20 GHZ LTCC PHASED ARRAY MODULE

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ABSTRACT

A phased array multi-chip module has been developed that supports four, individually-controllable radiating elements with integral five-bit phase shifters and power amplifiers at 20 GHz. LTCC technology has been demonstrated as a valuable substrate/package material, enabling low loss, multi-layer topologies to aid the microwave circuit/package designer in creating unique solutions in three dimensions.

I. INTRODUCTION

The development of high-performance, solid state, phased array antennas relies directly on the ability to integrate and operate a large amount of complex circuitry in a small physical volume [1]. This packaging challenge is increasingly difficult as operating frequencies move into the K and Ka-bands, where radiating element spacing decreases to fractions of a centimeter and the available space behind the radiators approaches the size of the MMIC devices alone. Furthermore, the packaging is further constrained by the requirements that each MMIC be individually controlled, electrically isolated, and protected from environmental hazards. Although the challenges to the packaging engineer are formidable, an approach has been investigated that offers one possible solution to the phased array packaging/integration problem.

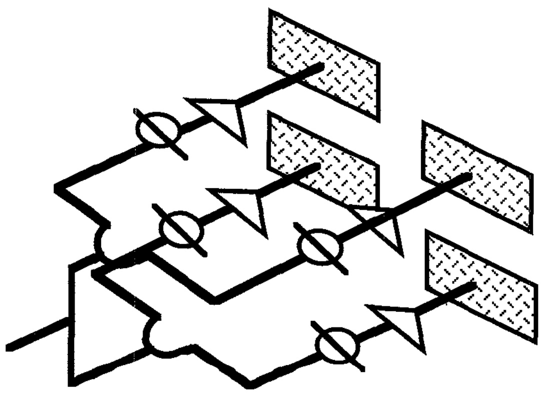

Figure 1. Block diagram of transmit module.

In this paper, a phased array multi-chip module (MCM) has been developed that supports four, individually-controllable radiating elements with integral five-bit phase shifters and 300 mW power amplifiers at 20 GHz. The module is constructed in a "tile" configuration, in which the active MMIC components and interconnects are integrated into a multi-layer structure parallel to that of the probe fed patch, shown in a block diagram in figure 1. Modules of this type are typically more difficult to design and construct because of the high component density required within the physical boundaries behind each radiating element. The advantage of the tile configuration, conceptually shown in figure 2, is that the resultant antenna is extremely low-profile and can be mounted conformably on the surface of a vehicle or with minimum penetration into the vehicle interior. The construction of the module package is enabled by the development of a low-temperature co-fired ceramic (LTCC) material that provides low RF insertion loss at the 20 GHz operating frequency. Microstrip patch radiating elements are printed directly onto the bottom surface of the module and probe fed through the substrate to ensure a hermetic enclosure.

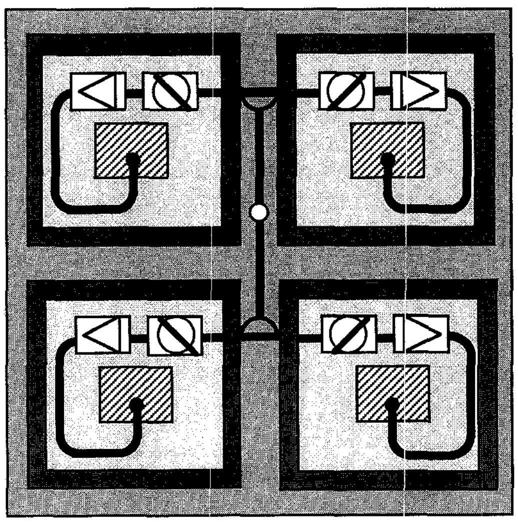

Figure 2. Conceptual tile layout of the transmit array.

The phased array module developed under this effort will serve as a building block to construct larger arrays for a variety of communication and radar needs. Experiments and studies by NASA and the Army have indicated that MMIC-based phased arrays are fully capable of communications to geosynchronous and low earth orbiting spacecraft, thereby offering greatly enhanced and new capabilities to both civilian and defense users [1]. The packaging technology described herein is transmit-only configuration, but is intended to be generic; readily allowing modification to transmit/receive operation or to other operating frequencies.

II. MCM DEVELOPMENT

As a co-operative research project, ARL and NASA set out to prototype a tile architecture transmit module using LTCC [2,3], the design goal of the module was to have 300 mW of output power per antenna and beam steering capability. The frequency of operation was chosen to be nominally 20 GHz, as to be compatible with NASA's Advanced Communication Technology Satellite (ACTS) down link band and commercial allocations.

A. MMIC Design

A commercially available medium power MMIC amplifier was used in each element, however five bit phase shifters were not available. Therefore, a 20 GHz MMIC phase shifter was designed and fabricated. ARL designed a switched line five bit phase shifter and then processed the chip using a commercial foundry. CAD programs were utilized to simulate and layout the MMIC phase shifter, shown in figure 3. On wafer phase measurements were taken on the five bit phase shifter and can be seen in figure 4.

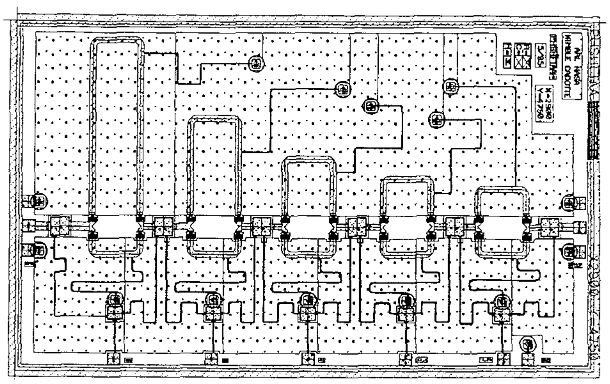

Figure 3. 20 GHz five bit switch line phase shifter.

The array performance goal was to have a five bit phase shifting capability and to output at least 300 mW of power per element. The amplifier required high gain to overcome the 13 dB of loss from the phase shifter, ≈2.5 dB per bit, and 6 dB of loss from the distribution network. The MMIC amplifier had >20 dB of gain and an output power of 300 mW, thus satisfying the array requirements. The phase shifter/amplifier combination was assembled on LTCC and tested. Results are shown in figure 5 and 6. The phase shifter/amplifier combination achieved 10 dB of gain with negligible change shifting all five phase states.

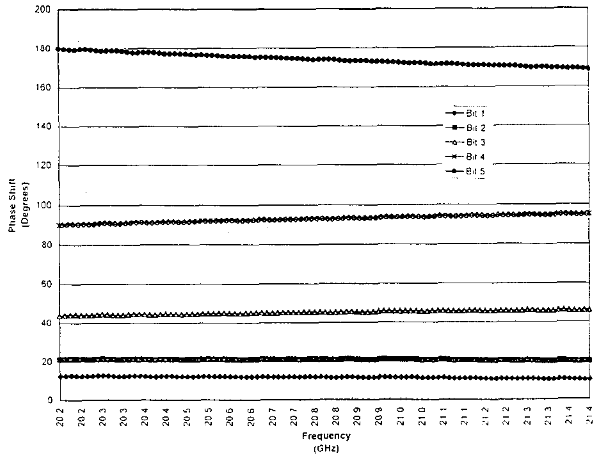

Figure 4. On wafer results of the five bit phase shifter.

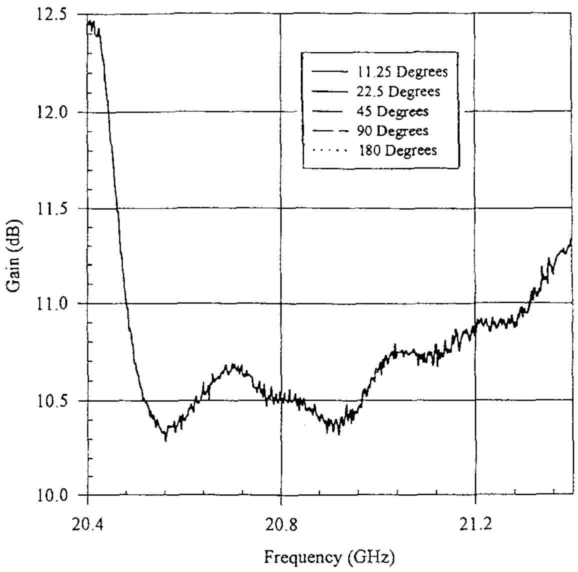

Figure 5. Phase shifter/amplifier gain response.

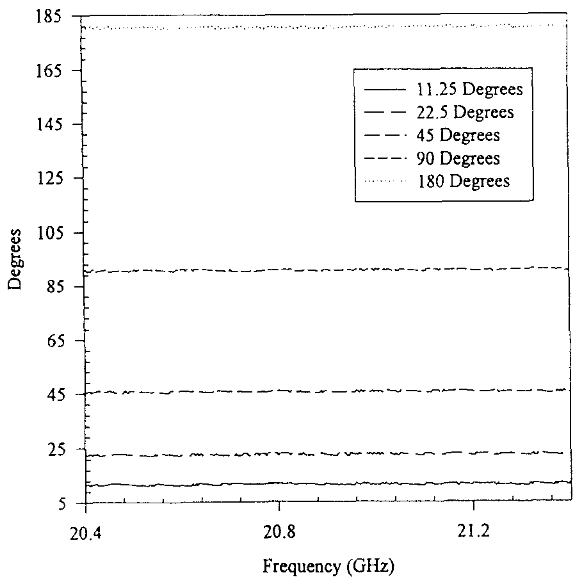

Figure 6. Phase shifter/amplifier phase response.

B. Antenna Design

Two antenna configurations were investigated, a probe fed patch and an aperture coupled patch. Both patch antennas were designed, however, due to the module size constraints only the probe fed antenna was feasible. Because the ground plane above the antenna is used for routing bias and the microstrip transmission lines. The patch layout is shown in figure 7 for both the probe fed patch and the aperture coupled patch. The patch size for 20 GHz is 2895 x 4165 μm. The 50 ohm impedance point was optimized using EM analysis CAD and determined to be 965 μm from the edge of the patch, centered in the horizontal dimension.

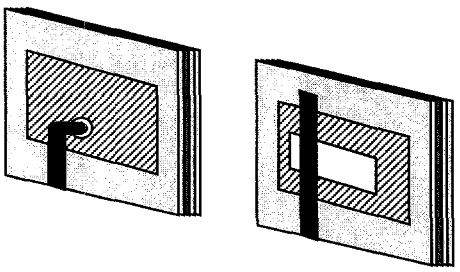

Figure 7. Layout of single probe fed and aperture coupled patch.

The probe fed patch antenna has an 279.4 μm wide microstrip transmission line feeding a 254 μm diameter via. The 254 μm via is through all four layers such that it connects to the 50 ohm impedance point on the patch. The buried ground plane is in the center of the 381 μm thick substrate. A 508 μm diameter opening in the ground plane is used to pass the 254 μm probe via. When the aperture coupled antenna is used the working area above the aperture and around the microstrip line would not be available for MMIC use and force a larger inter-element spacing. The simulated and measured results of a single probe fed patch can be seen in figure 8.

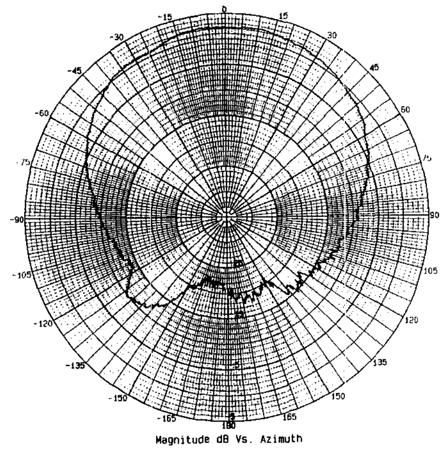

Figure 8. Measured antenna pattern for probe fed patch.

The design frequency for the patch was approximately 20 GHz, however the best measured results were achieved at 19.1 GHz. The reason for the difference is that after fabrication, the measured patch size was 2997 x 4191 μm. The additional 102 μm shifted the resonant frequency lower. Even though the exact frequency was not achieved for the first design, tighter processing calibration will eliminate this processing error due to shrinkage. The next step was to fabricate a four element array. All four probe patch antennas were fed by a four way microstrip distribution network. Figure 9 shows the simulated and measured beam patterns of the four element array.

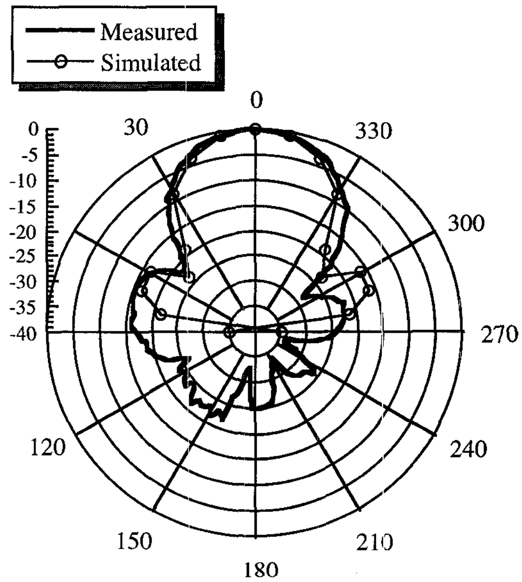

Figure 9. Simulated and measured patterns of four element array.

C. Module Design

The antenna array spacing was designed to be 0.7 λ, thus making it a challenge to fit the relatively large phase shifter (2900 μm x 4750 μm) and amplifier (5000 μm x 2500 μm) behind the patch while maintaining the array spacing of 1.05 cm. To achieve this goal and maintain a low module cost, we mount the MMIC chips directly behind the radiating elements, again shown conceptually in figure 2. The advantages of using the same substrate for incorporating the radiating elements and MMICs is lower cost, single substrate, hermetic enclosure by attaching a single lid, easy fabrication, and elimination of potentially lossy microwave interconnects between module and antenna as well as difficult multiple substrate integration techniques.

The 2x2 module array consists of a corporate feed network, eight MMICs and four patch antennas all integrated on LTCC substrate/housing. A commercially available ceramic tape system was selected for its low loss at microwave frequencies (<0.4 dB/cm at 20 GHz), and multi-layer, buried passive component capabilities. Figure 10 shows the actual module layout. The module size is 2.0650 cm x 2.0650 cm. The module operation is as follows: The transmit signal is fed through the back center of the module. It then splits into 4 paths by using a microstrip tee and two Wilkinson power dividers. Each element consists of a MMIC five bit phase shifter cascaded to a MMIC amplifier followed by a patch antenna.

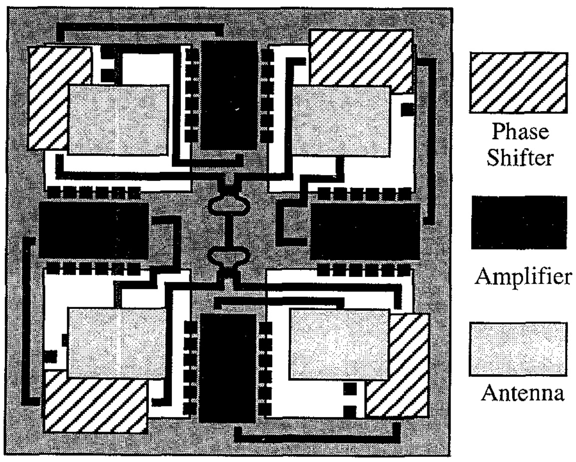

Figure 10. Actual LTCC module layout.

The total substrate thickness is 381 μm, which consists of four 95.25 μm thick layers of tape after lamination and sintering. The substrate has three major metalized regions: the bottom of the substrate which contains the patch antennas and a ground plane, the middle of the substrate which contains the buried RF ground plane, and the top of the substrate which contains the microstrip lines and the chip pads. The bottom layer ground plane is mounted to a metal skeleton which give the substrate mechanical strength and also performs as a heat sink. The 381 μm vias on 1270 μm centers go through the bottom two dielectric layers to connect the bottom ground plane to the buried ground plane. Thermal vias are located underneath the power amplifiers and connect all four layers to the bottom ground plane. The 254 μm RF vias go through all four layers to the 50 ohm impedance point on each patch. Finally the bias lines for the amplifier and phase shifter are routed between the top and first tape layer to the substrates edge to avoid coupling from the microstrip lines.

III. CONCLUSION

The components of a 20 GHz communications MCM phased array module have been described. The technology thrust of this effort is to combine state-of-the-art technologies, LTCC, MMIC, vias, to demonstrate mass produceable, low cost, high performance modules that can be adapted to a variety of communication and radar systems. LTCC technology is a valuable substrate/package material, enabling low loss, multi-layer technology for microwave circuit/package designers to create unique solutions in three dimensions. This module serves as a demonstration vehicle for a new crystallizable LTCC tape and assembly process, providing useful information to designers.

IV. REFERENCES

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