Advances in Gallium Arsenide Monolithic Microwave Integrated-Circuit Technology for Space Communications Systems

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Abstract — Future communications satellites are likely to use gallium arsenide (GaAs) monolithic microwave integrated-circuit (MMIC) technology in most, if not all, communications payload subsystems. Multiple-scanning-beam antenna systems are expected to use GaAs MMIC's to increase functional capability, to reduce volume, weight, and cost, and to greatly improve system reliability. RF and IF matrix switch technology based on GaAs MMIC's is also being developed for these reasons. MMIC technology, including gigabit-rate GaAs digital integrated circuits, offers substantial advantages in power consumption and weight over silicon technologies for high-throughput, on-board baseband processor systems. In this paper, current developments in GaAs MMIC technology are described, and the status and prospects of the technology are assessed.

I. INTRODUCTION

STUDIES conducted by NASA in the late 1970's showed that the demand for orbital locations and frequency allocations for fixed satellite service will exceed the orbit and spectrum capacity (at the C- and Ku-band) by the early 1990's [1], [2]. NASA's approach to addressing these problems was to develop new technologies 1) to open the Ka-band, 2) to use multiple-beam antennas to obtain the benefits of manifold frequency reuse, and 3) to use onboard processing and multiple scanning beams to address "customer premises" traffic so that large, complex Ka-band satellites would be economically viable in the 1990's, notwithstanding advances in optical-fiber-based competing systems for trunking traffic. The experimental Advanced Communications Technology Satellite (ACTS) is expected to complete the planned development.

Second-generation operational satellites that apply the concepts proven by ACTS can exhibit greatly improved performance and economics by capitalizing on the longer range monolithic microwave integrated-circuit (MMIC) technology developments recently initiated [3]. These include 1) 20-GHz transmitter modules and 30-GHz receiver modules with digitally addressed amplitude and phase control; 2) matrix switches at both 20 GHz and intermediate frequencies; 3) GaAs digital integrated-circuit (IC) modules for high-speed, low-power baseband processor components; and 4) optical fiber/MMIC monolithic interfaces. All of these technology elements are in NASA's MMIC program. They will be addressed, respectively, in
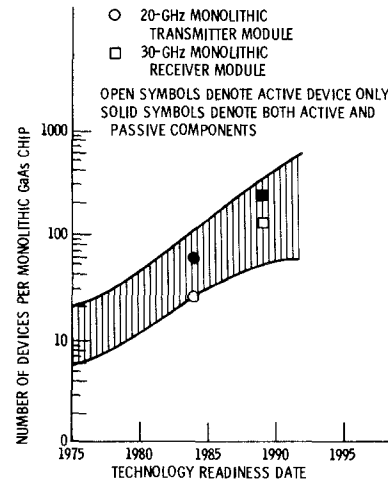
Fig. 1. Level of monolithic integration of microwave devices and passive components on GaAs substrate.

Sections II to VI, followed by concluding remarks on their status and potential. General ideas concerning the impact of MMIC's are also discussed.

II. GaAs MMIC TECHNOLOGY — STATUS

GaAs MMIC's are increasingly becoming a practical reality [4], [5]. Their use is being extended to millimeter-wave frequencies [6]. The driving factor behind the development of this technology has been batch processing, leading to low cost, high performance, small size, and reproducibility similar to that for silicon integrated circuits. The excellent microwave properties of semi-insulating GaAs substrates, GaAs crystal and epitaxial film growth techniques, the development of the GaAs metal–semiconductor field-effect transistor (MESFET), and MESFET computer-aided circuit design have provided additional impetus for this rapid growth in recent years.

A GaAs MMIC consists of several active and passive components. The active components are GaAs MESFET's and Schottky-barrier diodes. The major passive components are thin-film resistors, metal–insulator–metal overlay capacitors, interdigitated capacitors, and spiral inductors. Lumped- or distributed-element circuitry is used. Plated air bridges are used for circuit element connections,
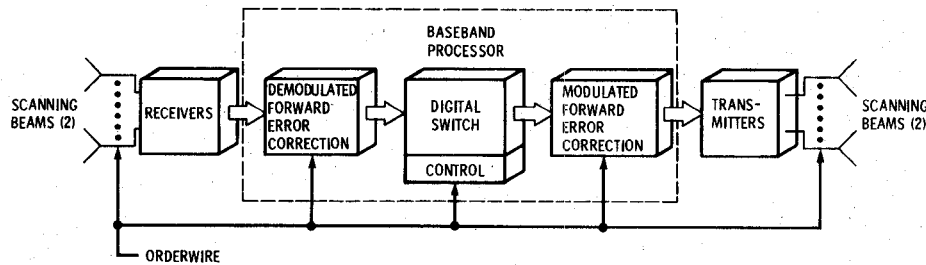
Fig. 2. Communications payload for experimental flight system based on phased-array antenna and baseband processing technology.

and through-substrate holes are used for ground interconnections.

The active layers in GaAs MESFET's for MMIC's are commonly formed by ion implantation and chemical vapor deposition (CVD). Molecular beam epitaxy, organometallic chemical vapor deposition, and vapor-phase epitaxy are examples of CVD techniques. These techniques are also providing new microwave device structures based on the properties of heterojunctions. High-electron-mobility transistors are emerging as a promising structure and will soon find their way into high-performance MMIC's [7], [8].

The level of microwave devices and passive component integration has been steadily increasing in the past few years, as shown in Fig. 1, for MMIC's developed in the 20–30-GHz band. However, several aspects of the technology still need to mature to produce low-cost, reliable MMIC's for system applications. Improvements in material quality, accuracy in circuit modeling, faster and easier techniques for circuit characterization, and advances in circuit packaging are required. Recent advances in MMIC technology for future space communications systems are described in the next section.

III. GaAs MMIC Technology for Scanning-Beam, Phased-Array Antennas

A block diagram of the communications payload for future 20–30-GHz advanced communications satellites is shown in Fig. 2. This payload contains phased-array antennas and baseband processing and switching. MMIC technology is under development in each of these areas. Several types of MMIC modules for use in scanning-beam, phased-array antennas are discussed here.

A. 20-GHz MMIC Transmitter Module

Rockwell International, under NASA contract, has developed a fully monolithic 20-GHz transmitter module on a GaAs substrate. The technology goals for these devices are given in Table I, and the module is shown in Fig. 3.

The module consists of five cascaded, single-bit, switched-line phase shifters, employing field-effect transistor (FET) devices for switches. The phase shifters, with phase bits of 11.25°, 22.5°, 45°, 90°, and 180°, can be easily identified in Fig. 3. FET's in series–shunt configurations are employed to effect a single-pole, double-throw switch (SPDT). The series and shunt FET gate widths are 290 and 190 μm, respectively. Two of each of these FET's

TABLE I
TECHNOLOGY GOALS FOR MMIC COMPONENTS

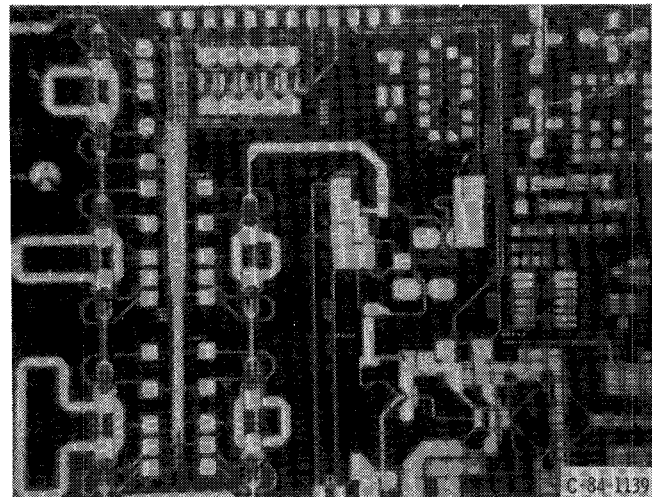|	Variable phase shifter	Constant-gain amplifier	Variable-power amplifier
RF band, GHz	17.7 to 20.2	17.7 to 20.2	17.7 to 20.2
RF power output, W		200x10^{-3}	0 to 0.5 (variable)
Gain, dB	0	16	20 max. (variable)
Phase bits, deg	11.25,22.5,45,90,180		
Phase control	Five-bit digital input		
Amplitude control			Four-bit digital input
Efficiency, percent		15	15/6
Mechanical design	Monolithic	Monolithic	Monolithic
Chip size, mm	4.7 by 4.7	3.1 by 1.5	3.05 by 6.45

Fig. 3. 20-GHz monolithic phase shifter module (4.8×6.4×0.127 mm).

are employed in each SPDT switch. All FET gates are 1 μm long. A two-stage buffer amplifier follows the phase shifters to compensate for their insertion loss, and a final three-stage power amplifier provides the required output power. The module represents the highest level of component and function integration for circuits operating near 20 GHz. The total active device count is 73 (FET's and diodes); the passive devices number approximately 75.

Fig. 3 shows the digital-to-analog (D/A) converter employed as the interface between the transistor–transistor logic input signals and the switch control for the 20-GHz phase shifter. Experimental data for five phase shifter states are presented in Fig. 4. The circuit represents the first monolithic integration of digital functions with microwave circuit functions above the X-band on a single chip [9].
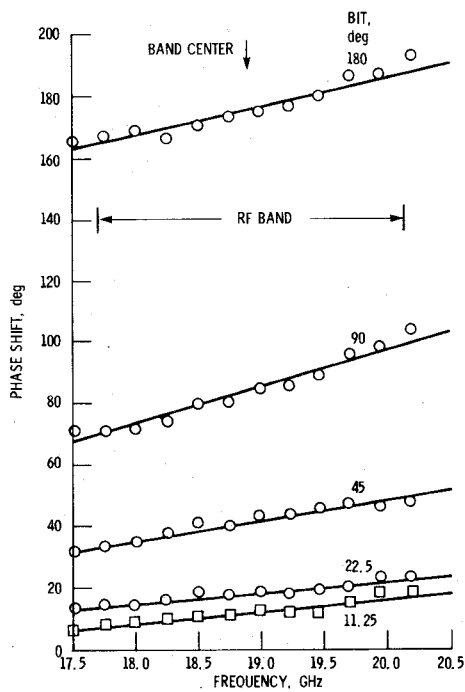
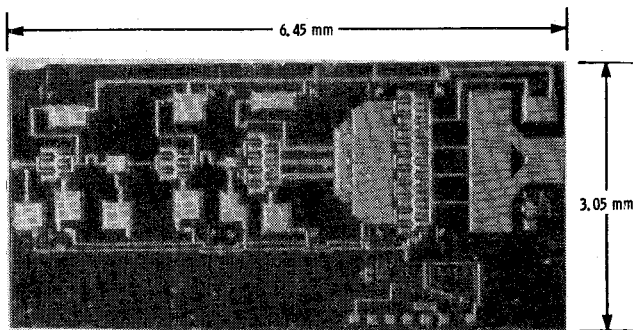Fig. 4. Phase shift versus frequency for five phase shifter states for 20-GHz variable-phase-shifter module.

Fig. 5. MMIC chip for 20-GHz variable-power amplifier.

B. 20-GHz Variable-Power Amplifier

Texas Instruments is developing, on NASA contract, a 20-GHz variable-power amplifier (VPA) for power level control in a phased-array antenna feed [10]. The technology goals for the VPA are given in Table I, and the amplifier is shown in Fig. 5.

The objective of the VPA development is to provide an amplifier that is electronically switchable to any one of five output power levels: 500, 125, 50, 12.5, and 0 mW. The efficiency varies from 15 percent at 500 mW to 6 percent at 12.5 mW. The VPA consists of a four-stage, dual-gate FET amplifier and a D/A converter on a 3.05 × 6.45-mm GaAs chip. The D/A converter controls the output power level by providing the required bias voltage to the second gate of the dual-gate FET in each stage. Power control with a dual-gate FET has several advantages. The FET gain can be changed over a large dynamic range (20 to 40 dB). Over most of this range, the transmission phase shift is less than 5 percent, and the FET input/output impedances are essentially constant,
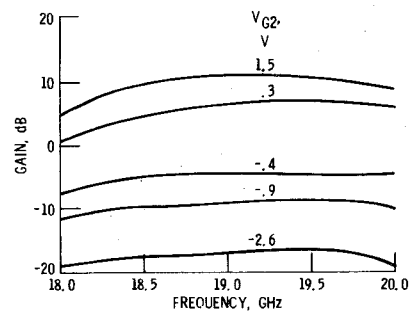

Fig. 6. Measured gain versus frequency response of variable-power amplifier. RF input: 0 dBm. Drain voltage: 5.5 V. Drain current: 300 mA. First gate voltage: 0.73 V. Second gain voltage (V_{G2}) is varied as shown.
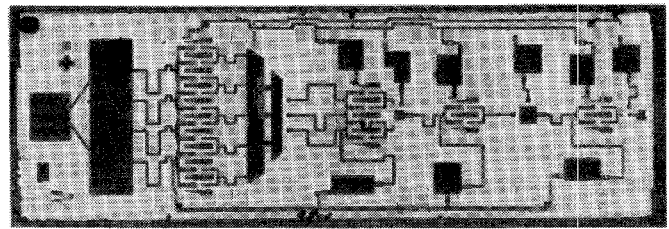

Fig. 7. 20-GHz dual-gate amplifier (6.5 mm × 0.1 mm).

providing a gain-versus-frequency-response curve with a nearly constant shape (Fig. 6).

The VPA module employs four stages of amplification. The initial single-gate amplifier module has achieved an output power of 630 mW with 25-dB gain and 21-percent power-added efficiency. The four-stage, dual-gate amplifier (Fig. 5) has demonstrated an output power of 250 mW with 15-dB gain. The chip size is 6.45 × 3.05 mm. The four stages of amplification employ a total gate periphery of 2.7 mm. The final-stage power combines the output of 11 FET's (0.5-μm gates) with 1.5 mm of gate periphery.

Both the single- and dual-gate amplifier versions were the first reported 20-GHz amplifiers to monolithically integrate large-periphery power FET's. Total gate peripheries of 2.7 mm of 0.5-μm-gate FET's were used.

The monolithic four-stage, dual-gate amplifier (Fig. 7) represents the first demonstrated dual-gate amplifier above the X-band. The four-bit D/A converter (Fig. 5) will be incorporated on the same chip with the dual-gate amplifier. The newly integrated amplifier will thus be the first monolithically implemented 20-GHz VPA.

In a related effort, a high-power, high-efficiency monolithic power amplifier for the 19–21-GHz band is being developed by Texas Instruments for other advanced communications applications. The objectives are 20-percent efficiency and 15-dB gain with a power output of 2.5 W at saturation.

Two approaches are being considered to meet these objectives, a three-stage amplifier and a power-combined distributed amplifier. The three-stage amplifier (Fig. 8) has achieved 2.5-W output power with 18-dB gain and 16-percent efficiency at 18 GHz. The amplifier's total gate periphery of 9.6 mm of 0.5-μm-gate FET's produced the highest reported output power from a single chip — 2 W.
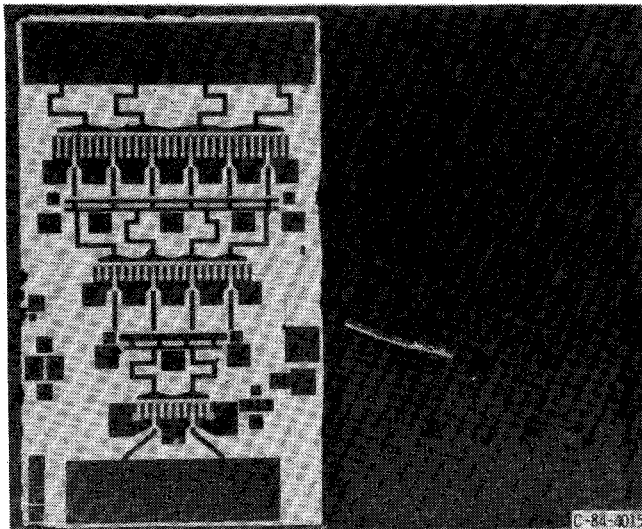
Fig. 8. Dual-stage amplifier.

TABLE II
TECHNOLOGY GOALS FOR 30-GHz RECEIVER

RF band, GHz	27.5 to 30
IF center frequency, GHz	4 to 8
Noise figure at room temperature, dB	5 (7 for LNA)
RF/IF gain, dB	30 at highest level of gain control
Gain control, dB	At least six levels (30, 27, 24, 20, 17, and off)
Module power consumption, mW	250 in all states except off. In off state, 25
Phase and gain control	Five- and four-bit digital input
Mechanical design	Monolithic
Chip size, mm	12 by 7

The amplifier gain was 12 dB with a 20-percent power-added efficiency.

C. 30-GHz Monolithic Receiver Module

Several groups have fabricated and tested GaAs monolithic receivers in the X-band [11] and the K-band [12]. However, fully monolithic receivers with variable phase shifting and gain functions for application in phased-array satellite receivers have not been demonstrated. To achieve this objective, an effort has been undertaken to integrate a low-noise amplifier, a variable phase shifter, a mixer, and an intermediate-frequency (IF) amplifier on a single GaAs MMIC chip for operation in the 27.5–30-GHz band. The technology goals for this 30-GHz MMIC receiver module are shown in Table II.

Two approaches have been taken to achieve the desired performance. The first approach has a phase shifter and a variable-gain control at the receiver frequency. The receiver module under this approach (Fig. 9(a)) is being developed at Honeywell Physical Sciences Center under NASA contract. The second approach uses a large coupler and a pair of GaAs Schottky diodes to form an analog phase shifter that operates at the local oscillation frequency (23.5–26 GHz). The variable-gain control is achieved at the intermediate-frequency stage. This approach (Fig. 9(b)) has been taken by Hughes Torrance Research Center under NASA contract. With the first approach, Honeywell has demonstrated a 30-GHz variable-phase-shift MMIC submodule [13] and a variable-gain-control amplifier mod-
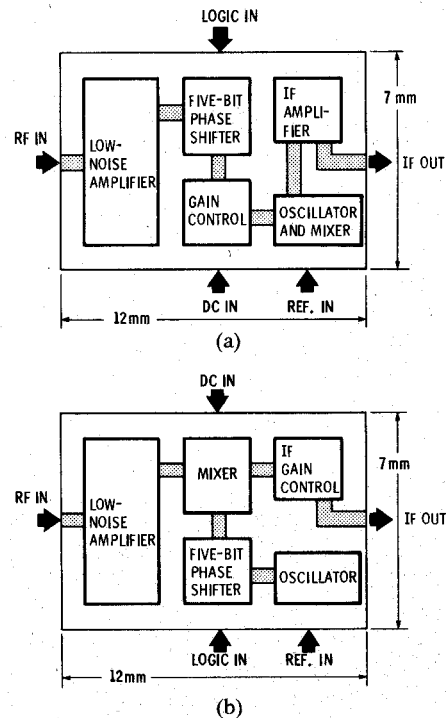

Fig. 9. Block diagrams of fully integrated 30-GHz receiver MMIC concepts. (a) Honeywell approach. (b) Hughes approach.
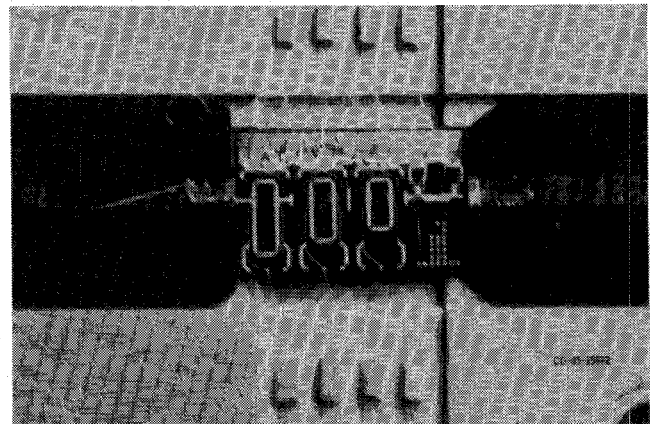

Fig. 10. 30-GHz variable-phase-shifter MMIC submodule.

ule [14]. The phase shifter module is shown in Fig. 10, and experimental data are presented in Fig. 11. The phase shifter uses FET switches to divert radio-frequency (RF) signals between two differential line lengths for three bits (45°, 90°, and 180°). An analog loaded line is tapped and calibrated at the three lower levels (11.25°, 22.5°, and 45°) to provide the more difficult smaller two bits.

A two-stage low-noise amplifier (LNA) with 14-dB gain and 7-dB noise figure has been demonstrated under the second approach by Hughes [15]. The low-noise amplifier is shown in Fig. 12, and the experimental data are presented in Fig. 13. An IF amplifier (Fig. 14), a mixer (Fig. 15), and a phase-shifter module (Fig. 16) have also been fabricated. The IF amplifier has 13-dB gain with 30-dB control range. The mixer and phase shifter have conversion loss and insertion loss of 10.5 and 11.6 dB, respectively [16].
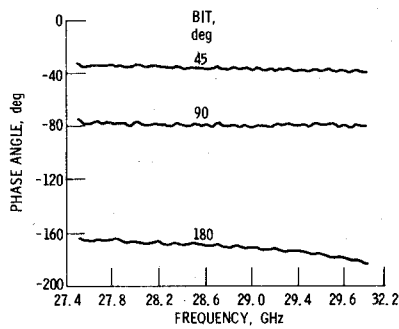
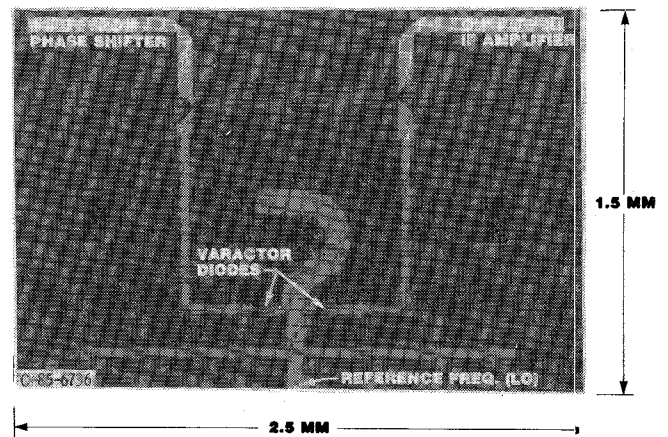Fig. 11.   Experimental measurement for 30-GHz monolithic phase shifter. Maximum insertion loss: −8 dB.

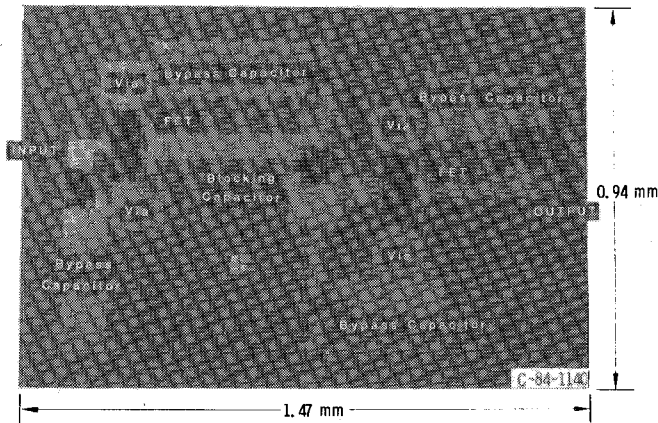Fig. 15.   *Ka*-band mixer.

Fig. 12.   27.5–30-GHz monolithic low-noise amplifier.
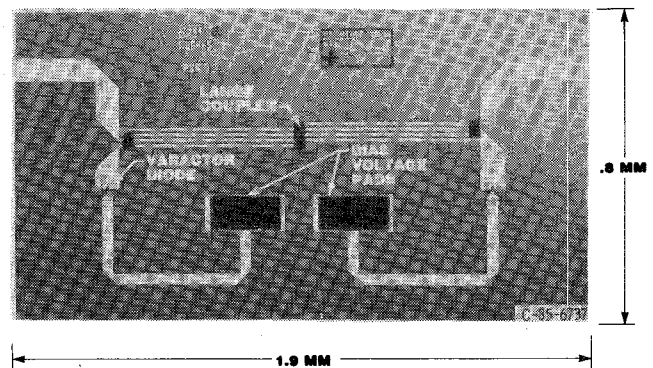

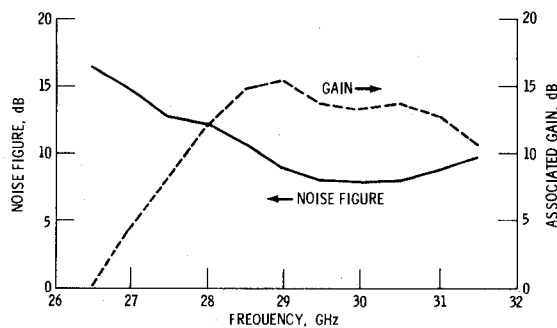Fig. 16.   23.5-GHz phase shifter.

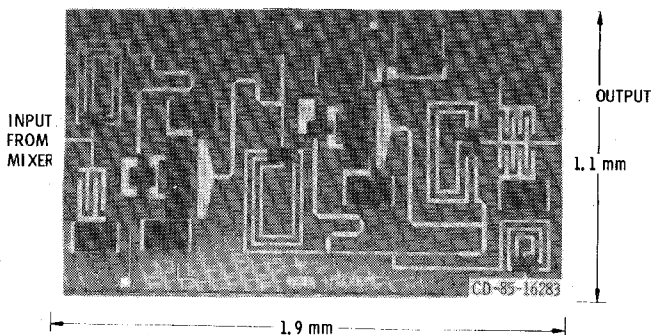Fig. 13.   Performance of 27.5–30-GHz monolithic low-noise amplifier.

Fig. 14.   2–6-GHz intermediate-frequency amplifier.

D. Packaging Considerations

NASA plans 1) to characterize all types of MMIC devices, 2) to fabricate, test, and evaluate small subarrays in order to demonstrate the effectiveness of individual functions such as variable phase shift or variable gain, and 3) to design and fabricate an experimental antenna system for demonstrating and evaluating most of the antenna configurations developed in the studies.

Although many of the MMIC chips are still under development, their packaging and systems connections are being evaluated. For the 20-GHz MMIC transmitter module, a ceramic-based holder has been designed and fabricated (Fig. 17). The design of this holder takes into account physical protection, electrical interconnections, and the thermal dissipation requirements of the MMIC chip. The MMIC chip is to be bonded to the holder with a eutectic solder that will provide a good electrical ground-plane connection to the chip and high thermal dissipation.

Another important consideration in bonding the MMIC chip is minimizing the thermal expansion stress between the chip and the holder. The electrical interconnections between the chip and the holder are of two basic types: 20-GHz RF input and output lines, and control and bias lines. The RF input and output lines will be the most critical since they are sensitive to propagation mismatch, resistive losses, contact losses, and step discontinuities. For system interconnection, the MMIC packages are mounted in the waveguide housing (Fig. 18). Van Heuven finlines
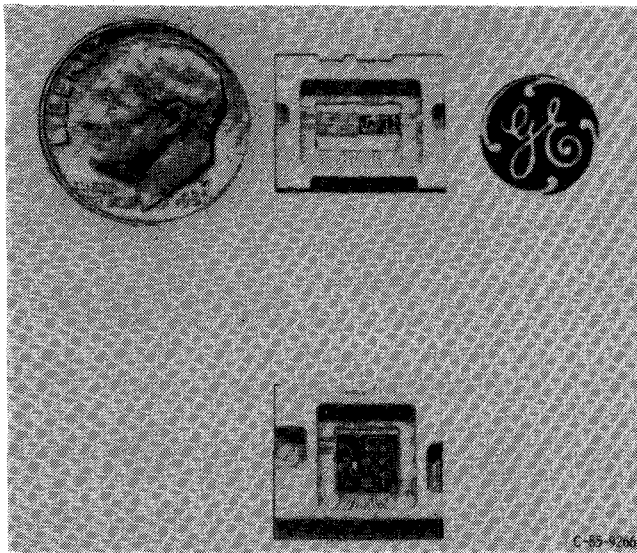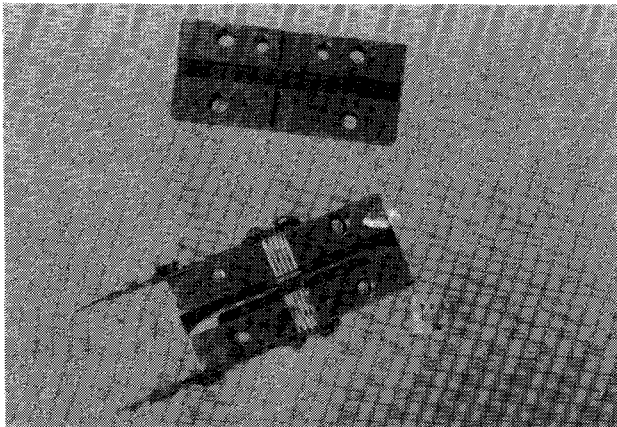
Fig. 17. Two designs for 20-GHz MMIC holders.

Fig. 18. 20-GHz waveguide housing.

have been used in the 30-GHz MMIC phase shifter for system interconnection [5, pp. 397–408]. These finlines allow planar integration of MMIC chips.

IV. MONOLITHIC OPTICAL INTEGRATED CONTROL CIRCUITRY FOR GaAs MMIC's

It is becoming apparent that using conventional microwave transmission-line components for signal distribution in a phased array results in a complex signal distribution system. Furthermore, using a waveguide for millimeter-wave frequencies adds weight and bulk.

Fiber-optic technology may provide an answer to the MMIC phased-array signal distribution problem [17]. Optical fiber can be used to transmit both analog and digital signals. It has other advantages — small size, light weight, flexibility, and large bandwidth. Optical wavelength division multiplexing, which allows distribution of diverse signals simultaneously on a single fiber, will further reduce signal distribution complexity. Since short links are involved in the phased-array signal distribution network, the shorter 850–900-nm wavelength will suffice. Also, GaAs-based optoelectronic devices, required to provide the interface between the optical fiber and the GaAs MMIC's,

operate in this region. Several GaAs optical integrated circuits, such as a P-type intrinsic N-type (PIN) photodiode/FET/amplifier [18], [19] and a laser/FET/transmitter [20], [21] have been demonstrated. The optical electronic integrated circuits (OEIC) required to interface with GaAs MMIC's have not yet been integrated on a single chip. Their feasibility depends on the development of compatible fabrication techniques.

In an active solid-state phased array based on a fiber-optic network, an optical fiber from the central processing unit will be connected to the MMIC module for the phase and gain control functions. The RF input or IF output to the MMIC's will be connected to the baseband processor by an optical fiber if feasible. It may be possible to combine the two links on a single fiber. Implementing these optical fiber links for an MMIC phased-array signal distribution network will require integrated optical transmitters and receivers on GaAs substrates. As an example, an MMIC transmitter module with optical integrated feed circuitry is shown in a conceptual diagram (Fig. 19). Interfaces for phase and amplitude control of a transmitter module require transmission of the digital signal by optical fiber. The input signal to the transmitter module will require RF optical links. Design and component considerations for these connections are described here.

Optical intensity modulation techniques, either direct or indirect depending on the frequency limitation of the various optical components, can be used for distributing the RF signal to the MMIC. The major considerations in using optical fiber for distributing the RF signal are insertion loss, stability, dynamic range, and signal-to-noise ratio. The major advantage is that a single fiber can carry multiple signals.

Direct laser modulation to 8 GHz (using a GaAs/AlGaAs semiconductor laser) has been demonstrated [22] and is being extended to ever higher frequencies [23]. The highest modulation frequency achievable with this technique is limited for fundamental reasons [23]. An insertion loss of 25 dB has been observed for a single fiber link [19]; under optimum performance conditions, the loss can be reduced to 10 dB.

Distributing the RF input signal to the transmitter module, to the local oscillator, and to the IF signal output of the receiver module by intensity modulation will require the following GaAs optical integrated circuits:

1) a high-frequency, high-efficiency external modulator with a high optical damage threshold on a GaAs substrate;

2) a wide-band integrated GaAs photodetector (to 100 GHz) and preamplifier for demodulating the signal integrated with the MMIC;

3) a high-power laser source capable of being directly or indirectly modulated at high frequencies with an integrated driver;

4) a power splitter with a minimum insertion loss on a GaAs substrate; and

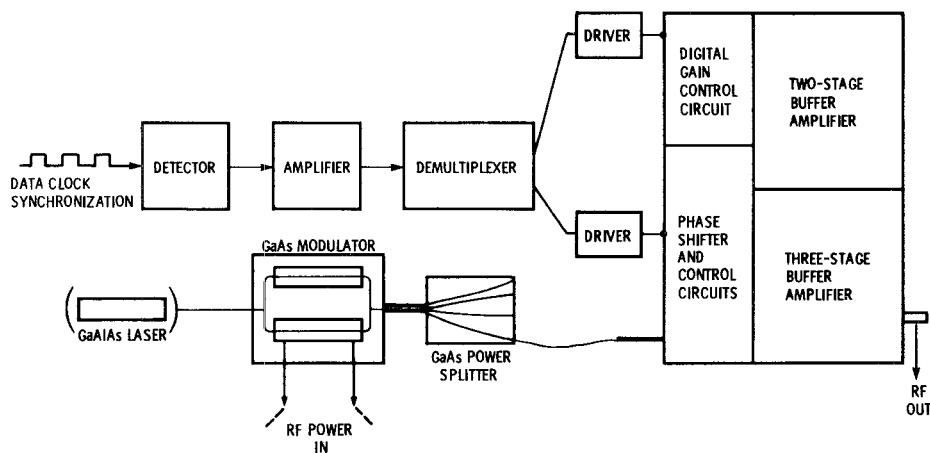5) an integrated laser and low-frequency driver with an extremely linear performance to carry the IF signal

Fig. 19. Block circuit diagram of optical/MMIC interface.

TABLE III
TECHNOLOGY GOALS FOR GaAs OPTICAL INTEGRATED CIRCUIT

```
Optical input . . . . . . . . . . . . 1-Gbps optical signal on multimode fiber
                                                   (50-μm core diameter)
Electrical input:
  For optical receiver . . . . . . . . . . . . . . . . . . . . . . . . . +5 Vdc
  For voltage interface circuits . . . . . . . . . . . . . . . . . . . . +5 Vdc
Timing input . . . . . . . . . . . . . . . . . . 1-V minimum pulse amplitude at
                                                   100-MHz repetition rate
Receiver performance . . . . . . . . Sensitivity higher than -30 dB with bit
                                                   error rate less than 10⁻⁹
Power consumption
  For receiver and control logic . . . . . . . . . . . . . . . . . . . . <50 mW
  For output drivers to interface TTL . . . . . . . . . . . . . . . 30 mW/bit
    logic levels for MMIC modules
Output to control MMIC phase shifter . . . . . . . 16-bit parallel data stream
  and MMIC gain TTL compatible and
  for circuits clocked at 50 MHz
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from the MMIC receiver module to the on-board processing system.

Phase and amplitude control of GaAs MMIC's can be achieved via a single fiber from the array processor rather than the several electrical connections needed currently. Such an interconnect will require monolithic integration of optical components (laser, photodiode, etc.) with GaAs MMIC's and an array processing chip.

The NASA Lewis Research Center has taken the initiative in developing a photoreceiver on a GaAs substrate that will control the phase and gain functions of an MMIC. Subsequent optical electronic integrated circuitry, required for an optical interface to MMIC's, that will digitally control phase shifting and gain functions includes:

1) an integrated photodetector, a preamplifier, and timing circuitry on a GaAs substrate (the detailed performance objectives of this optical integrated circuit to be developed under NASA contract being given in Table III); and

2) an integrated laser capable of operating at a high bit rate with the compatible high-speed computer for the phased-array control system.

This optical integrated circuitry will be most effective if it can be monolithically integrated with GaAs MMIC's. Fabrication techniques for OEIC's and MMIC's need to be compared in order to evaluate the feasibility of monolithic integration.

V. MONOLITHIC GaAs IF SWITCH MATRIX

An IF switch matrix for on-board satellite signal processing is being designed, fabricated on a single GaAs chip, and evaluated by Microwave Monolithics, Inc., for NASA. FET switches are used for signal steering. FET buffer amplifiers provide an overall insertion loss of 0 dB, allowing two-dimensional cascading to form very large arrays (up to 100×100), also with 0-dB insertion loss. Switching is obtained by a proprietary crosspoint element design technique.

A monolithic GaAs IF switch array (100×100) will weigh only 17 lb in 200 in^3. For comparison, a hybrid crosspoint switch matrix will weigh 500 lb in approximately 12 000 in^3 of volume. Additional benefits of 60-dB isolation between input and output lenses and higher reliability are also anticipated.

VI. GaAs SERIAL–PARALLEL INTERFACE MODULE

Because of an anticipated growth in the volume of communications, on-board data processing is a key area of development for advanced communications systems. High-speed, low-power parallel-to-serial (P/S) and serial-to-parallel (S/P) converters are being developed on a GaAs substrate in order to interface on-board high-speed processors to large volumes of on-board solid-state memory. Gallium arsenide converters (1–6, 1–32, and 1–64 S/P and 16–1, 32–1, and 64–1 P/S) are under development. To date, 16:1 multiplexers and 1:16 demultiplexers with enhancement/depletion-mode, direct-coupled MESFET logic have been fabricated by Honeywell's Physical Science Center. Two versions of the 16:1 and 1:16 were designed, each with TTL-compatible input and output ports. One design of the 16:1 and 1:16 operated at 200 MHz with 25–30 mW per chip. A faster design operated at 450 MHz with 50 mW per chip.

In these modules, low power was obtained by multiplexing or demultiplexing in two separate stages. For the 16:1 multiplexer, the outputs of four low-speed 4:1 multiplexers are fed into a single high-speed 4:1 multiplexer. Simply, the 1:16 is implemented as a high-speed 1:4 demultiplex operation and four low-speed 1:4 demultiplex operations.

Thus, only four registers are required to clock at the maximum data rate. These S/P and P/S interface module characteristics will greatly reduce the power required for this function from that required with currently available electronic coupled logic technology.

VII. CONCLUDING REMARKS

The developments in GaAs MMIC technology presented in this paper have shown that high levels of device and component integration are feasible up to 30 GHz. These developments have also demonstrated integration of substantial power capability and integration of digital and microwave functions.

It is not overly optimistic to extrapolate the ultimate capabilities of this technology to higher frequencies, perhaps to 100 GHz. Passive components tend to become smaller with increasing frequency. At 30 GHz, they are not even close to the limits of available microfabrication techniques. Active components presently limit the frequency range of MMIC's, but GaAs FET operation has already been demonstrated at 70 GHz. MMIC-compatible active device technologies, such as high-electron-mobility transistors, promise to substantially extend the frequency range available with MMIC's. It is clear that MMIC technology will eventually allow the manufacture of very low-cost millimeter-wavelength components. Potential applications in consumer, industrial, and military products could constitute an enormous market for these components.

An important concept to focus longer term technology developments in satellite communications is global interconnectivity through hierarchical switching satellite networks [24]. Key system technologies will include multibeam antennas, switching and processing, low-cost user terminals, and laser intersatellite links. All of these technologies except laser intersatellite links may be substantially affected by incorporation of MMIC components. Current developments in the NASA MMIC program are in the feasibility demonstration stage, where the circuit yield is expected to be small and unpredictable and where there are substantial chip-to-chip variations in the device performance parameters. Emphasis will shift to maturing these devices to the point where the technology could support proof-of-concept system or subsystem developments [25]. It is hoped that the MMIC program funded by the Department of Defense will stimulate development of MMIC fabrication capability in the United States and greatly reduce the NASA investment necessary to develop MMIC-based satellite communications components.

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