BRUCE A. KOPP and JONATHAN C. BARNETT

C–BAND RECEIVE MODULE FOR PHASED–ARRAY ANTENNA APPLICATIONS USING COMMERCIALLY AVAILABLE MONOLITHIC MICROWAVE INTEGRATED CIRCUITS

Thanks to the availability of commercial off-the-shelf monolithic microwave integrated circuits (MMIC's), low-volume multifunction microwave systems can now be developed cost effectively. In particular, the receive modules needed for prototyping active antenna design concepts can be made in small quantities at low cost and with short development times. The Applied Physics Laboratory has developed a receive module operating at 4.8 to 5.2 GHz that consists primarily of off-the-shelf MMIC's and is suitable for active antenna applications.

INTRODUCTION

Advances in gallium arsenide (GaAs) monolithic microwave integrated circuits (MMIC's) over the last decade have had many benefits for phased-array antenna applications. The MMIC technology has eliminated much of the test and assembly touch labor associated with building hybrid microwave circuits, thereby reducing the cost of producing high volumes of transmit and receive (T/R) modules.[1,2] Further, MMIC's are much smaller than hybrids for equivalent circuit functions, so that MMIC-based modules are ideally suited for use in antenna arrays with 180° scan requirements, which limit the module width to half the free-space wavelength to prevent power dissipation in undesirable sidelobes.

Although MMIC's are less expensive in high-volume production than hybrid circuits, small or prototype custom MMIC-based phased arrays are very expensive and time-consuming to produce. Indeed, using discrete packaged hybrid circuits for these small-quantity applications can often be more cost-effective than using custom MMIC designs, but the hybrids' size, weight, and—often—cost make them unacceptable for use in the high-frequency applications typical of APL antennas.

Developments over the last several years provide a solution to this problem. Many companies, such as Texas Instruments, M/A-COM, and Raytheon, have begun to offer MMIC low-noise amplifiers (LNA's), general gain blocks, attenuators, and switches as off-the-shelf items. Phase shifters and high-efficiency power amplifiers are still not generally available, but the phase shifters can be realized as a combination of MMIC switches and passive phase elements. We can thus fabricate the receive function of a T/R module primarily from off-the-shelf MMIC components, an approach that is much more cost- and time-effective than using custom MMIC's and/or packaged hybrid circuits to produce prototype receiving antenna arrays.

The APL Technical Services Department has implemented this approach by developing the microwave and control circuitry for a C-band (~5 GHz) phased-array receive module composed of commercially available MMIC's. In this article, we briefly discuss the theory of phased-array antennas as a basis for understanding the function of the components of a T/R module, and then describe our module design and performance.

PHASED-ARRAY ANTENNA SYSTEM

A phased-array radar system consists of a group of individual antenna radiators whose amplitude and phase responses can be individually controlled to steer the resultant beam electrically (rather than mechanically with the antenna). Such radars are capable of accurate electronic beam scanning in microseconds, which enables them to carry out several tasks, unlike mechanically steered antennas. Tailoring the excitation amplitudes of the individual elements controls the shape of the antenna beam, and modifications to the excitation phases of the individual elements control the position of the beam.

The electronic components used to control the amplitude and phase of the individual antenna elements are the T/R modules, which are basically bidirectional amplifiers with a phase shifter and a variable attenuator. The transmitter amplifier is normally located as close as possible to its antenna element to provide the maximum amount of power to the antenna. Close placement also minimizes the demands on the antenna power supply and cooling systems, and so can lead to a reduction in the weight of the radar system.

The receiving amplifier is also located as close as possible to the antenna element to minimize the receiver's noise figure. The phase shifter and attenuator impose the phase and amplitude on each antenna radiator necessary to achieve the desired overall radiation pattern. A

circulator, T/R switch, and limiter in each T/R module protect both the receiver and transmitter from electronic damage. Additional amplifier stages are used in the transmit and receive chains to set the receive gain and linearity (a measure of distortion).

The amount of power radiated from an antenna and the accuracy with which the beam can be formed are both limited by the number of T/R modules in the phased-array system. Thus, arrays often incorporate hundreds or even thousands of elements. With module production costs well in excess of $1000, development costs for even one antenna prototype can amount to millions of dollars. Clearly, the more prudent course is to conduct experiments with a small array before committing to an antenna/module design.

RECEIVE MODULE DESIGN

To test the feasibility of using commercial MMIC's to build a T/R module for prototyping antenna arrays, we designed and built a receive module for a C-band receiving array, with the following operational parameters:

Frequency: 4.8–5.2 GHz
Phase shift: 360° in 11.25° steps ±5.625°
Gain: 20 dB in 0.5-dB steps ±0.25 dB
Noise figure: 3 dB min.
Voltage standing-wave ratio (VSWR): 1.8:1 for all combinations of phase and gain.

These requirements are typical for an APL radar or communication system. Figure 1 shows a block diagram of the module.

As shown, this design incorporates two low-noise amplifiers, a driver amplifier, a five-bit phase shifter, and two analog attenuators. The LNA's essentially set the system's noise figure, and the driver amplifier provides the required output power and gain. The five-bit phase shifter allows precise beam steering. In a T/R module, the phase shifter must be bidirectional so that it can be used to both transmit and receive. Since our module is intended to receive only, the phase-shifter bits can be distributed among the amplifiers. The amplifiers can therefore serve as isolators between the passive 180° and 90° phase-shifter bits to prevent the formation of large voltage standing waves in the system.

Phase-Shifter Design

To meet the system requirements, the individual bits of the phase shifter were designed to have a maximum VSWR of 2:1, a maximum insertion loss of 2.0 dB, a 0.5-dB

maximum amplitude imbalance between the two states, and a maximum phase error of ±5.625°. The VSWR of any phase-shifter bit can be larger than the system requirement because the LNA sets the input VSWR, and the attenuators set the output VSWR. The insertion loss of the phase shifter does not have to be particularly low for this application, because the LNA also sets the system noise figure and the attenuators can be used to compensate for any amplitude imbalances. Phase accuracy is the only critical specification, since the design does not include an analog phase shifter.

An off-the-shelf MMIC phase shifter was not available to meet these requirements, but several companies offer single-pole double-throw switches commercially. Two such switches alternating between two different phase elements can produce a desired phase shift. Transmission lines of different lengths are also a simple, low-loss way of providing a phase shift, but they do not yield a flat phase response over frequency for large phase shifts. Moreover, at 5 GHz, the transmission lines required are prohibitively long. For these reasons, we used transmission line phase elements for the 11.25° and 22.5° circuits only, and high-/low-pass filter combinations with switches to realize the phase-shift elements for the 45°, 90°, and 180° phase shifters.[3,4]

We chose M/A-COM MA4MG202 (M/A-COM, Inc., Lowell, Mass.) parts for the phase-shifter switches because they include silicon positive-intrinsic-negative (PIN) diodes, which have a lower insertion loss for equivalent isolation than GaAs field-effect transistor (FET) devices—less than 1 dB per switch. Since these M/A-COM parts are 0.023 in. thick, they were embedded in an alumina substrate of matching thickness (0.025 in.) to minimize the length of the bond wire (inductance) connecting the MMIC to the substrate. Plated laser-drilled holes (vias) in the alumina substrate provide a connection from the top surface of the substrate to its backside ground plane. The substrate is attached to a 0.005-in.-thick Kovar shim on which the switches are mounted directly through a laser-drilled cutout in the substrate.

The filter inductors are realized as printed spirals on the alumina, and the low-pass filter's shunt capacitors are printed parallel plate patches with the substrate acting as the capacitor dielectric. The high-pass filter's series capacitors are discrete chips. Equal phase lengths of microstrip line route the signals from the switches to the filters, and wire-bonded breaks permit phase tuning. Figure 2 is a photograph of the 45° phase shifter; Table 1
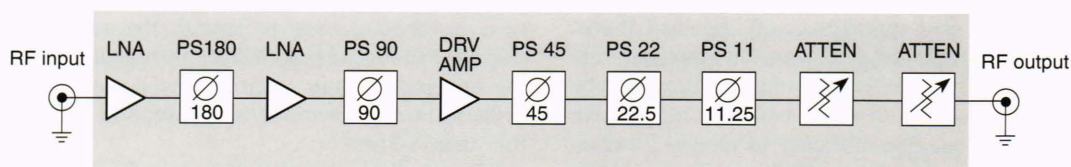

Figure 1. Block diagram of a phased-array receive module. Incoming target signals are amplified, phase shifted, and attenuated to produce maximum receiving gain in each direction. Components include low-noise amplifiers (LNA's), individual phase shifters (PS's), a driver amplifier (DRV AMP), analog attenuators (ATTEN's), transmission line phase elements (for the 11.25° and 22.5° phase-shifter bits), and a high-/low-pass filter combination (for the 45°, 90°, and 180° phase shifters). Commercial silicon positive-intrinsic-negative (PIN) diode-based switches are used in the phase shifters.

summarizes the untuned measured results for all five circuits. Since all bits easily met the targeted specifications without tuning, the tuning bonds were not used.

Low-Noise and Driver Amplifier Design

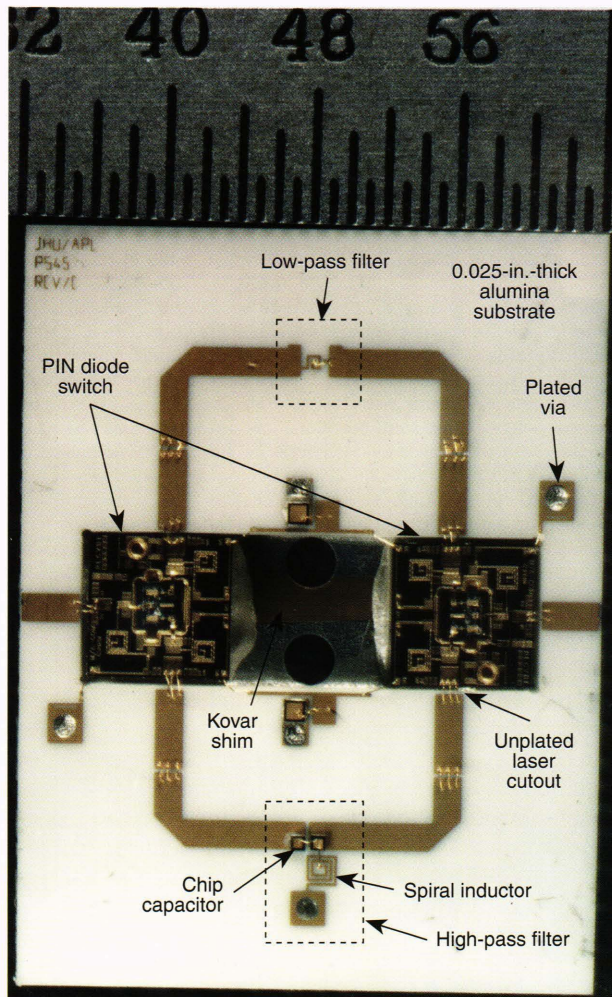For this system, the low-noise amplifier should have a 2-dB maximum noise figure and a 1.8:1 maximum input VSWR for the frequency range of 4.8 to 5.2 GHz. M/A-COM's MAAM37000 low-noise MMIC amplifier meets these requirements, and also has 15 dB of gain with a 1.8:1 maximum VSWR. These 0.004-in.-high parts were embedded in a 0.010-in.-thick alumina substrate to minimize the transition distance to the input and output microstrip lines. (A thinner alumina substrate would be too fragile to work with.) The amplifiers are mounted on a Kovar carrier similar to the one for the phase shifter but 0.020 in. thick. All of the circuits were fabricated in this manner so that they could be individually tested before insertion into the receiver. Table 2 summarizes the measured results for the low-noise amplifier; Figure 3 is a photograph of the amplifier.

The driver amplifier has to provide isolation between the 90° and 45° phase-shifter bits and sufficient uncompressed output power to prevent signal distortion. We selected Texas Instruments' TGA8226 distributed amplifier (Texas Instruments, Inc., Dallas, Tex.) for this purpose. The measured data for this circuit are shown in Table 3.

Analog Attenuator Design

Each analog attenuator must provide good VSWR's and 15 dB of attenuation in 0.5-dB steps. We used Triquint's TQ9161 chip (Triquint Semiconductor, Inc., Beaverton, Ore.), which is 0.007 in. thick, a 0.010-in.-thick substrate, and a 0.020-in.-thick Kovar carrier, similar to the ones for the LNA and driver amplifier. Thus, all of the circuits were 0.030 in. thick, which prevented step discontinuities between components at the system level. The measured data for this circuit are shown in Table 4.

RECEIVE MODULE CONTROLLER REQUIREMENTS

In a phased-array radar operation, the phase and amplitude of each module must be controllable over a specified range so that the beam can be steered and shaped by control algorithms. Therefore, the module must be interfaced to a centralized controller that issues commands for setting the phases and amplitudes of the various modules of an array to specific values. This interface is usually digital.

The same interface is also used to calibrate the individual elements to resemble each other electrically as much as possible, ensuring that any phase and amplitude differences in array elements are due to the configuration of the array and not the variability of the modules themselves.

Finally, the interface must provide power to the various microwave, analog, and digital circuits.

Figure 2. Photograph of the 45° high-/low-pass filter phase shifter. Transmission line phase elements are used for the 11.25° and 22.5° phase-shifter bits, and a high-/low-pass filter combination for the 45°, 90°, and 180° phase shifters. Commercial silicon positive-intrinsic-negative (PIN) diode-based switches are used in the phase shifters.

Table 1. Untuned measured results for the five-bit phase shifter.

Bit	Nominal phase (deg)	VSWR (:1)	Insertion loss (dB, max.)	Phase flatness (±, deg)	Amplitude balance (dB, max.)
1	11.25	1.30	1.3	+0, −3.4	0
2	22.5	1.50	1.3	+0.8, −0.8	0
3	45	1.60	1.6	+1.5, −0	0.25
4	90	1.60	1.8	+2.6, −0	0.20
5	180	1.90	1.9	+0, −1.1	0.25

Table 2. Untuned measured results for the low-noise amplifier (LNA).

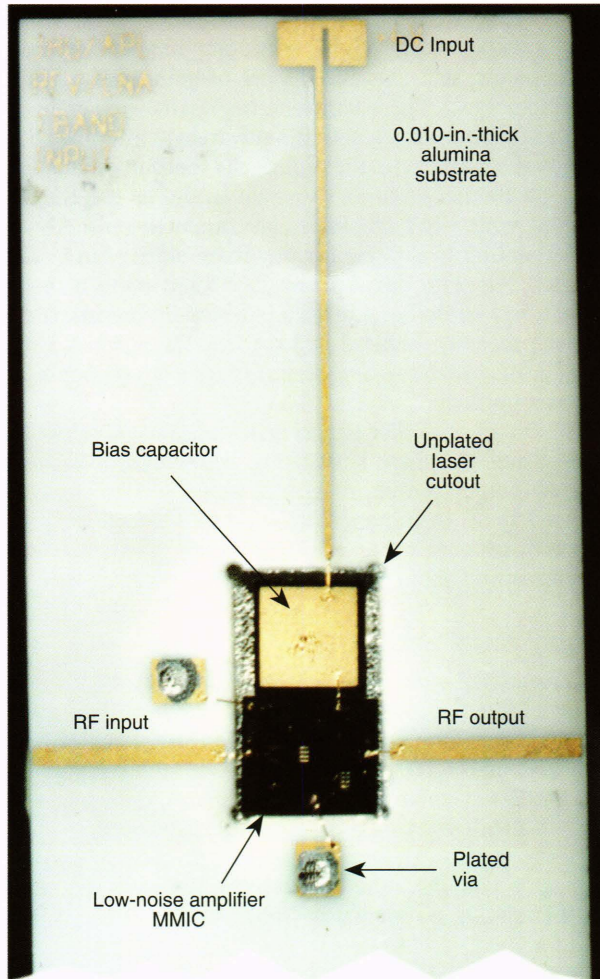| Frequency (GHz)	Nominal gain (dB)	Noise figure (dB, max.)	Input VSWR (:1)	Output VSWR (:1)	Power out at 1 dB (dBm, min.)
4.8–5.2	15.5	2.3	1.35	1.35	+15.9

Figure 3. Photograph of the low-noise amplifier (LNA). The LNA is a commercial microwave monolithic integrated circuit (MMIC) with a 15-dB gain and a maximum noise figure of 3 dB, embedded in an alumina substrate. The overall dimensions of the LNA module and substrate are 0.25 in. wide × 0.6 in. high.

Table 3. Untuned measured results for the driver amplifier.

Frequency (GHz)	Nominal gain (dB)	Input VSWR (:1)	Output VSWR (:1)	Power out at 1 dB (dB, typ.)
4.8–5.2	12.5	1.50	1.50	+17.8

Table 4. Untuned measured results for the analog attenuator.

Frequency (GHz)	Insertion loss (dB, max.)	Input VSWR (:1)	Output VSWR (:1)	Attenuation range (dB, min.)
4.8–5.2	1.8	1.30	1.30	15

Controller Design

A block diagram of the C-band receive module controller is shown in Figure 4. The module enters a new state in response to an 11-bit serial command word sent
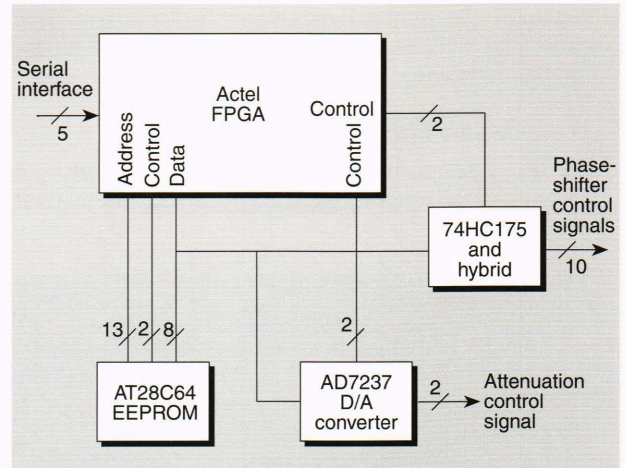

Figure 4. Receive module controller block diagram. The controller sends reset, command, and calibrate signals to the module through a five-signal serial digital interface. Commercial components include a field-programmable gate array (FPGA) (Actel Corp., Sunnyvale, Calif.), an electrically erasable programmable read-only memory (EEPROM) (Atmel Corp., San Jose, Calif.), a digital-to-analog (D/A) converter (Analog Devices Corp., Norwood, Mass.), and a 74HC175 (Texas Instruments, Inc., Dallas, Tex.) and hybrid (Linear Technology Corp., Milpitas, Calif.). The FPGA decodes and implements the various commands by accessing data from or writing data to the EEPROM. The D/A converter generates control signals to the attenuators, and the remaining circuitry generates the control signals for the five phase shifters.

by the controller over the serial digital interface. The word consists of five bits of phase data and six bits of attenuation data, where the five phase bits specify one of 32 possible phase states from 0° to 348.75° in 11.25° steps, and the six attenuation bits select one of 41 possible attenuation states from 0 to 20 dB in 0.5-dB steps. As the command is received, it is shifted into a field-programmable gate array (FPGA), a programmable logic device. The FPGA uses the command as a base address to access four bytes of data stored in an electrically erasable programmable read-only memory (EEPROM). Three bytes of data are read from the EEPROM and written to the digital-to-analog (D/A) converter to generate the two analog attenuation control signals. The fourth byte from the EEPROM is written to a latch circuit. The outputs of the latch feed into special-purpose hybrids that convert digital voltage levels to the voltage and current levels required by the five phase shifters.

In programming mode, the 11-bit serial word is clocked into the module, followed by four bytes of data. One of the digital inputs selects between the command and program modes. The 11-bit word is used as a base address to write the four data bytes to the EEPROM. When the module is being calibrated, this programming mode is used to adjust its phase and amplitude response. The module is controlled by a C program running on a PC, which communicates with a vector network analyzer. The C program selects a phase/amplitude state, programs an initial estimate into the module, and commands the vector network analyzer to take a phase/amplitude measurement. If the measurement is not within the error specifications of the module, the program adjusts the data it

is sending to the module and tries again. When measurements move within the error limits, the program repeats the algorithm in turn for the rest of the 1312 phase/amplitude states. This procedure is necessary because the phase/amplitude response varies from module to module as a function of processing variables.

MODULE PACKAGING

Packaging the prototype controller circuitry is difficult for two reasons: (1) element spacing requirements at 4.8 GHz to prevent grating lobes limit the module width to no more than 1.25 in., and (2) we used commercially available parts wherever possible to minimize cost. The controller circuits sit in a cavity on the opposite side of the housing from a topside cavity containing the microwave circuits. The two types of circuits are connected by

an interface board with soldered-on feedthrough pins on one side and sockets on the other. (Because of the location of the feedthrough pins on the microwave side, we used an interface board that translated the feedthrough pins outside the controller area.) The interface board allows the controller to fit on a small double-sided circuit board. Except for the specialized hybrid (for the outputs of the latch feed), all parts of the controller are commercial surface-mounted components. The hybrid saves space and contains commercially available bare dice mounted on a ceramic substrate. The power supplies and digital interface are connected to the module via a 15-pin microminiature D connector (pins on 0.050-in. centers). The photograph in Figure 5 shows, from top to bottom, the microwave circuit side of the module, the interface board, and the controller circuit board.
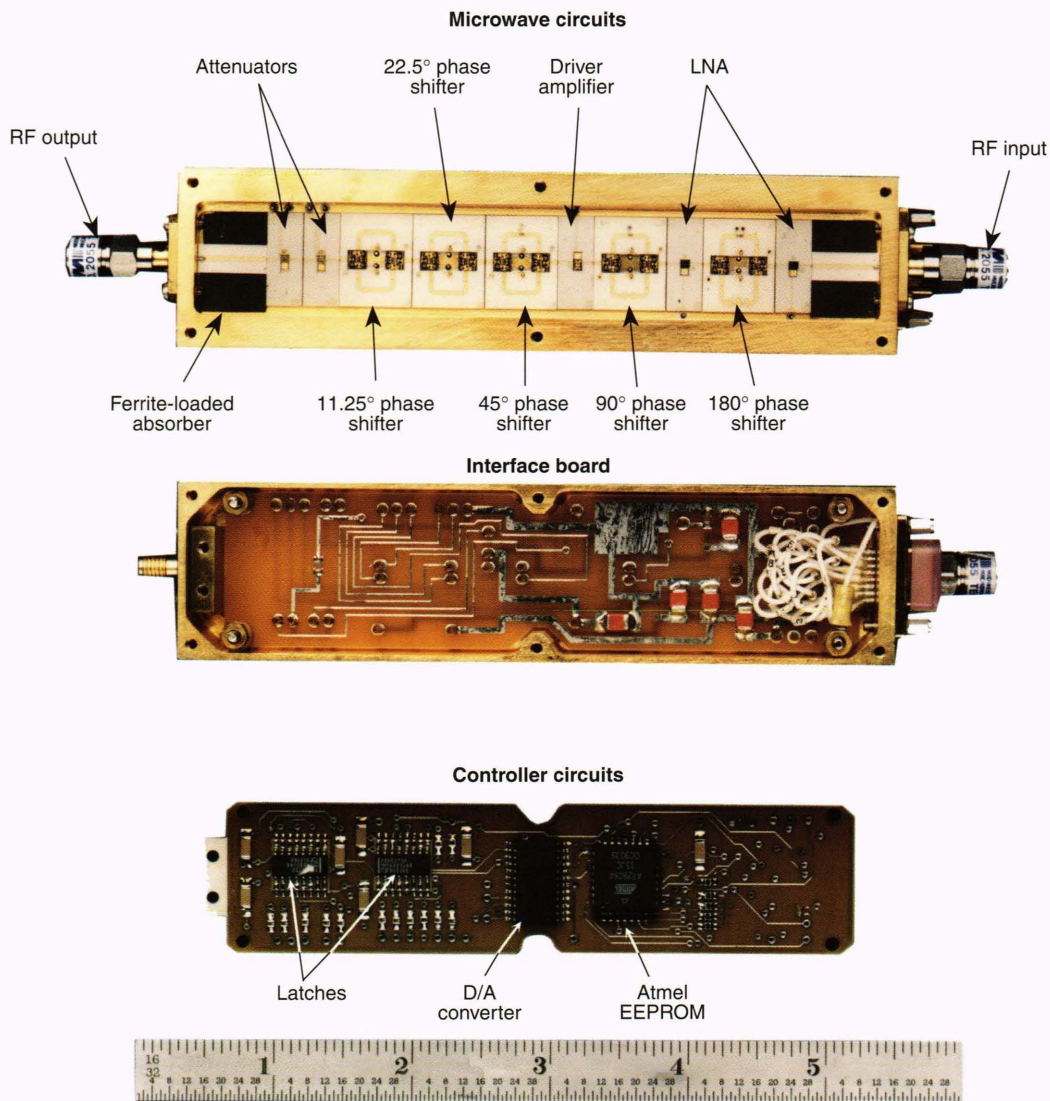

Figure 5. Photograph of the complete phased-array 4.8- to 5.2-GHz receive module and controller, showing (from top to bottom) the microwave circuits, the interface board, and the controller circuits. The interface board allows the controller to fit on a small double-sided circuit board. The Actel field-programmable gate array (FPGA) and the 74HC175 and hybrid are mounted on the back of the controller board. Almost all parts of the controller are commercial surface-mounted components.
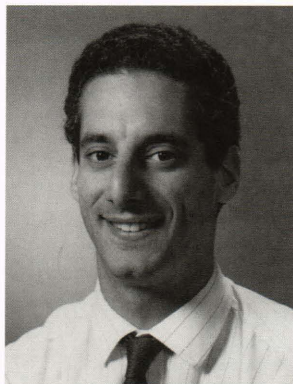
PHASED–ARRAY RECEIVE MODULE PERFORMANCE

All of the 1312 receive module states were successfully programmed. The module achieved 20 dB of attenuation in 0.5-dB steps in every phase state with a minimum accuracy of 0.25 dB. The average amplitude accuracy for any state was 0.08 dB. The phase shift was 360° in 11.25° steps in any attenuation state with an average accuracy of 3.2°. The maximum phase error exceeded the original design goal of 5.625° because of component interactions, but the more important root-mean-square phase value was below 5.625°. The noise figure for the complete receive module has not been measured, but it should be near the desired 3 dB on the basis of the LNA's 2.3-dB noise figure. The maximum input or output VSWR in any of the 1312 states was 1.38:1. Table 5 summarizes the microwave system performance.

CONTROLLER PERFORMANCE

The response time of the module to a new phase and amplitude command was on the order of hundreds of milliseconds. This relatively long time is due in large part to the slow speed of the digital serial input/output board in the PC that interfaces with the module. The time could be reduced to a few microseconds if we used a faster dedicated serial interface.

The time required to calibrate all 1312 phase/amplitude states of the module was about four hours, which is satisfactory for a small-volume run. A faster serial interface to the module could shorten this time also. Part of the calibration time, however, is consumed by communications between the PC and the vector network analyzer, in addition to the measurement process. Also, the calibration program is iterative, which means that it spends time searching for the optimum phase and amplitude settings for a particular state.

Table 5. Microwave system performance over the 4.8- to 5.2-GHz bandwidth for all possible phase and amplitude states.

Parameter	Specification	Measured
Nominal gain	≥20 dB	27 dB
Average amplitude accuracy	≤0.25 dB	0.08 dB
Average phase accuracy	≤5.625°	3.2°
Noise figure	≤3 dB	2.3 dB[a]
VSWR	≤1.80:1	1.38:1

[a]Measured on low-noise amplifier without input connector.

CONCLUSIONS

Our program has demonstrated that a calibrated high-performance C-band microwave receive module for phased-array antenna radar or communication applications can be successfully designed and implemented using commercially available MMIC's. Our module met or exceeded all of the microwave, packaging, and control design specifications for a typical antenna requirement.

REFERENCES

[1]Pengelly, R. S., "GaAs Monolithic Microwave Circuits for Phased-Array Applications," *Proc. IEEE* **127**, pp. 301–311 (1980).
[2]Naster, R. J., Jacomb-Hood, A. W., and Lang, M. R., "Affordable MMIC Designs for Phased Arrays," *Microwave J.* **30**, 141–150 (1987)
[3]Garver, R. V., "Broad-Band Diode Phase Shifters," *IEEE Trans. Microwave Theory Tech.,* **MTT-20**(5), 314–323 (1972).
[4]Kopp, B. A., "Passive Lumped Element Multi-Layer Thin-Film Circuits," *European Microwave Conf. Proc.,* in cooperation with IEEE and IEE, Microwave Exhibitions and Publishers, Ltd., London, England, pp. 653–655 (1989).

THE AUTHORS

BRUCE A. KOPP received a B.S.E.E. degree from Arizona State University in 1986 and an M.S.E.E. degree from Stanford University in 1988. From 1986 to 1990, he worked at Avantek, Inc., in Milpitas, California, designing over 100 passive and active printed lumped-element-based components operating at 0.01 to 26 GHz for commercial and military applications. Mr. Kopp joined the Microelectronics Group in the Technical Services Department at APL in 1990, where he worked on the development of microwave systems, polyimide and green tape filters, and MMIC amplifiers. He subsequently transferred to the Radar Systems Development Group of the Fleet Systems Department, where he is currently developing phased-array antennas. He has published several papers on the design of passive microwave components.

JONATHAN C. BARNETT received a B.S. in electrical engineering from Lafayette College in 1987 and an M.S. in electrical engineering from The Johns Hopkins University in 1990. He joined the Microelectronics Group at APL in 1987, where he designed digital and application-specific integrated circuits for a variety of satellite programs, including the SPINSAT altimeter and the Midcourse Space Experiment. He is currently a software engineer in the Submarine Technology Low Frequency Active Acoustics Group. He is a member of Eta Kappa Nu and Tau Beta Pi.