A Compact Beamforming Matrix Module for Use in Multibeam Communication Satellites

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***Abstract* — A 16×4 beamformer has been designed, fabricated and tested. It provides 6 bits of phase shift and 8 bits of attenuation in 64 paths in a single multichip module (MCM) for use in multibeam antenna systems. It can be operated with 16 beams and 4 radiating elements or 4 beams and 16 radiating elements. The MCM is fabricated using the Lockheed Martin/GE high-density interconnect (HDI) technology to interconnect 16 multifunction MMICs and digital control circuits. The HDI technology is used to fabricate 42 Wilkinson dividers with greater than 40% bandwidth on the same layers as the RF stripline interconnects. The resulting beam former matrix module (BFMM) is approximately 63×41×1.3 mm (3.5 cm^3) and weighs 7 grams.**

I. Introduction

Modern multibeam solid state antenna systems require active phase shifters in each of the beam paths to steer the individual beams [1]. The number of phase shifters required increases in proportion to the number of beams. Each element of the array requires an individual phase shifter for each beam as well as a combining network to sum all of the individual beam signals to a single element input. The number of phase shifters is then $n \times m$ where n = the number of beams and m = the number of elements. A 32-beam communications satellite in geosynchronous orbit might have 1200 elements and require 32×1200 = 79,360 phase shifters. These phase-shift elements may be realized using GaAs MMICs or ferrite devices. The combining networks are realized using waveguide or stripline techniques. Typical hybrid and wave-guide construction of beamformers has resulted in large and heavy assemblies that are not suitable for space-based applications. The goal of this effort was to design and fabricate a small, low-mass beamformer that could be mass fabricated at low cost in high volume.

The Lockheed Martin/GE HDI process has demonstrated the ability to reduce the volume and mass of conventional T/R modules [2] compared to conventional hybrid chip and wire packaging technology. HDI provides a compact design while providing greater than 120 dB of isolation between individual adjacent RF lines. This isolation is achieved by the use of thin, low dielectric constant dielectric layers and multiple microvias that are used to provide and shield between lines. In addition, the HDI process can be extended to multiple layers to provide fully shielded RF cross-overs that maintain the high isolation of the BFMM while not adding extra mass. Integral thin film resistors are patterned with the RF interconnect to provide compact isolation resistors for the 42 Wilkinson combiners in the BFMM to further reduce the size and mass [3].

II. Device and Fabrication

Fig. 1 is a schematic representation of the RF connectivity of the BFMM described in this paper. It contains 16 beam inputs and 4 element outputs and requires 64 phase shifter,

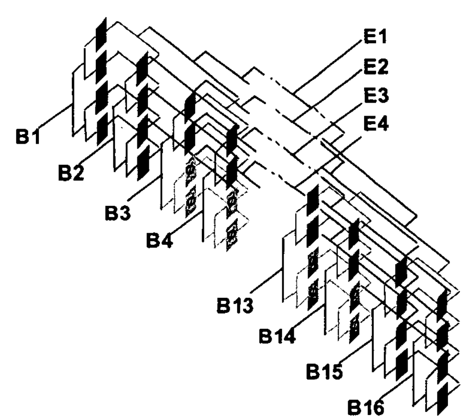

Fig. 1. Schematic representation of 16×4 BFMM showing connectivity of the MMICs and Wilkinson divider/combiners (64 phasors and 108 Wilkinsons required).

attenuator circuits to provide the proper beam steering and shaping. The circuit is fully reciprocal, and so it can also be operated with 4 beam inputs and 16 element outputs. Quad phasor MMICs were utilized to minimize the number of components in the BFMM. Each quad phasor contained four 6-bit phase shifters, four 8-bit attenuator circuits and four

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Wilkinson divider/combiners. Each beam input is divided by a single Wilkinson and routed to two quad phasors where it is further split into four paths and connected to four phase shifter/attenuator circuits. The signal is then combined by two on-chip Wilkinson combiners and connected to the four output terminals by an 8:1 Wilkinson combining network realized in the HDI interconnect.

The HDI MCM process is best described as a chips-first, sequential overlay process that utilizes laser-formed microvias for interlayer connections and subtractive patterning of the interconnect patterns. The BFMM cross section is shown in Fig. 2 with one RF interconnect layer and two DC/Logic layers separated by a continuous ground plane. The RF interconnections are completed as offset striplines with a ground spacing of 96 μm. The Wilkinson [4] divider/combiners are realized using two 50-ohm legs in series with a quarter-wave matching transformer. The Wilkinson isolation resistor is realized using a 25-ohm/square integral thin film resistor formed on the same dielectric layer as the Wilkinson divider elements, thereby eliminating the parasitic losses associated with discrete isolation resistors.

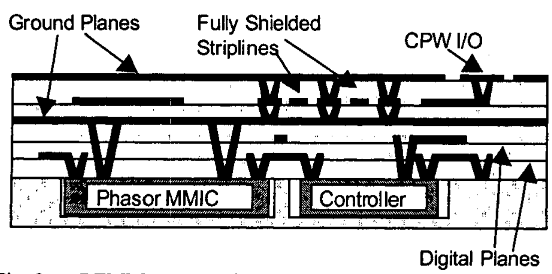

Fig. 2. BFMM cross section showing complete shielding of RF lines from the DC/logic and external fields.

The HDI interlayer microvias are laser formed using a 355 nm CW laser that is scanned across the face of the BFMM, forming all of the vias in a single process step. Each microvia is 40 μm across and is from 40 to 60 μm deep, resulting in very low inductance (55fH) [5] that allows the use of HDI circuits up to millimeter wave frequencies. These microvias are used to connect 50-ohm transmission lines (striplines) directly to the terminals of the quad phasor die, resulting in excellent match and bandwidth.

Fig. 3 shows a completed BFMM with the 20 RF CPW connections and mounting pads for 6 DC bypass capacitors on the top surface. The RF interconnect and Wilkinson combiners are fabricated on the fourth metal layer in a stripline implementation as shown in Fig. 4. The use of a ground-to-ground spacing of 96 μm and microvias enables the design of fully shielded 50-ohm striplines with a center-to-center distance of 336 μm and measured isolation of >110 dB at 10 GHz. Careful attention was given in the module layout to achieving high isolation as this is critical to achieving useful performance.

Typical Wilkinson combiners are shown in Fig. 5 where

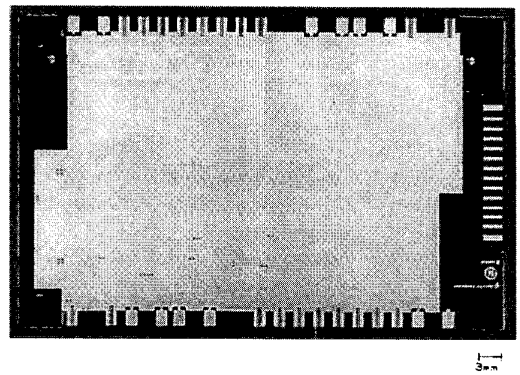

Fig. 3. Completed BFMM with 20 CPW I/O pads.

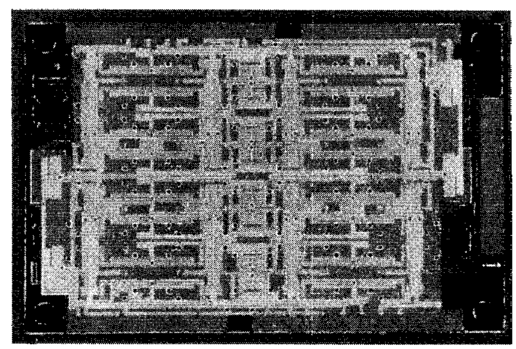

Fig. 4. The RF interconnect layer showing the Wilkinson divider/combiners with integral resistors. The use of thin (100 μm) dielectrics allows high routing density (336 μm center to center) on the stripline interconnect.

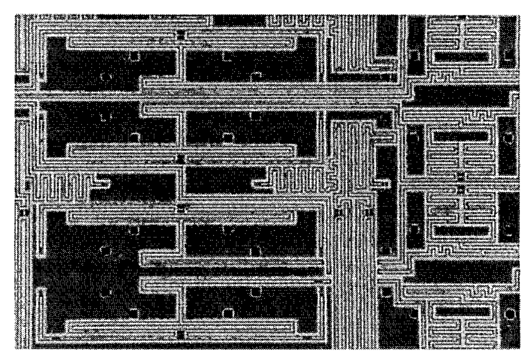

Fig. 5. The Wilkinson divider/combiners fabricated with meandering striplines and integral thin film resistors. The use of the integral thin film resistors eliminates parasitics normally encountered with the use of discrete resistors.

the quarter-wavelength (10.48 mm) sections are implemented in fully shielded meandering striplines to produce a compact circuit element that can be shaped to fit the existing space. These Wilkinson combiners exhibit a 1.6 GHz bandwidth centered at 4 GHz and show excellent isolation resulting from the use of the integral thin film isolation resistor formed on the same layer as the interconnect. The paper will elaborate on the design and performance of the modified [6] two-stage Wilkinson combiners.

The dc/control interconnect of the BFMM is realized using the first two interconnect layers to provide the 3328 individual interconnections on 84 μm centers as shown in Fig. 6. The first two interconnect layers are used to form a Faraday shield about each phasor die that allows the RF interconnect layer to be routed over the phasors without interaction or cross talk. The Faraday shield also minimizes cross talk between the digital signals, the phasor and the RF interconnect. The two digital layers are shielded from the overlying RF interconnect by a continuous ground plane on the third interconnect layer. The fifth interconnect layer is fabricated with a gold-plated-wire bondable surface, and it also provides a ground plane for the RF striplines.

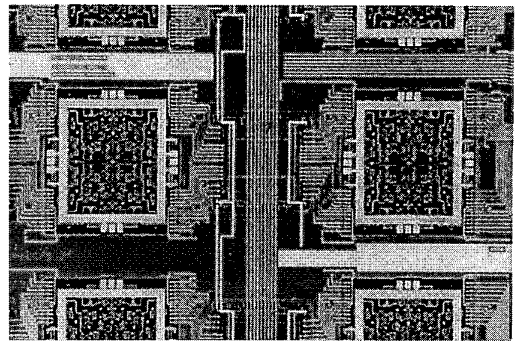

Fig. 6. The DC/Logic layers showing the 42 μm/42 μm line and spacing of the DC and logic interconnects on layers 1 and 2 of the BFMM. The Faraday shield used to shield each of the quad phasors is fabricated by adding a ground ring on layers 1 and 2 and a lid on layer 3.

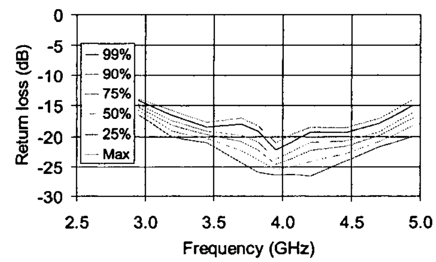

Fig. 7. Statistical plot of the input match for the worst I/O port. Typical I/O ports have ~2 dB better matches.

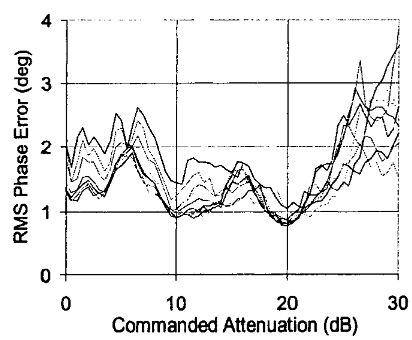

Fig. 8. Plot of RMS phase error from 2.95 to 4.95 GHz over a 30 dB control range.

III. Test Results

The BFMM has been evaluated, and some of the results are shown in Figs. 7 and 8. RMS phase errors of under 3° have been obtained over a 2 GHz bandwidth and a 25 dB amplitude control range. The match in the worst-case state is better than 15 dB over a 1.6 GHz bandwidth. Ninety percent of the states have better than 20 dB match over a 0.75 GHz bandwidth. The input match is excellent because of the phase shifter performance and the use of the Wilkinson combiners in place of simple reactive combiners. Additional test results will be presented in the paper.

IV. Conclusion

The BFMM described in this paper has been designed and fabricated with excellent performance. In addition, the BFMM is smaller than any reported beamformer module, and at 7 grams it has a mass that will enable the fabrication of active-array space-based communication links. The BFMM uses a fully shielded stripline implementation to provide a complex interconnect and 42 Wilkinson combiners.

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