A C-BAND BEAM-FORMING MATRIX FOR PHASED-ARRAY ANTENNA APPLICATIONS

G. Estep, R. Gupta, T. Hampsch, M. Zaharovits, L. Pryor,
C. Chen, A. Zaghloul, and F. Assal

COMSAT Laboratories, Clarksburg, MD 20871-9475

ABSTRACT

A design description and measured performance of a modular beam-forming matrix (BFM) are presented. Advanced GaAs monolithic microwave integrated circuit (MMIC) phase shifter and attenuator designs ensure repeatable performance and small size. A novel BFM integration approach is used which ensures state-of-the-art performance, low mass, and high reliability, as well as low-risk/low-cost assembly. The 8 × 8 BFM shelf includes 192 GaAs MMICs, 200 silicon ICs, and 16 eight-way power dividers/combiners in an assembly measuring only 21 × 16 × 1.5 cm. While the design presented is for an eight-beam C-band phased array, the modular architecture easily accommodates other array configurations at different frequency bands with different numbers of beams and elements.

BACKGROUND

In recent years, communications satellites have required the use of high-gain antennas capable of producing multiple spot beams [1]. Active phased-array antennas offer an improved method for forming these beams by providing on-orbit reconfigurability and steerability and by conserving satellite DC power by sharing RF power among beams [2]. In addition, with the formation of narrow beams, higher equivalent isotropically radiated power (EIRP) can be achieved, making communication with small earth stations possible. A critical element in the realization of active phased-array antennas is the beam-forming matrix (BFM), which provides beam shaping and steering.

Over the past decade, COMSAT Laboratories has been developing phased-array antenna technologies to meet future satellite requirements [3],[4]. These efforts have resulted in the realization of single- and multiple-beam arrays.

A single-beam, low-power Ku-band transmit phased-array antenna using gallium arsenide (GaAs) monolithic microwave integrated circuit (MMIC) technology was successfully demonstrated at COMSAT in 1990. Subsequently, COMSAT Laboratories demonstrated a multibeam Ku-band high-power phased-array antenna capable of forming four simultaneous beams in a 24-element array. Use of modularity at the BFM shelf level was demonstrated during this effort. The BFM design described herein builds on the modular concept by reducing the shelf into several 1 × 8 BFM modules. These modules are further broken down into MMIC packages, each containing phase and gain control elements and the digital control associated with each crosspoint. This improvement in modularity translates into reduced manufacturing costs and increased design flexibility.

ARCHITECTURE

COMSAT Laboratories is currently developing an advanced C-band (3.625- to 4.2-GHz) array which requires an 8 (beam) by 69 (element) BFM. A standard crossbar approach, with phase and gain control provided at each crosspoint, was chosen for the BFM as shown in Figure 1. The modular design provides low mass, small size, high reliability, and superior performance. In addition, the BFM's modular architecture can be easily modified to accommodate arrays with more (or fewer) beams and elements.

The microwave circuit design approaches were selected for the phase and gain control elements that offered the smallest size, while still meeting the performance requirements. The control circuitry and mechanical packaging were designed in parallel with the microwave circuits to achieve very small size and provide for testability and repairability. These features ensure that the BFM could be manufactured to rigid performance specifications with low fabrication costs.

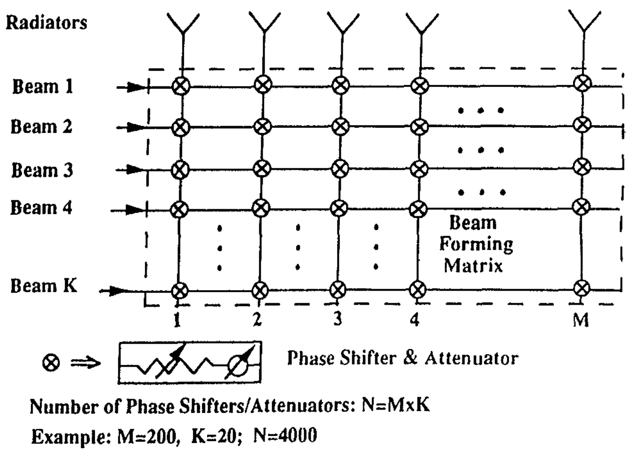

*Figure 1. General Crossbar BFM Configuration**

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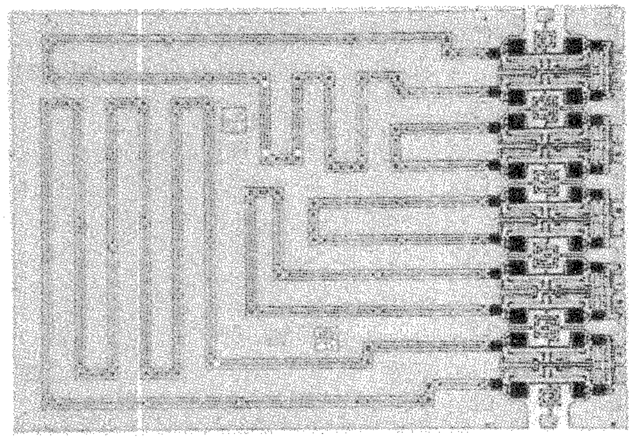

*Figure 2. 5-bit C-Band MMIC Phase Shifter (3.8 × 2.5 mm)**

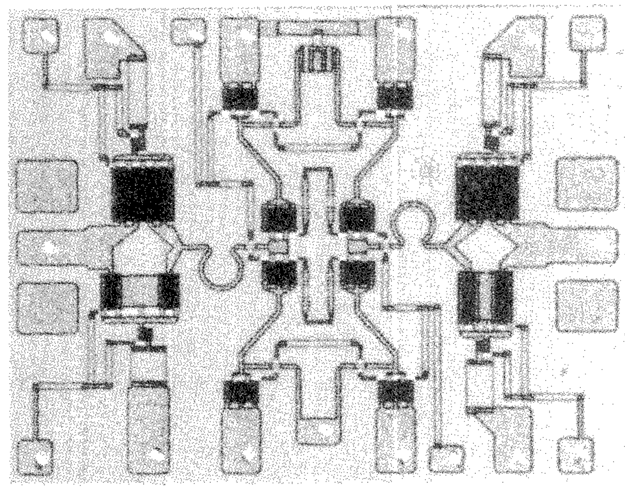

*Figure 3. 3-bit MMIC Attenuator (1.9 × 1.3 mm)**

MMIC CIRCUIT DESIGNS

BFM phase and gain control is realized using digitally controlled MMICs. Digital control was chosen to simplify the overall control architecture and allow for reduced unit-to-unit and temperature variations between circuits. The MMICs employ 0.5-μm gate length metal-semiconductor field-effect transistors (MESFETs) for repeatable, broad bandwidth performance at reasonable fabrication cost.

Phase Shifter

The 5-bit C-band MMIC phase shifter (Figure 2) is actually a switchable delay line. This circuit provides 360° of phase shift at 4 GHz, in 11.25° steps, and has very low insertion loss variation with phase state. MESFETs are arranged as double-pole double-throw (DPDT) switches to allow selection of either a reference or a delay path in each of the five bits. The delay circuits are implemented using coplanar waveguide (CPW) on the MMIC, to minimize overall chip dimensions [6]. The phase shifter MMIC includes on-wafer RF probing capabilities.

Attenuator

The attenuator is divided into two chips, one containing the 1-, 2-, and 4-dB bits, and the other containing the 8- and 16-dB bits. The attenuator design is similar to an existing COMSAT-patented design which incorporates MESFET DPDT switches in order to route the signal through either a reference or an attenuation path [7]. The new chip has been fabricated on a 90-μm-thick substrate with via-holes and includes on-wafer RF probing capabilities. The 3-bit attenuator is shown in Figure 3.

MMIC PACKAGING

A custom package was designed to provide an hermetically sealed environment for the MMIC control components. Digital control circuitry, which provides a serial interface, was included in this package to minimize the number of feedthroughs in the package. Each MMIC package contains all of the circuitry for one crosspoint: the 5-bit MMIC phase shifter, the 2- and 3-bit MMIC attenuators, three digital control ICs, and the microwave feedthrough to the opposite side of the BFM shelf. This rugged package is designed to allow complete DC and RF testing prior to insertion in the next level of BFM integration. Also, this package can be removed for easy replacement. Figure 4 shows details of the MMIC package design.

1 × 8 BFM MODULE

Eight MMIC packages are assembled, together with an eight-way power divider and digital control circuitry, to produce a completely testable and replaceable 1 × 8 BFM assembly (Figure 5). A carefully designed multistage Wilkinson divider was used to achieve an eight-way power split, with equal phase and amplitude performance, in only a 0.86-cm width [8]. The 8.6-cm-long circuit was fabricated on 10-mil alumina and includes thin-film load resistors.

8 × 8 BFM SHELF

By combining eight 1 × 8 modules with eight 8-way combiners, an 8 × 8 BFM shelf (Figure 6) is realized which measures 21 × 16 × 1.5 cm and has a total mass of 690 g. This shelf is a complete BFM for an eight-element, eight-beam phased array. For a practical array with a larger number of elements, the shelves are designed to be easily stacked and fed by eight multi-way power dividers. For instance, an eight-beam, 96-element array can be fed by a stack of 12 of the 8 × 8 BFM shelves. Eight 12-way power dividers are needed to complete the matrix.

(Originally published in a paper entitled "A Modular Beam-Forming Matrix for Active Phased-Array Antennas," by G. Estep et al., Copyright AIAA, 1993)

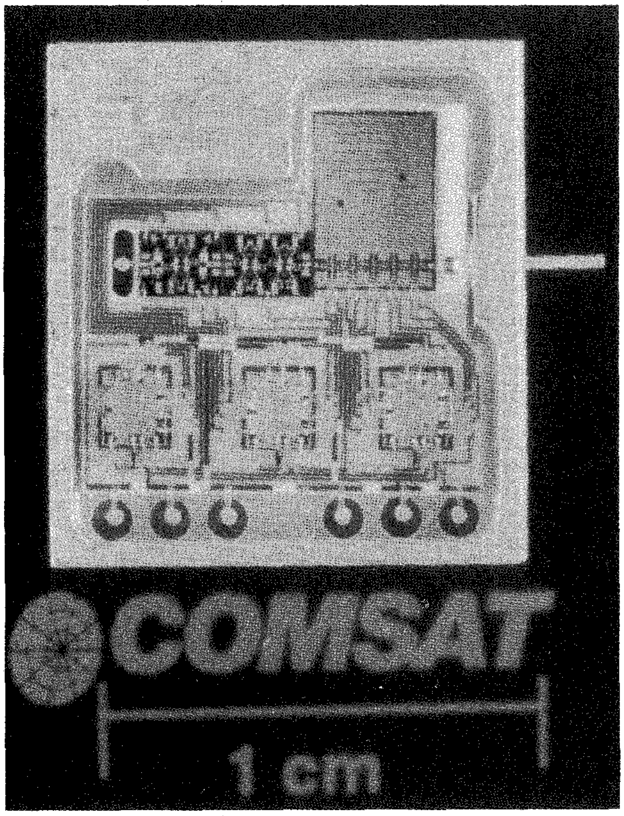

Figure 4. MMIC Package Detail

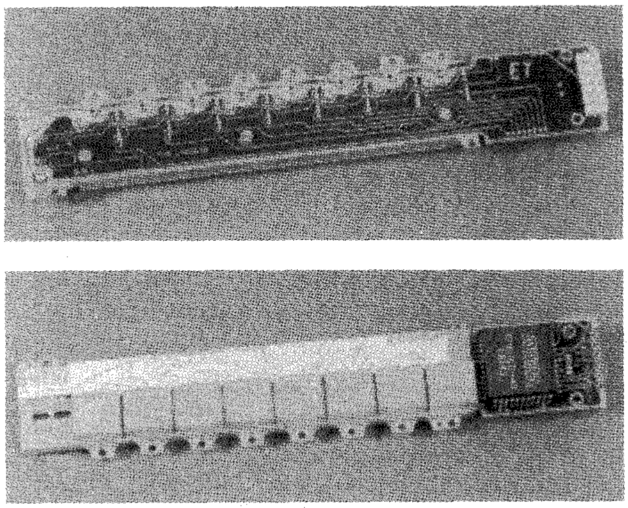

Figure 5. 1 × 8 BFM Assembly

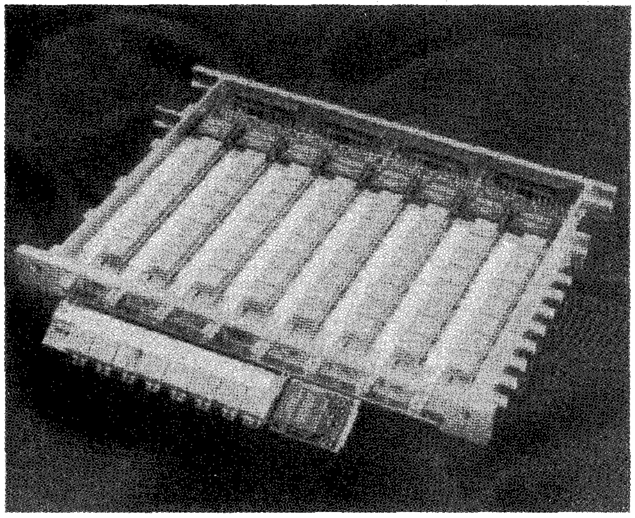

Figure 6. 8 × 8 BFM Shelf Detail

MEASURED RESULTS

The performance of each of the 64 paths of the 8 × 8 BFM shelf was measured and recorded with all bits set to reference state. Each path was also tested in 10 other states: five for the attenuator states and five for the phase shifter states. These tests provided full characterization of the BFM. Each MMIC package was subjected to additional amplitude and phase states at a lower level of assembly.

Figure 7 shows the amplitude and phase performance for all paths within a typical beam in the 8 × 8 shelf, and Figure 8 shows the measured insertion loss. The phase variation within each beam has been minimized. Measured results show ±3-dB phase variation for this beam.

SUMMARY

A novel BFM architecture which incorporates state-of-the-art MMIC designs in a unique modular architecture has been developed, fabricated, and tested. This approach provides high performance while offering the advantages of low mass and ease of manufacture. Details and measured results for an 8 × 8 BFM shelf at C-band demonstrate repeatable performance and the validity of the design and manufacturing approaches.

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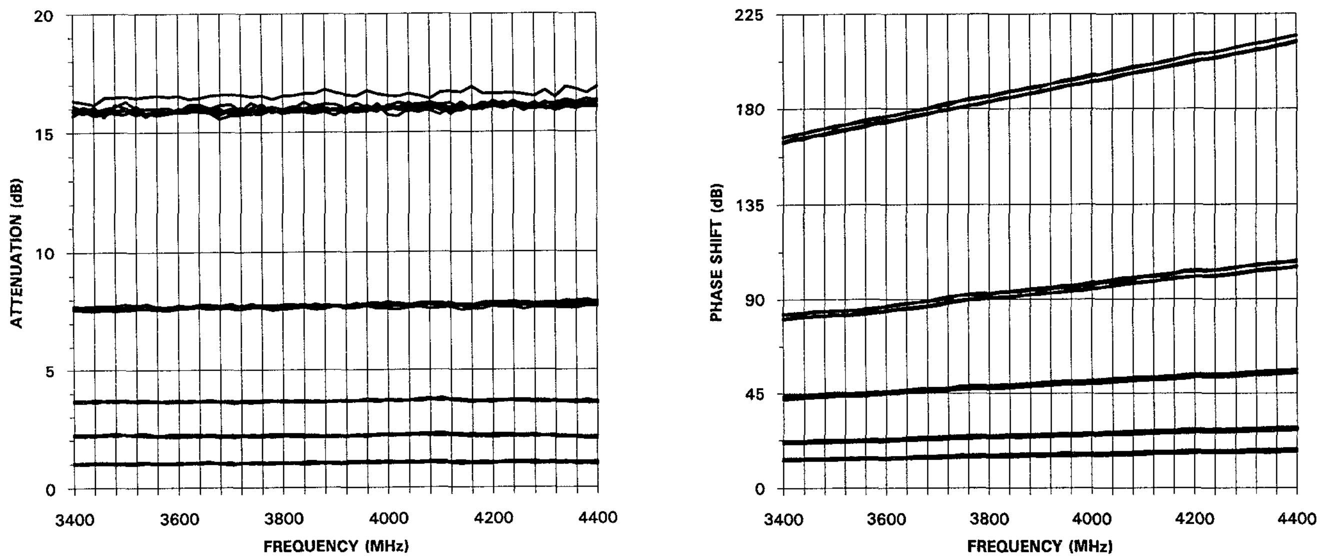

(a) Attenuation

(b) Phase Shift

Figure 7. Performance for Eight Paths Within a Single Beam (5 bits shown)

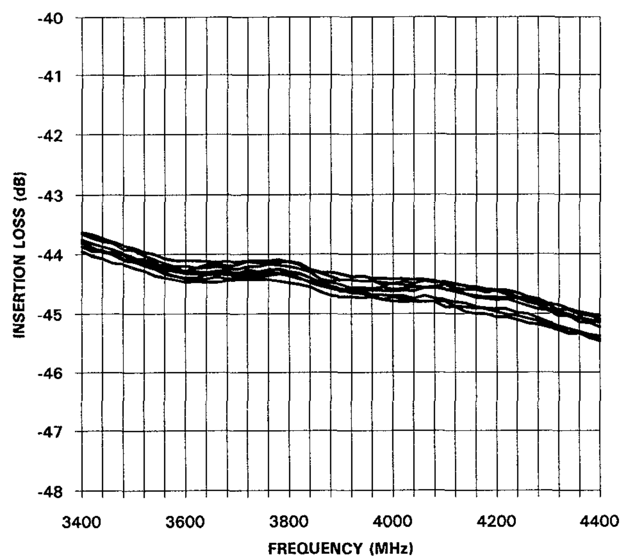

Figure 8. Measured Insertion Loss of 8 × 8 BFM Shelf for Eight Paths Within a Single Beam

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