percent chips are within ±0.25° of the mean value of 90°, 45 percent are within ±0.5°, 81 percent are within ±1°, 94 percent are within ±2°, and 100 percent are within ±4°. The mean insertion loss and the standard deviation, in reference path, of the phase shifter at 12.2 GHz are 12.6 dB and 0.34 dB, respectively.

These results have been achieved during the very first phase shifter design and fabrication cycle. While the measured values of 11.25°, 22.5°, and 180° bits deviate from the expected values by approximately 10 percent, they show very good uniformity as evidenced by the low values of standard deviations and the coefficients of variation.

Digital Attenuator

The 5-bit digital attenuator consists of 0.5-, 1-, 2-, 4-, and 8-dB attenuation bits in cascade, resulting in 15.5-dB dynamic range and 0.5-dB step resolution. Each bit contains a reference path and an attenuation path (4).

The statistical performance of 64 attenuator chips are shown in Table 2 and Figure 4. Table 2 shows the measured mean values and standard deviation for each bit. Figure 4 presents a histogram of the measured characteristics of 64 attenuators. The abscissa shows several attenuator performance windows around the mean, and the table indicates the percent of attenuators whose measured values are within these windows. Using a 0.5-dB step as one example, it can be seen that 84 percent are within ±0.05 dB of the mean value of 0.55 dB, and 100 percent are within ±0.1 dB. The mean insertion loss and the standard deviation, in reference path, of the attenuator at 12.2 GHz are 9.6 dB and 0.35 dB, respectively. While the results presented above are at 12.2 GHz, the attenuator performance is very similar from DC to 13 GHz (4). These results have been achieved during the very first design and fabrication cycle.

The statistical results shown in Table 2 are for attenuators fabricated using chips from several locations in one wafer and chips from several wafers. Although the measured values deviate somewhat from the expected values, the low-standard deviation and coefficient of variation values show that the performance of all attenuators are very similar.

Table 2. Statistical Parameters of Digital Attenuators

Phase Expected (deg)	Mean Measured (deg)	Standard Deviation	Coefficient of Variation (SD/Mean)*100
0.5	0.55	0.05	9.0
1	1.2	0.07	5.8
2	2.2	0.09	4.1
4	3.8	0.11	2.9
8	7.1	0.12	1.7

Buffer and Driver Amplifiers

The driver amplifier has a nominal gain of 18 dB ±0.3 dB across 11.7 to 12.7 GHz. The buffer amplifier provides a minimum of 18-dB input and output return loss across 11.7 to 12.7 GHz and a gain of 4 dB.

Both amplifiers use self-bias and require only one bias voltage. Each circuit has bias adjustment capability through on-chip tapped resistors (5). The average gain and standard deviation of the 64 driver amplifier are 18.1 dB and 0.85 dB, respectively, and those of the buffer amplifier are 3.6 dB and 0.4 dB, respectively.

ACTIVE ELEMENTS

A photograph of an active element is shown in Figure 1. The measured responses in the reference state and 0.5-, 1-, 2-, 4-, and 8-dB attenuation states are shown in Figure 5 and those in 11.25°, 22.5°, 45°, 90°, and 180° phase states are provided in Figure 6.

The relative phase and amplitude variations of the 64 paths (including the 64-way power divider, an active circuit module, and an OMT) have been measured between the power divider input port and a probe inserted into the radiating horn. The normalized phase and amplitude variations of the active elements in the reference path are shown in Figure 7. Across the 11.7- to 12.7-GHz band, the phase and amplitude variations are within ±10° and ±1.5 dB, respectively.

ANTENNA PERFORMANCE

The radiation patterns of the antenna have been measured for a number of shaped beams and several scanned spot beams and were compared with computer predictions. Figure 8 shows one example of a measured azimuth cut for a shaped beam designed for low sidelobes (<-27 dB) at distances greater than 9° from the beam peak. As can be seen, the agreement between the measured and predicted patterns is very good. A detailed discussion of the calculated and measured antenna patterns can be found in a companion paper (2).

CONCLUSIONS

A 64-element K_u-band active phased array antenna has been developed for application in communications satellites. Antenna radiation pattern and spatial isolation measurements show good agreement with the predictions.

In order to minimize the performance variations among the array elements, the 5-bit digital phase shifter, the 5-bit digital attenuator, and the amplifiers have been realized using MMIC technology. This allowed the realization of 64 active modules whose amplitude and phase variations over 11.7 to 12.7 GHz are within ±1.5 dB and ±10°.

The successful development of this broadband active phased array has demonstrated maturity of MMIC technology and the feasibility of active arrays in future communications satellites.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of many colleagues at the Microwave Components, Microelectronics, and Spacecraft Technology Divisions of COMSAT Laboratories and the support of project managers at COMSAT World Systems and INTELSAT.

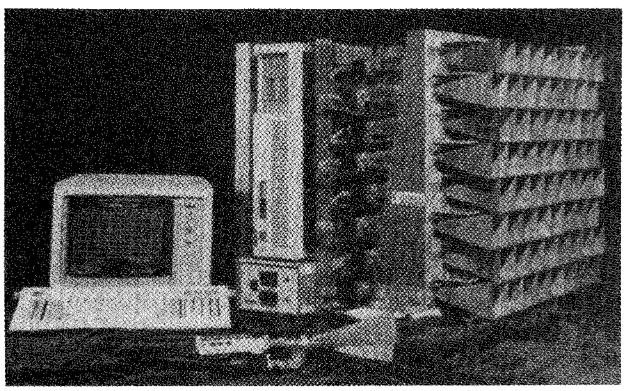


Figure 1. Active Array Photograph

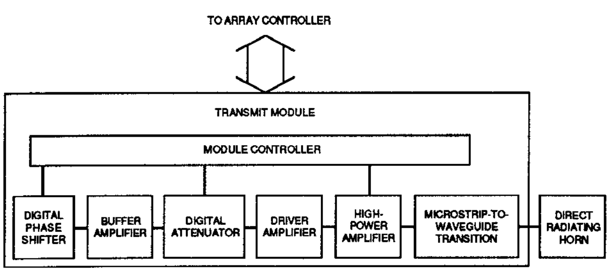


Figure 2. Active Element Functional Block Diagram and Photograph

REFERENCES

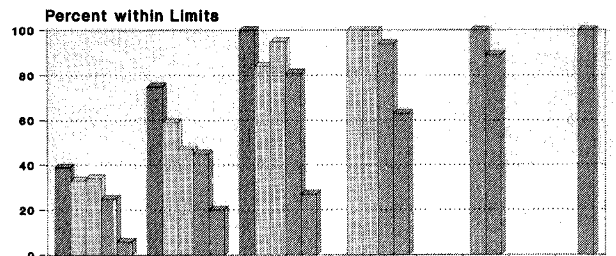
(1) F. T. Assal, A. I. Zaghloul, and R. M. Sorbello, "Multiple Spot-Beam Systems for Satellite Communications," AIAA International Communications Satellite Systems Conference, March 1988, pp. 322-331.

(2) A. I. Zaghloul, R. C. Mott, J. R. Potukuchi, F. T. Assal, and H. B. Williams, "Measurement/Prediction Comparison for K_u-Band MMIC Active Phased Array for Satellite Communications," IEEE AP-S Symposium Digest, May 1990.

(3) S. E. Gourley, S. Siddiqi, J. R. Potukuchi, F. T. Assal, R. K. Gupta, and R. C. Mott, "An Ultrabroadband Linear Phase Shift Module for Phased-Array Applications," SBMO International Microwave Symposium, Sao Paulo, Brazil, July 1989, pp. 53-58.

(4) R. K. Gupta, L. B. Holdeman, J. R. Potukuchi, B. D. Geller, and F. T. Assal, "A 0.05- to 14-GHz MMIC 5-bit Digital Attenuator," IEEE GaAs IC Symposium Digest, October 1987, pp. 231-234.

(5) R. C. Mott, J. R. Potukuchi, R. K. Gupta, A. I. Zaghloul, S. Siddiqi, and S. E. Gourley, "Monolithic Transmit Modules for a Multibeam K_u-Band Phased Array Antenna," 18th European Microwave Conference, Stockholm, Sweden, September 1988, pp. 759-763.

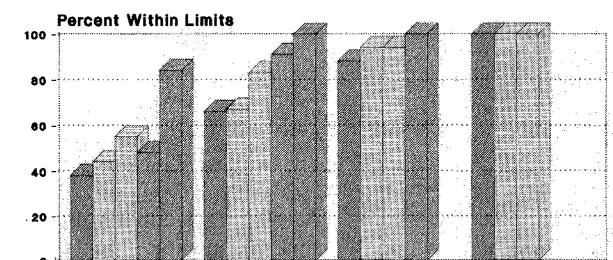


	+/- 0.25	+/- 0.5	+/- 1.0	+/- 2.0	+/- 4.0	+/- 5.0
11.25	39	75	100			
22.5	33	59	84	100		
45	34	47	95	100		
90	25	45	81	94	100	
180	6	20	27	63	89	100

Phase Limits (Deg)

11.25 22.5 45 90 180

Figure 3. Performance of 64 Phase Shifters



	+/- 0.05 dB	+/- 0.1 dB	+/- 0.2 dB	+/- 0.3 dB
8 dB	38	66	88	100
4 dB	44	67	94	100
2 dB	55	83	94	100
1 dB	48	91	100	
0.5 dB	84	100		

Attenuation Limits

8 dB 4 dB 2 dB 1 dB 0.5 dB

Figure 4. Performance of 64 Attenuators

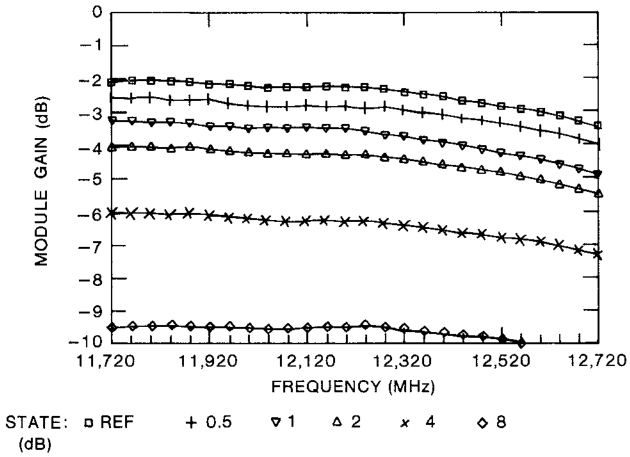


Figure 5. Active Element Performance in Reference, and Five Attenuation States

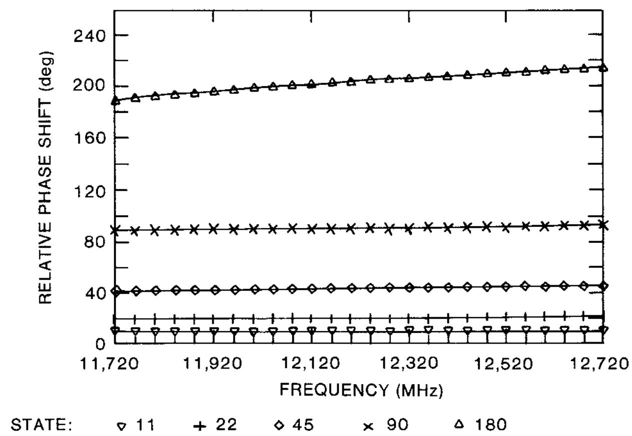
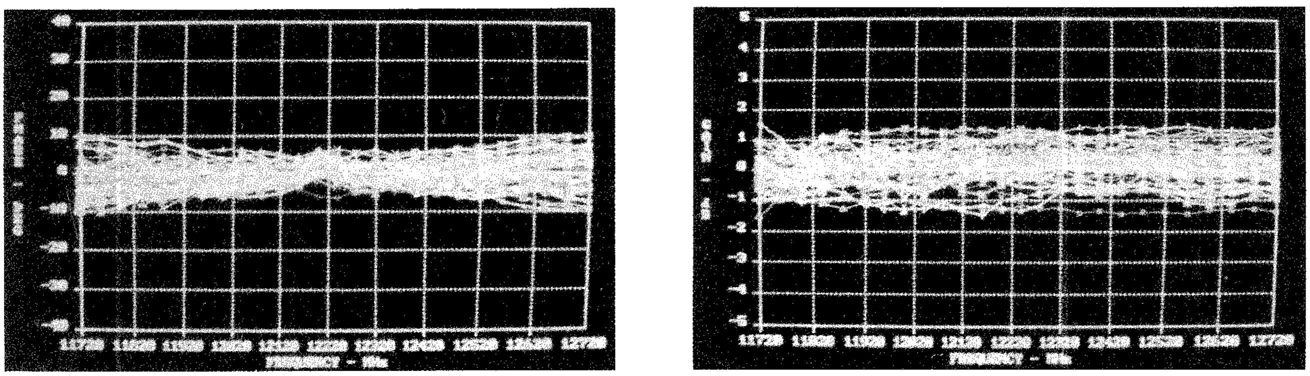


Figure 6. Active Element Performance in Five Phase Shift States



(a) Normalized Phase

(b) Normalized Amplitude

Figure 7. Normalized Phase and Amplitude Variation of 64 Active Elements

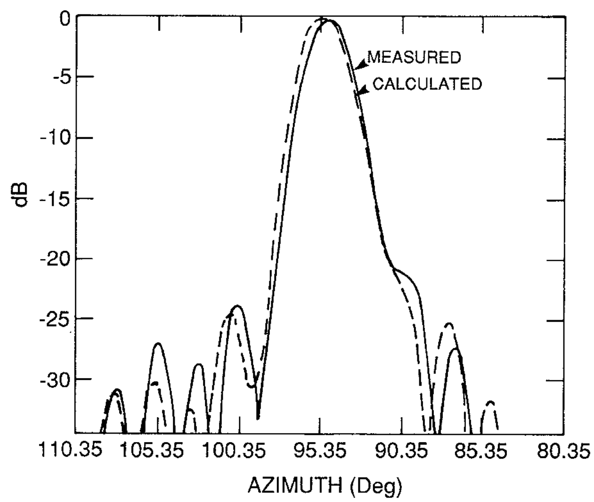


Figure 8. Measured and Calculated Antenna Cuts for a Shaped Beam