SYSTEM-LEVEL INTEGRATED CIRCUITS FOR PHASED ARRAY ANTENNA APPLICATIONS

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ABSTRACT

A new, high-density microwave circuit has been developed for use in advanced communication system antennas. These System-Level Integrated Circuits, or "SLICs", include integral features and functions facilitating reliable operation, improved performance, and ready application. An optical fiber feeds both control and 20-GHz RF signals to an 8-element phased array module, wherein SLIC circuitry provides automatic gain control, thermal compensation, voltage regulation, control signal processing, and health/status feedback. Modules have been fabricated using the new SLIC MMICs and the Microwave High Density Interconnect (MHDI) multilayer lamination process.

INTRODUCTION

While the theory of operation of phased array antennas has been known for many years, the actual hardware implementation and successful demonstration of arrays, especially in the K band and above, has been a significant technical challenge. Several factors have impeded array development, including lack of effective packaging and MMIC integration technologies, and generally the need to place (and operate) large amounts of complex circuitry in a very small volume. Furthermore, MMIC device variations due to temperature fluctuation, aging, and fabrication inconsistency presently require that significant amounts of support circuitry be included in the array electronics to maintain proper operation of each element. The System-Level Integrated Circuit Development Program described in this paper has attempted to address some of these issues by creating a new type of integrated circuit that includes support and interface circuitry merged directly with RF components. The paper then discusses a direct path to integrating the SLIC MMIC into a compact, multilayer structure configured for use as a two-by-four element phased array module. The SLIC MMIC and module are considered to be the building blocks from which larger array antennas can be assembled for use in space, airborne, and terrestrial communications applications.

BACKGROUND

To date, thousands of solid state devices have been developed under research and development contracts. Many of these devices operate at frequencies of 20 GHz and higher, and have very successfully demonstrated new circuit designs, device structures, fabrication processes, and semiconductor materials. In order to transition these devices from the laboratory environment to application in phased array antenna systems, however, several features and capabilities must be added to each MMIC to maximize and maintain device performance while addressing system integration issues. Conventional approaches to handling problems such as RF power distribution, control signal processing and line distribution, thermal stability, device health and status monitoring, bias regulation, and environmental protection often add tremendous complexity to the antenna or support instrumentation systems, making the antenna large, heavy, expensive, and unreliable. These needs, along with the pursuit of higher levels of integration and RF performance, are the primary drivers of the SLIC program.

DESIGN APPROACH

Several constraints were applied to the design of the SLIC module to focus on a configuration generally representative of future phased array antenna structures. The operating frequency was selected to be 20 GHz, where the radiating element spacing (and, thus, unit cell area) is near MMIC physical dimensions and where aggressive integration and packaging challenges would be experienced. Additionally, the maturity of MMIC technology at this frequency was

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such that device variations would likely be experienced and could be used to demonstrate autonomous calibration and correction. It was not a goal of the program to develop improved MMIC structures or materials, so the 20-GHz frequency allowed use of some existing designs from other development programs.

A photograph of the SLIC MMIC is presented in Figure 1. The architecture selected yields a die that includes RF functions for two individual RF channels, each channel having a cascaded, three-bit (eight-state) phase shifter and continuously-variable attenuator. Digital control functions are shared by the two channels, and provide the necessary processing capability to individually adjust the phase delay and amplitude of each channel. With this capability, the SLIC is able to sense the output power level of a channel and automatically adjust to compensate for gain variation imposed by the phase shifter state change, by amplifier thermal drift, or drive level changes. The amplitude correction is made based on the output of individual peak detectors (sampling at the end each RF channel) and its relationship to a user-selectable setpoint that is downloaded over the fiber to the SLIC MMIC. This feature allows the amplitude distribution over the radiating aperture of an array to be tapered or regulated for best beam characteristics. The die size is commensurate with a 0.6λ array radiating element spacing. The SLIC MMIC presented in Figure 1 includes:

- two, 3-bit artificial delay line phase shifters with very low insertion loss (<5.5dB),
- two analog attenuators with 20 dB gain control range,
- shift registers for serial control of the MMIC, reducing control line count to 3 per MMIC,
- a microwave peak detector that samples MMIC output for comparison to a reference level,
- a temperature-compensated automatic gain control (AGC) loop which adjusts attenuator to maintain a constant RF output power level, and
- a digital modulator that reports performance status over a fiber optic cable to the array controller.

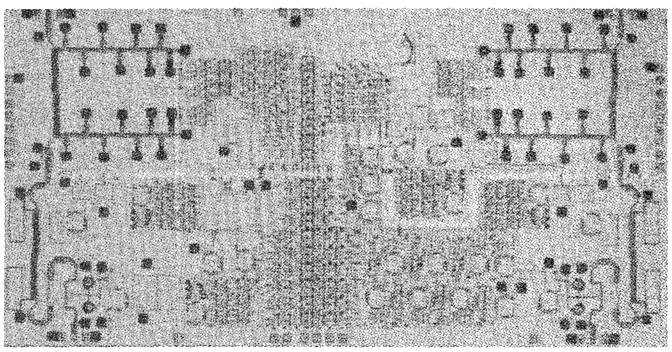

Figure 1: Two-channel SLIC MMIC die (310x163 mils)

Four SLIC MMICs, along with other MMIC, logic, and photonic devices, were integrated to form an eight-element phased array module. A photograph of the module and a functional block diagram are shown in Figures 2 and 3. The module was implemented using the Microwave High-Density Interconnect (MHDI) process developed at General Electric's Corporate Research and Development Laboratory and Lockheed Martin. The MHDI process eliminates the use of wirebonds, providing multilayer routing of DC and RF lines to achieve a 2x reduction in size compared to chip-and-wire technology. Using this process, the 8-element SLIC circuit was configured as a 2x4 element phased array, measuring only 0.75 by 1.5 inches.

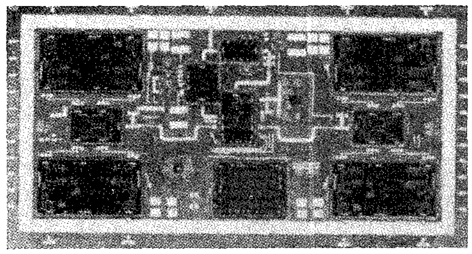

Figure 2: Two-by-four element array using four SLIC MMICs

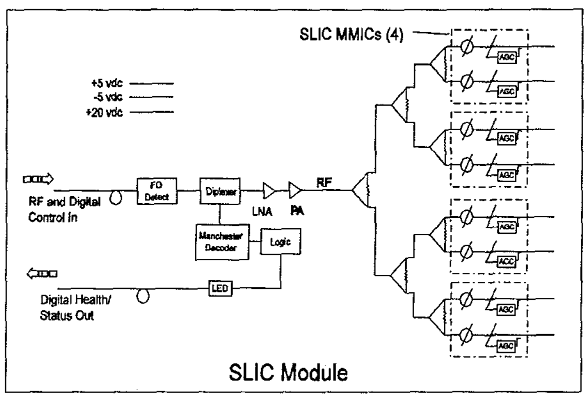

Figure 3::Block diagram of SLIC module

In the functional block diagram presented in Figure 3, the reader will notice that a single optical fiber is used to supply the input signals, which include both the 20-GHz RF signal and the digital control signal. The optical signals are received by the SLIC module, converted back to separate electrical signals, then routed down either the 8 RF paths or to the control signal digital electronics. The RF path out of the diplexer includes a cascaded low-noise amplifier and power amplifier to raise signal levels from the optical detector into a range suitable for amplitude detection and autocorrection by the SLIC. A second optical fiber exits the SLIC and carries health and status information back to a remote controller.

The SLIC module was designed to operate from a minimum number of DC power lines. For possible diagnostics during the development period, a large number of redundant control points were added to isolate various chips, allow direct injection of signals, and as test points. In subsequent iterations of the SLIC module, these inputs will be removed, leaving a total of only 5 DC lines for all optical, RF, and digital circuitry.

FABRICATION

The SLIC MMIC was fabricated using a commercially-available GaAs foundry service (TriQuint QED/A) which was ideal for providing both low loss microwave switching/control elements as well as low power consumption digital/analog circuitry. Numerous unique elements were designed to achieve required features/functions, including A/D and D/A convertors, peak detectors, comparators, and shift registers. The resultant MMIC yielded excellent RF performance, and demonstrated successful operation of the AGC loop. Figures 4 and 5 show the measured phase shift and gain control range of a typical channel. A 5.5 dB average insertion loss (with return loss >12 dB) was obtained for the phase shifter while maintaining the characteristic phase performance of a true time delay device. The attenuator achieved 1.5 dB of insertion loss with a 20 dB attenuation range and, importantly, introduced only a 5° phase error over the full gain control range - an important criteria for phased arrays.

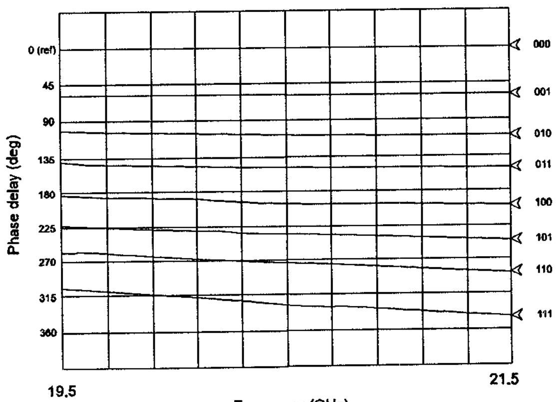

Figure 4: Phase delay of SLIC phase shifter at 8 phase states.

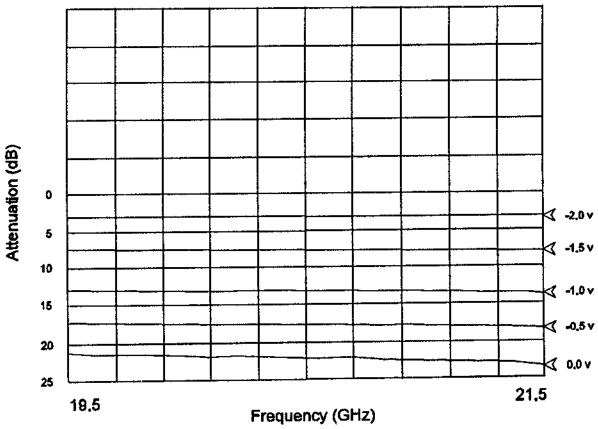

Figure 5: RF attenuation for SLIC MMIC attenuator at 5 discrete settings.

Four SLIC MMICs, the LNA and PA MMICs, silicon digital chips, the photodetector and LED, and other GaAs support chips were integrated on a single carrier to form the SLIC module. The integration was accomplished using the microwave high-density interconnect (MHDI) process developed by General Electricand Lockheed Martin, which eliminates the need for wirebonds and applies low-cost batch-manufacturing technology found in the semiconductor industry. Semiconductor circuits were first mounted flush in a Silvar base. Layers of photo-definable polyimide were then laminated over the entire module, with air gaps constructed over the active regions of the MMICs. Metalization was selectively added within the layers using laser definition to construct RF and dc interconnect, vias, ground planes, and feedthroughs. The entire 8-element module weighs less than 14 grams and is less than 0.2 in thick.

TESTING

The AGC loop within the SLIC MMIC was designed to compensate for RF amplitude variations contributed from any of several sources. These sources include: 1) variation in phase shifter state-to-state insertion loss, 2) changes in LNA and PA gain due to temperature or aging, and 3) changes in SLIC input drive level. The easiest way to observe AGC operation in response to such changes was to intentionally impose a large variation on the input power to the SLIC. Figure 6 shows that the output port amplitude variation of the SLIC in response to an 8-dB input change was only ±0.2 dB. As expected, the SLIC AGC circuit sensed the deviation from the down-loaded setpoint, and caused the attenuator to automatically compensate to maintain the output level. A subsequent test was conducted to examine the circuit response to a change in phase shifter state. In this case, the relatively small, 0.6 dB gain variation of the phase shifter was again reduced to the 0.2 dB with the use of the AGC. Had the phase shifter performance been poorer, the leveling effects of the AGC would have been even more significant.

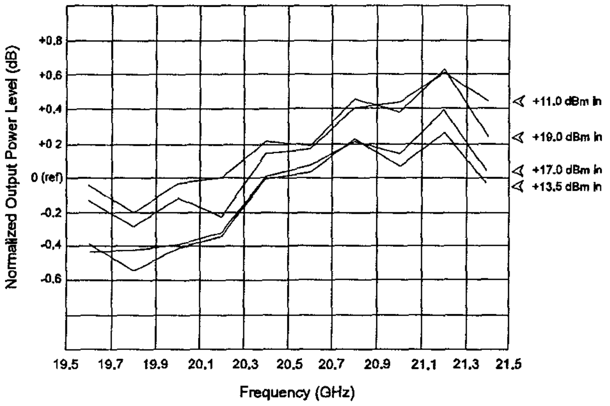

Figure 6: AGC leveling capability for 8 dB input variation.

Testing of the AGC loop within the SLIC is continuing, and will be examining the limits of AGC operation. As presently configured, the comparator within the peak detector circuit supports at least a 10-dB "window" over which it can maintain good sensitivity, which is more than adequate for many applications. The SLIC MMICs include external AGC sense inputs, which will allow further amplification to be added at each of the eight SLIC outputs yet be included in the AGC control loop. The peak detectors are temperature-stabilized to assure consistent operation during thermal excursions.

CONCLUSIONS

A new, highly-integrated, MMIC has been developed for advanced communication system antennas. This System-Level Integrated Circuit includes advanced features and functions that facilitate reliable operation, improved performance, and ready application into antennas. Excellent RF performance has been recorded, along with the demonstration of a new level of integration with built-in automatic gain control. The SLIC technology described in this paper is being directed towards several flight experiments, being primarily considered for small, low-cost, communications spacecraft with high data throughput. The SLIC MMIC clearly demonstrates the ability to integrate advanced supporting functions with the more common RF functions of a MMIC, thereby improving RF operation. It is envisioned that the improvements in performance, capability, autonomy, and size will lead to application in antenna systems in both commercial and government domains.