AN ULTRA-BROAD-BAND PHASE SHIFTER IN GLASS-BASED INTEGRATED CIRCUITRY (GMIC)

Timothy A. Murphy*, John W. Gipprich, Marion E. Hines*, David Kryger*
*M/A-COM Inc., Burlington, MA 01803, Westinghouse Elec. Corp., Balt., MD 21203

SUMMARY

This paper describes the design principles used in the development of an integrated six-bit phase shifter for the band 6-18 GHz. It utilizes a new glass-dielectric microwave integration technique, GMIC, in which all non-semiconductor components are fabricated in-situ using photolithographic methods. It utilizes hybrid coupled reflection circuitry with PIN diode chips as switching elements.

INTRODUCTION

Modern phased-array technology involves the use of individual "modules", one for each of the large number of antenna elements of the array. Typically, each module incorporates a number of functional blocks, including transmitting and receiving amplifiers and various control functions. One of the most important of the control functions is a digitally controlled bi-directional phase shifter which provides precision control of insertion phase covering 360° as a means to steer the antenna beam. We report here specifically on the development of a six-bit, low loss phase shifter for the 6-18 GHz band, using M/A-COM's GMIC manufacturing technology.

Initial consideration of the design objectives indicated that this bandwidth would be attainable with hybrid-coupled switching circuitry using diodes or transistors. Conventional hybrid integration technology on quartz or ceramic substrates appeared to present excessive variabilities in assembly with the multiplicity of wire bonds required and their poorly understood parasitic network effects. M/A-COM's GMIC technology provided means to realize a low loss phase shifter covering the 6-18 GHz band using a repeatable, low cost, wafer-level, batch process manufacturing approach.

GMIC

GMIC is a new design and manufacturing technology for microwave circuits that has been developed by M/A-COM.[1] It provides a high level of repeatability, high performance, and low manufacturing costs. All of the passive circuitry is fabricated on a laminated substrate that incorporates a dielectric layer (glass) and a carrier layer (silicon). A gold film between the two layers carries the ground currents to minimize losses. Figure 1 is a cross section schetch illustrating some of the construction features of the GMIC technique.

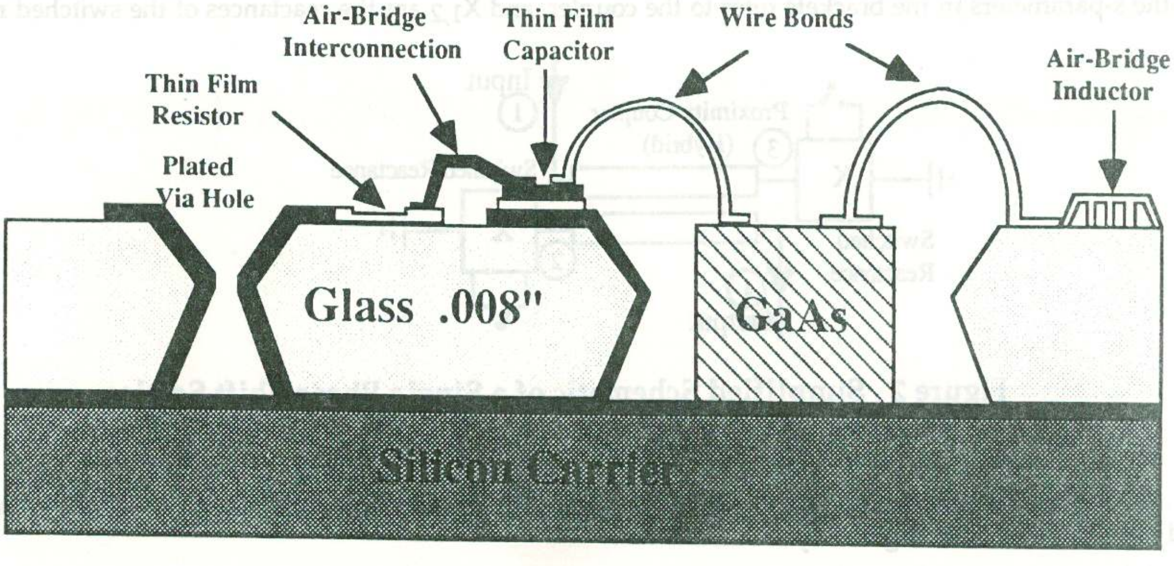

Figure 1 GMIC Cross Section

(Not to Scale)

Note the use of: MIM thin-film capacitors, thin film resistors, airbridge interconnects, airbridge spiral inductors, and via holes. The via holes, which are chemically etched, are used for contact to the ground plane from the top of the glass. The via holes also facilitate the mounting of semiconductor devices on the silicon carrier which serves as a good heat sink. The silicon is heavily doped for good electrical conductivity and provides the chassis ground.

Some of the advantages of GMIC are obvious while others are more subtle. Since all of the passive elements are batch processed, using semiconductor processing technology, there is a dramatic reduction in the number of piece parts needed and assembly time is greatly reduced. Furthermore, manufacturing variables are minimized leading to a highly reproducible, reliable product. Once the wafer has been produced, the subsequent assembly (insertion of semiconductor devices) can be conducted at the wafer level. Wire bonding, DC screening and RF test can be performed at the wafer level as well. These procedures are easily automated using GMIC. While GMIC is not unique in its use of these techniques, it is the only fabrication method to our knowledge that combines them on a low cost substrate with an integral carrier.

PHASE SHIFTER DESIGN

To meet our requirements for miniaturization, low power consumption, bandwidth, etc. we chose to use microstrip circuitry with GMIC planar fabrication technology. This involved Lange type hybrids with all non-semiconductor elements being formed in place by photolithographic means. Silicon PIN diode chips provided the switching elements. When reverse-biased, their capacitances were key elements in the design. When forward-biased they were treated as small resistors.

Figure 2 shows a highly simplified schematic sketch of a typical phase shift section. This involves a proximity "hybrid" directional coupler nominally with 3dB coupling. Ports 2 and 3 are connected to two identical switched networks which are ideally purely reactive in character. This is a well known class of phase shifter where the hybrid first splits the input wave into two equal parts. The reactive networks reflect the waves back into the hybrid, where they recombine at port 4. When the networks are switched from one state to the other the reflected waves are switched in phase, providing the desired function.[2],[3],[4] The transmission S-parameter for the total network is given by:

$$T_{41} = \frac{jX_{1,2} - Z_o}{jX_{1,2} + Z_o}\left[S_{21}S_{42} + S_{31}S_{43} \right] \qquad (1)$$

where the s-parameters in the brackets refer to the coupler, and $X_{1,2}$ are the reactances of the switched networks.

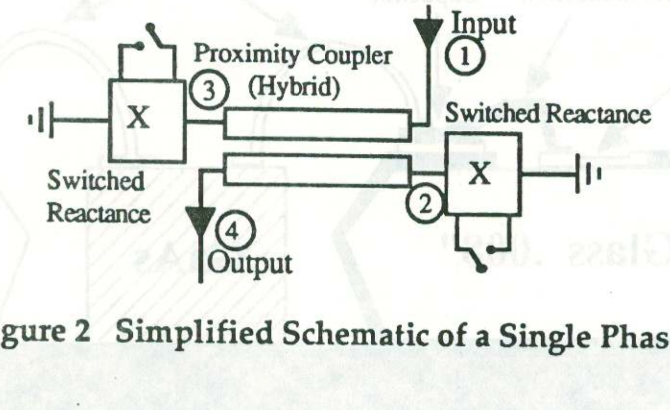

Figure 2 Simplified Schematic of a Single Phase Shift Section

In the ideal case of a lossless 90 degree hybrid and purely reactive networks with two different reactances X_1 and X_2, the phase shift is given by:

$$\Delta\theta = 2\tan^{-1}\frac{X_1}{Z_0} - 2\tan^{-1}\frac{X_2}{Z_0} \qquad (2)$$

For broad-band applications, it is commonly desired to have the phase shift be as independent of frequency as possible over the band of interest. A basic design approach, to provide a starting point, is to choose a network design for which the derivative of the phase shift is zero at the center of the band. In our ideal lossless case, the expression for the derivative is:

$$\frac{d(\Delta\theta)}{d\omega} = 2\,\frac{\frac{d}{d\omega}\left(\frac{X_1}{Z_0}\right)}{1+\left(\frac{X_1}{Z_0}\right)^2} - 2\,\frac{\frac{d}{d\omega}\left(\frac{X_2}{Z_0}\right)}{1+\left(\frac{X_2}{Z_0}\right)^2} \qquad (3)$$

Equations (1), (2), and (3) provide a preliminary set of design parameters for each section. This was followed by a more rigorous simulation analysis, and optimization, which included as many parasitic elements as we could justify, including stray capacitances, inductances and resistance values. Figure 3 shows the basic elements of the individual phase shifter sections, still somewhat idealized and simplified. It is representative of each section of the six-bit phase shifter.

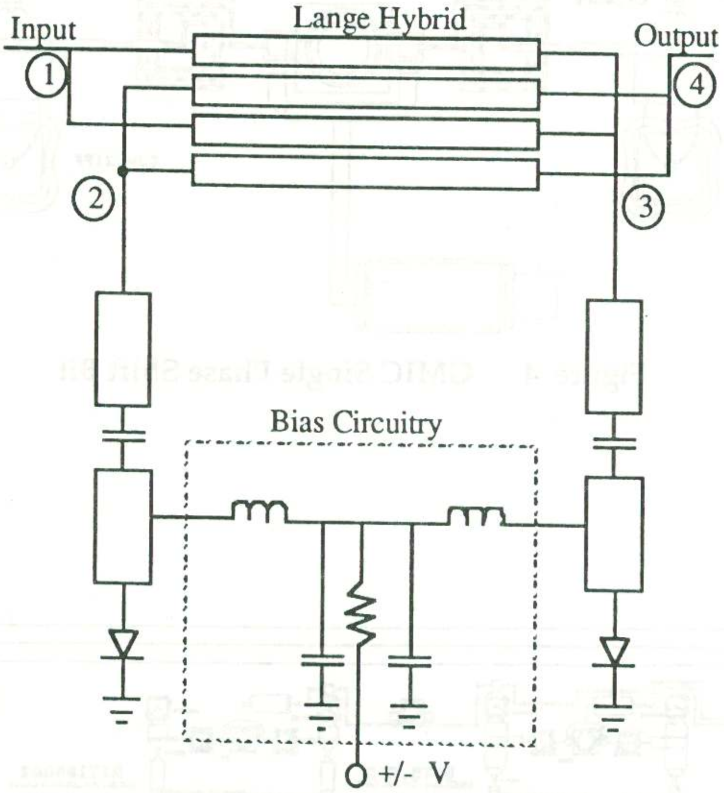

Figure 3 Schematic for a Single Section of the GMIC Phase Shifter

The GMIC layout of a single section of the phase shifter is shown in Figure 4. The entire six-bit phase shifter is shown in Figure 5.

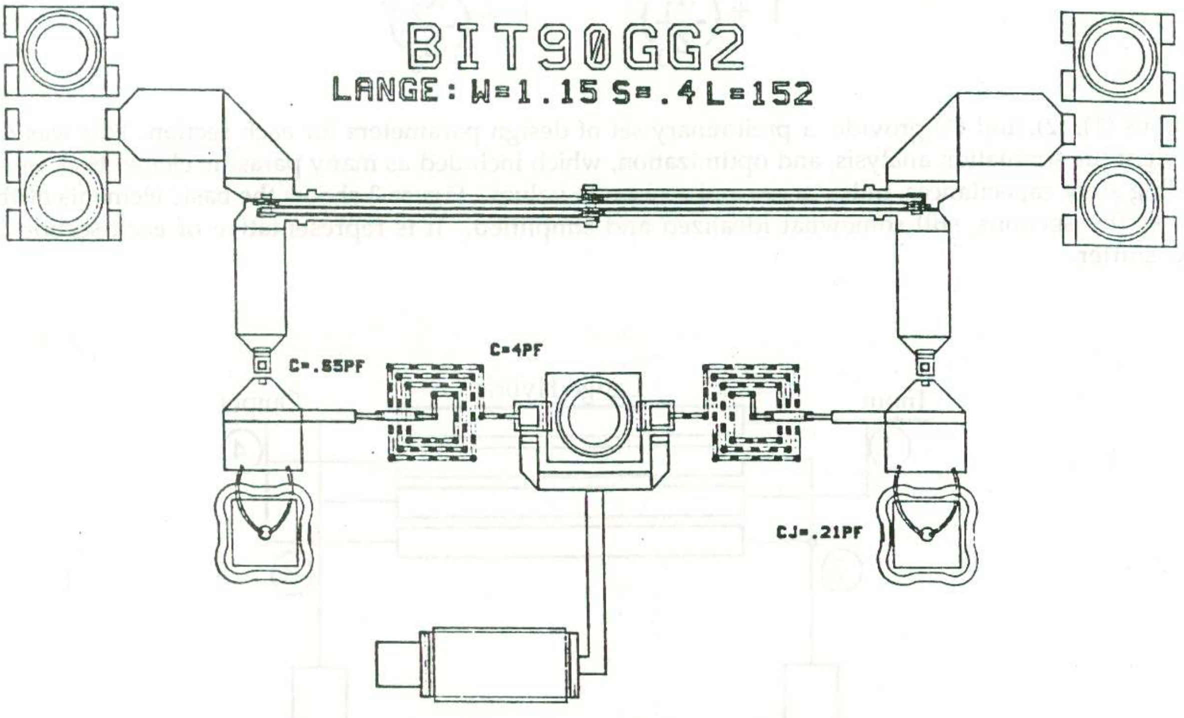

Figure 4 GMIC Single Phase Shift Bit

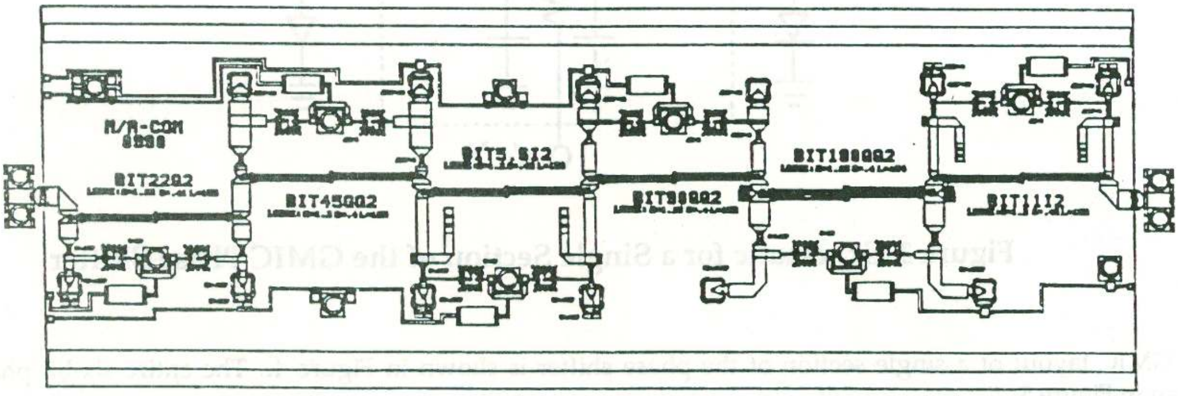

Figure 5 Six-Bit GMIC Phase Shifter (.967" x .325" x .025")

PERFORMANCE

In figures 6, 7 and 8, we show data for the entire phase shifter in 7 different states. In one state, all diodes are reverse biased. In the others, one section at a time is switched to forward bias. Testing was performed at the wafer level using coplanar waveguide probes on a fully automated test station. The .967 x .325 inch six-bit phase shifter yielded the following typical performance over the 6-18 GHz bandwidth: VSWR better than 2.3:1, an average insertion loss of about 3 dB at 6 GHz increasing to about 8 dB at 18 GHz, and a 3.5° RMS phase error. The measured performance agrees well with the simulated performance although there is a slight increase in insertion loss at the high end of the frequency band.

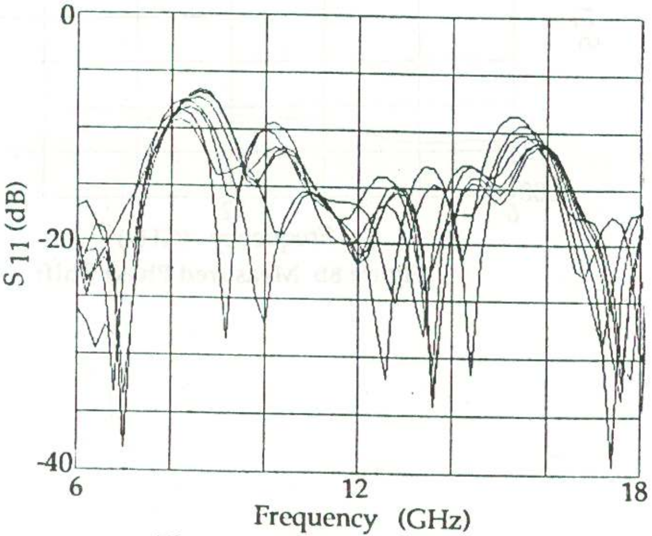

Figure 6a Simulated Return Loss

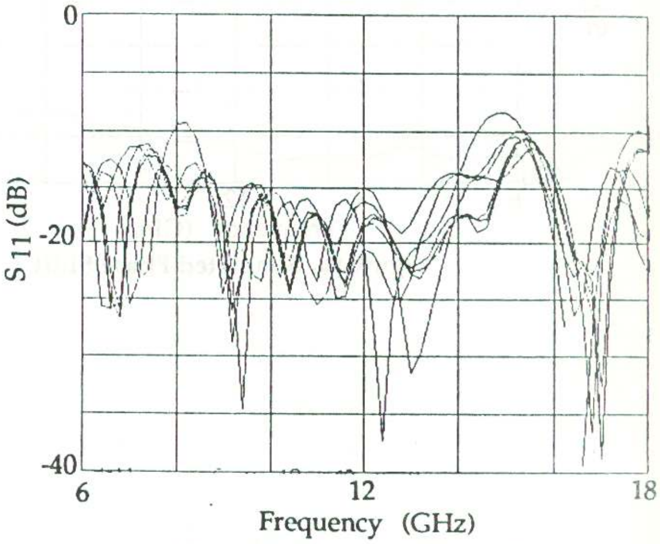

Figure 6b Measured Return Loss

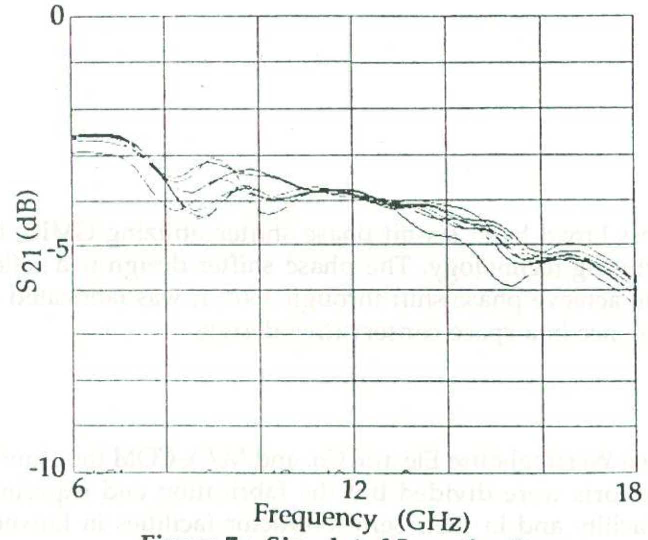

Figure 7a Simulated Insertion Loss

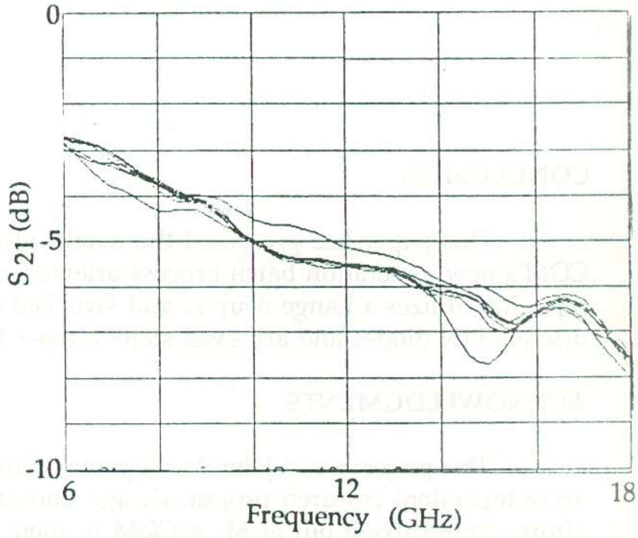

Figure 7b Measured Insertion Loss

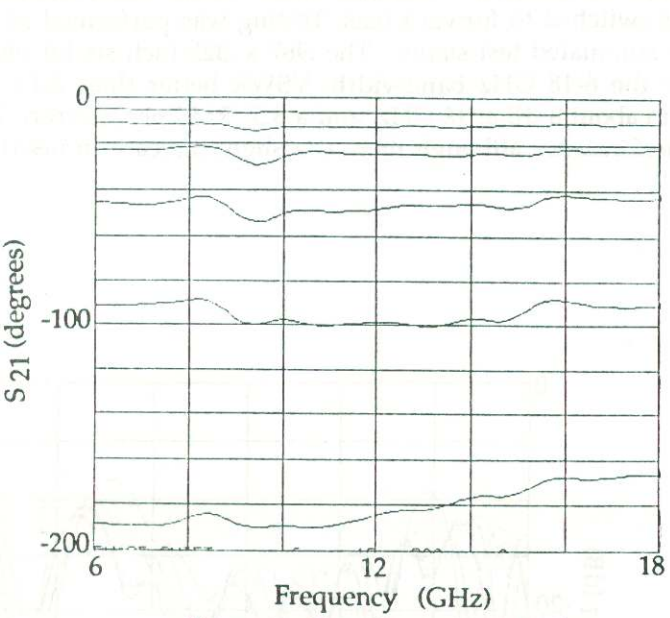

Figure 8a Simulated Phase Shift

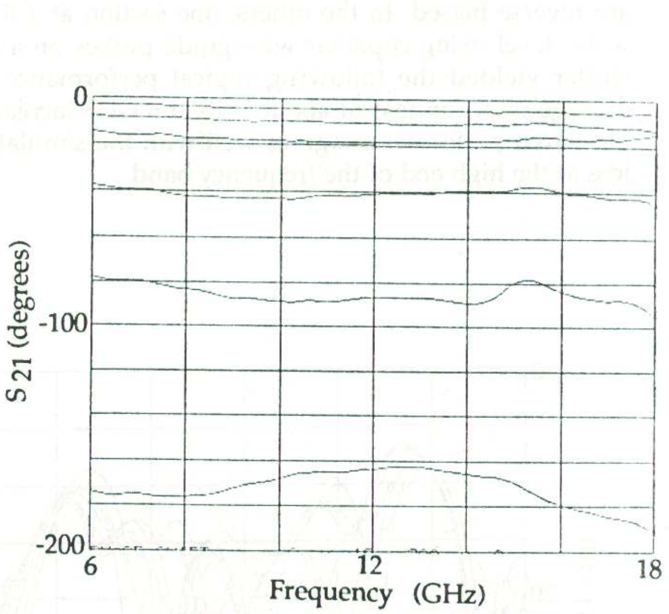

Figure 8b Measured Phase Shift

CONCLUSION

This paper has presented the results of a low loss broad band six-bit phase shifter utilizing GMIC, M/A-COM's new generation batch-process-oriented manufacturing technology. The phase shifter design is a reflective type that utilizes a Lange coupler and switched diodes to achieve phase shift through 360°. It was fabricated using discrete PIN diodes and achieved state-of-the-art performance in a space conservative design.

ACKNOWLEDGMENTS

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