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Monolithic Optical Integrated Control Circuitry for GaAs MMIC-Based Phased Arrays

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SUMMARY

Gallium arsenide (GaAs) monolithic microwave integrated circuits (MMIC's) have shown promise in phased-array antenna applications for future space communications systems. Their efficient usage will depend on the control of amplitude and phase signals for each MMIC element in the phased array and in the low-loss radiofrequency feed. For a phased array containing several MMIC elements a complex system is required to control and feed each element. Current techniques such as coaxial cables and waveguides are cumbersome. Such a complex control system offsets the advantages offered by the small size of MMIC's. Fiber optic technology has been proposed as a means to alleviate signal distribution problems. In this paper the characteristics of GaAs MMIC's for 20/30-GHz phased-array systems are discussed. The optical/MMIC interface and the desired characteristics of optical integrated circuits (OIC's) for such an interface are described. Anticipated fabrication considerations for eventual full monolithic integration of optical integrated circuits with MMIC's on a GaAs substrate are presented.

E-2835

INTRODUCTION

Recent developments in GaAs monolithic microwave integrated circuit (MMIC) technology (ref. 1) have increased the possibility of affordable fully solid-state microwave hardware for phased-array antennas (ref. 2). In a microwave phased-array antenna MMIC's act as individual radiating elements to provide a desired radiation pattern. MMIC chips designed to date control, in a single element, both amplitude and phase, which determine the radiation pattern and its direction. Each of these elements requires phase and amplitude control signals and a radiofrequency (RF) input signal. If conventional microwave transmission line components are used for signal distribution, a complex signal distribution system is anticipated. Furthermore for millimeter-wave operation the use of a waveguide for RF input adds weight and bulkiness.

Fiber optic technology may provide an answer to the MMIC phased-array signal distribution problem (ref. 3). Optical fiber can be used to transmit both analog and digital signals. Other advantages of fiber optic signal distribution include 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- to 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 field-effect-transistor (FET) amplifier (refs. 4 to 6) and a laser/FET/transmitter (refs. 7 to 9) have been demonstrated. The optical integrated circuits 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 this paper the characteristics of GaAs MMIC's for 20/30-GHz phased-array systems are discussed. The optical/MMIC interface and the desired characteristics of optical integrated circuits (OIC's) for such an interface are described. Anticipated fabrication considerations for eventual fully monolithic integration of optical integrated circuits with MMIC's on a GaAs substrate are presented.

GaAs MMIC CHARACTERISTICS

The NASA Lewis Research Center has a substantial ongoing program to develop MMIC circuits in the 20- and 30-GHz frequency bands primarily for phased-array antenna applications. The characteristics of the 20-GHz transmit module and the 30-GHz receive module pertaining to the optical interface are summarized here. By using a microstrip design and GaAs metal semiconductor field-effect (MESFET) technology, active and passive devices are fabricated on a GaAs semiconductor substrate to achieve monolithic integration. In addition, each of these modules has a digital-to-analog (D/A) converter circuit incorporated on the same GaAs substrate to control the signal phase shift and the RF output power level. The control of the D/A converters and possibly the distribution of the input RF sources for a system containing large numbers of MMIC's appear to be prime candidates for MMIC optical control interfaces.

An important feature of all three MMIC modules discussed here is their several-fold integration of many and varied types of devices onto a single module. The types of devices include FET's used both as switches and in amplifying circuits, capacitors, microstrip transmission lines, resistors, and diodes. The capability to monolithically incorporate many electronic circuit functions at microwave frequencies onto a single chip provides low-cost, reliable, and small MMIC modules. Because of the promised advantages of MMIC's a 20-GHz variable phase shift (VPS) module and a 20-GHz variable power amplifier (VPA) module are being used in the 44-month, contractual NASA phased-array Experimental Antenna System (EAS) program to demonstrate the feasibility of using MMIC devices. During this development it has become apparent that such a phased array will require a complex signal distribution network.

20-GHz Variable Phase Shifter (VPS)

A VPS module (table I, fig. 1) is under development by Rockwell International for use in the EAS program. The module contains a five-bit phase shifter with its D/A control and amplification circuitry on a 4.8- by 6.4-mm GaAs chip. The VPS module contains a phase shifter circuit with controls that provide a digitally selectable module phase shift capability of 0° to 360°, in increments of 11.25°. A two-stage buffer amplifier follows the phase shifter to compensate for the phase shifter losses. A three-stage power amplifier completes the module. This VPS module represents a high level of component and function integration for MMIC's operating near 20 GHz. There are 73 active devices (FET's and diodes) and 75 passive devices. Each submodule requires a minimum of five connections for phase shifting and several bias connections. More detailed information on this VPS module is presented elsewhere (ref. 10).

20-GHz Variable Power Amplifier (VPS)

Texas Instruments is developing a 20-GHz monolithic variable power amplifier module (table II, fig. 2) for NASA that is to be used in conjunction with the VPS module to provide the required power level and phase shift functions of a phased-array antenna beam control.

The objective is to provide an amplifier than can be electronically switched to any one of five output power levels: 500, 125, 50, 12.5, or 0 mW. The power-added efficiency goal is 15 percent at the 500-mW level and 6 percent at the 12.5-mW level. The VPA consists of a four-stage, dual-gate FET amplifier and a D/A converter on a 3.05- by 6.45-mm GaAs chip (ref. 11). The D/A converter provides the required bias voltage to the second gate of the dual-gate FET for control of the output power level. Control with a dual-gate FET has several advantages: The FET gain can be varied over a large dynamic range (20 to 40 dB). Over this range the amplifier has a minimum transmission phase shift (~5°) and the FET input/output impedances are essentially constant; providing a constant shape for the curves of gain against frequency response.

30-GHz Monolithic Receive Module

Two parallel efforts to develop a 30-GHz receive module are in progress: one with the Hughes-Torrance Research Center, and the second with the Honeywell Physical Sciences Center. A different approach is being taken by each contractor, but the technology goals for the receive module (table III) are the same for both contracts. The 30-GHz receive module development is the most ambitious of the NASA MMIC developments. It seeks to combine five separate submodules on a single GaAs chip: a low-noise amplifier, an amplifier with gain control, a variable phase shifter, a mixer, and an intermediate-frequency (IF) amplifier.

Even with only approximately one-half of the program having been completed, a number of advances in the receive module technology have been made. Hughes has fabricated a two-stage, low-noise amplifier with a 13-dB gain and a 6.5-dB noise figure (exceeding the goals of a 12-dB gain and a 4.5-dB noise figure). Hughes has also fabricated the IF amplifier (fig. 3). The output frequency range of the IF amplifier is 2 to 6 GHz. The phase shifter and mixer submodule have also been fabricated. Phase shifter design is based on the application of varying voltage to two Varactor diodes coupled by a Lange coupler until the desired phase shift is achieved. The mixer requires a signal from a local oscillator at the 24-GHz frequency level.

Honeywell has fabricated a 30-GHz, five-bit phase shifter (ref. 12). An important advance has been also been made in the gain control amplifier development with the fabrication of a 30-GHz dual-gate FET. Preliminary test results show the device gain to be approximately 10 dB. By varying the second gate bias a range in gain adjustment of 25 dB has been achieved. The phase shifter requires five transistor-transistor logic (TTL)-compatible electrical connections.

It is evident from the GaAs MMIC characteristics that numerous input lines are needed for RF feed and control signals. A scanning-beam phased array built from these GaAs MMIC modules would result in a complex signal distribution system if conventional interconnection techniques were used. However, the majority of input and signals to these MMIC's can be supplied by optical fibers and by optical integrated components on GaAs substrates. Requirements for such an interface are described in the following section.

OPTICAL/MMIC INTERFACE

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 various optical fiber links for an MMIC phased-array signal distribution network will require integrated optical transmitters and receivers on GaAs substrates for 0.8- to 0.9-μm wavelength transmission. MMIC transmit and receive modules with optical integrated feed circuitry are shown in conceptual diagrams (figs. 4 and 5).

Interfaces for phase and amplitude control of the receiver and transmitter require transmission of the digital signal by optical fiber. The input signal to the transmitter, the local oscillator signal to the receiver, and the IF output from the receiver will require RF-optical links. Design and component considerations for these connections are described in the following section.

OPTICAL/MMIC INTERFACE CONSIDERATIONS FOR RF SIGNAL TRANSMISSION

Direct or indirect optical intensity modulation techniques, depending on the frequency limitation of the various optical components used in either technique, 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 (ref. 13) and is being extended to ever higher frequencies (ref. 14). The highest modulation frequency achievable with this technique is limited for fundamental reasons (ref. 14). An insertion loss of 25 dB has been observed for a single fiber link (ref. 15); under optimum performance conditions the loss can be reduced to 10 dB.

Radiofrequency signal transmission via optical fiber by means of external modulation has been demonstrated at frequencies to 17 GHz by using lithium niobate ($LiNbO_3$) crystals (ref. 16). The operation of the external modulator is based on the linear electro-optical effect in single crystals such as $LiNbO_3$. When an external RF voltage is applied to the microstrip electrodes across the surface of the crystal, it changes the refractive index of the optical waveguide located next to the electrodes. This then varies the propagation constant of the light beam passing through the optical waveguide, providing the desired modulation. However, the threshold for optical power damage and the efficiency of integrated optical modulators require further improvement. GaAs offers an advantage in monolithic integration although it has lower electro-optical efficiency than $LiNbO_3$.

The distribution of the RF input signal to the transmit module, to the local oscillator, and to the IF signal output of the receive 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
(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
(5) An integrated laser and low-frequency driver with an extremely linear performance to carry the IF signal from the MMIC receive module to the onboard processing system or for antenna remoting

DIGITAL SIGNAL/MMIC INTERFACE

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. Recent developments in optoelectronic integrated circuit (OEIC) technology make this feasible. A variety of OEIC's such as a PIN photodiode/FET amplifier (refs. 4 to 6) and a laser/FET/transmitter (refs. 7 to 9) have been demonstrated, although their compatibility with MMIC fabrication processes has yet to be determined.

The NASA Lewis Research Center has taken the initiative to develop a photoreceiver on a GaAs substrate that will control the phase and gain functions of an MMIC. Subsequent OEIC's required for an optical interface to MMIC's that will digitally control phase shifting and gain functions are

(1) An integrated photodetector, a preamplifier, and timing circuitry on a GaAs substrate. The detailed performance objectives of this photoreceiver to be developed under NASA contract are given in table IV.

(2) An integrated laser capable of operating at a high bit rate with the microprocessor for the phased-array control system

The direct optical control of MMIC phase shifting and gain functions is also a possibility that can further simplify MMIC/optical interfaces. Optical control of a GaAs MESFET has been demonstrated (ref. 17). Such techniques can provide switching but not sufficient phase shifting. Monolithic integration of such techniques needs to be shown.

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.

COMPARISON OF MMIC AND OEIC FABRICATION TECHNIQUES

The fabrication processes for monolithic optoelectronic circuits must blend the technologies of GaAs MMIC fabrication and optical device fabrication. In addition, because of the inherent fabrication and design constraints placed on MMIC's, monolithic optoelectronic fabrication processes must be extensions of GaAs MMIC fabrication processes, and optical devices must be small enough that they do not restrict the circuit layout of the MMIC. This requirement is critical because of the sensitive nature of the MMIC layout. Small changes in the microstrip transmission lines used in MMIC's for device interconnections can cause impedance mismatch and unwanted phase shifts of the electromagnetic wave. Also, unnecessary bends or discontinuities in the microstrip line will greatly increase the losses in the circuit due to radiation.

Current MMIC processing makes use of semi-insulated GaAs wafers and ion implantation for the active device regions (ref. 18). Gallium arsenide wafers with an epitaxially grown layer can be used for MMIC fabrication if mesa structures are used for device isolation. Mesa structures were not used because of the nonuniform epitaxial growth over the entire wafer and the disadvantage of doing later processing steps on a nonplanar wafer. Planar substrates are needed for the critical lithography required to define the MESFET's gates, which are 1 μm or less in length. Ohmic contacts are fabricated by alloying an AuGe eutectic alloy, a nickel layer, and a gold layer at 460 °C. If higher temperatures are used, the semi-insulating (SI) GaAs must be protected with an encapsulant. Common gate metals are a Ti:W composite and a gold layer deposited on equal amounts of titanium and platinum. Silicon nitride is used both for metal-insulator-metal (MIM) capacitors and as a GaAs passivation layer. Eight mask levels are usually required to fabricate an MMIC.

The type of semiconducting laser used is therefore limited to one of the planar varieties, which can be fabricated on an SI GaAs wafer. A simple GaAs pn junction will create radiation but is generally not used because of the high threshold current required for stimulated emission of monochromatic radiation (50 A/cm^2 at 300 K). This high threshold current would create heat dissipation problems on the poorly heat-conducting GaAs.

A heterostructure or double heterostructure pn junction diode has a lower threshold current because the electrical carriers are concentrated in a smaller region. The junction barriers, besides concentrating the electrical carriers, also concentrate the optical radiation because of the differences in the indexes of refraction of the semiconducting layers. Aluminum gallium arsenide (AlGaAs) double heterostructures are ideally suited for integration on a GaAs substrate. The radiation emission has a wavelength of 0.65 to 0.91 μm depending on the amount of aluminum. This is ideally suited for fiber optics because of the low loss in the fiber at 0.85 μm.

The most complex OEIC's reported have used the transverse junction stripe (TJS) laser (ref. 7). This semiconducting laser must be fabricated from epitaxial layers to achieve the required heterojunctions. To remain in the constraints outlined, it is built in a well that is etched into the SI GaAs wafer (fig. 6). The epitaxial layers are then grown over the sample by using a Si_3N_4 and SiO_3 encapsulant to protect the SI GaAs substrate from the high-temperature growth and to serve as a mask for further processing steps. A chemical etch is used to remove the polygrowth and to obtain a planar surface for the MMIC fabrication. A diffusion is then done to create the laser's pn junction. The GaAs must again be protected during the high-temperature diffusion bake. The laser uses the same ohmic contact metals as the MMIC (ref. 9). Generally the wafer is scribed such that one surface of the chip acts as one of the laser's mirrors. In reported studies the other mirror has been formed by using the undercut mirror process. The OEIC requires five more masks than the MMIC.

This procedure shows the most promise because the MMIC fabrication steps are set first and the optical devices are designed to be added to the process. In another OEIC reported, the MESFET's are fabricated on a AlGaAs substrate. This structure will not replace the GaAs MMIC in the first generation of optoelectronic MMIC's because information on fabricating AlGaAs MMIC's is scarce.

Other heterojunction materials such as GaInAsP will not be seen in the first generation of optoelectronic MMIC's because these structures must be fabricated on InP and this, like AlGaAs, is an immature technology. Circuits on InP using GaInAsP would be highly desirable for space-borne systems because of the lower loss and dispersion at the 1.3-μm wavelength.

CONCLUDING REMARKS

Using optical fibers to control gallium arsenide (GaAs) monolithic microwave integrated circuit (MMIC) phase shifting and gain functions and to carry various radiofrequency signals offers several advantages for scanning-beam, phased-array antennas. Optical integrated circuitry on GaAs substrates will be required to interface the optical fiber to the GaAs MMIC. Furthermore MMIC fabrication processes are compatible with those of optical integrated circuits for monolithic integration.

Development of direct optical control of devices may eliminate the intermediate digital interface and further simplify the circuitry. In addition, the development of optical/microwave interfaces will benefit onboard optical processing and will connect optical intersatellite links to the up-and-down microwave links for future space communications systems.

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TABLE I. - CHARACTERISTICS OF VARIABLE PHASE SHIFTER

RF band, GHz	17.7 to 20.2
RF power out, mW	200
Gain, dB	16
Efficiency, percent	15
Phase control	Operates on digital input; five-bit parallel words

TABLE II. - CHARACTERISTICS OF VARIABLE POWER AMPLIFIER

RF band, GHz	17.7 to 20.2
RF power out (variable), W	0 to 0.5
Gain (variable), dB	20 (max.)
Efficiency (500 mW/12.5 mW), percent	15/6
Amplitude control	Operates on digital input; four-bit words in parallel stream

TABLE III. - CHARACTERISTICS OF 30-GHz RECEIVE MODULE

RF band, GHz	27.5 to 30
IF center frequency, GHz	4 to 8
Noise figure at room temperature, db	5
RF/IF gain (at highest level of gain control), dB	30
Gain control, dB	30, 27, 24, 20, 17, and off
Phase control	Five bits; each bit ±3° from band center
Module power consumption, mW	250 in all states except off; 25 in off state
Phase and gain control	Operates on digital input

TABLE IV. - PERFORMANCE OBJECTIVES OF GaAs OPTICAL INTEGRATED CIRCUIT

Optical input (optical signal on *multimode fiber*), bit/sec	10^9
Maximum electrical input, V dc:	
Optical receiver	+5
Voltage interface circuits	+5
Timing input:	
Minimum pulse amplitude, V	1
Repetition rate, MHz	100
Receiver performance:	
Sensitivity, dB	>30
Bit error rate	$<10^{-9}$
Power consumption, mW:	
Receiver and control logic	<50
Output drivers to interface TTL logic levels for MMIC modules	30/bit
Output	16-Bit parallel data stream to control MMIC functions

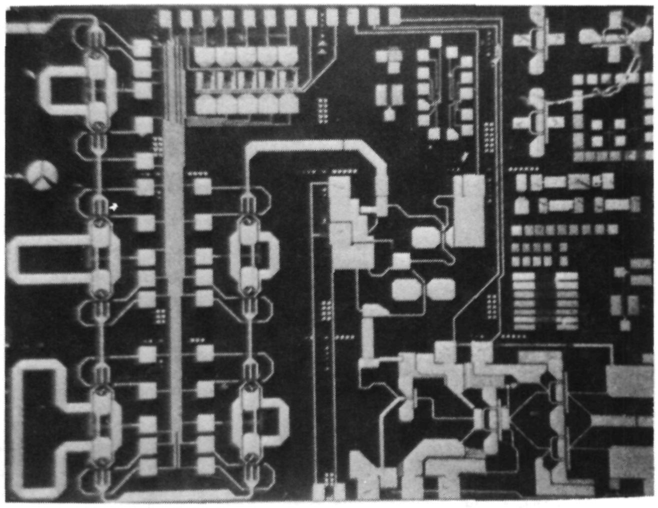


Figure 1. - 20-GHz monolithic transmit module (4.8 x 6.4 mm).

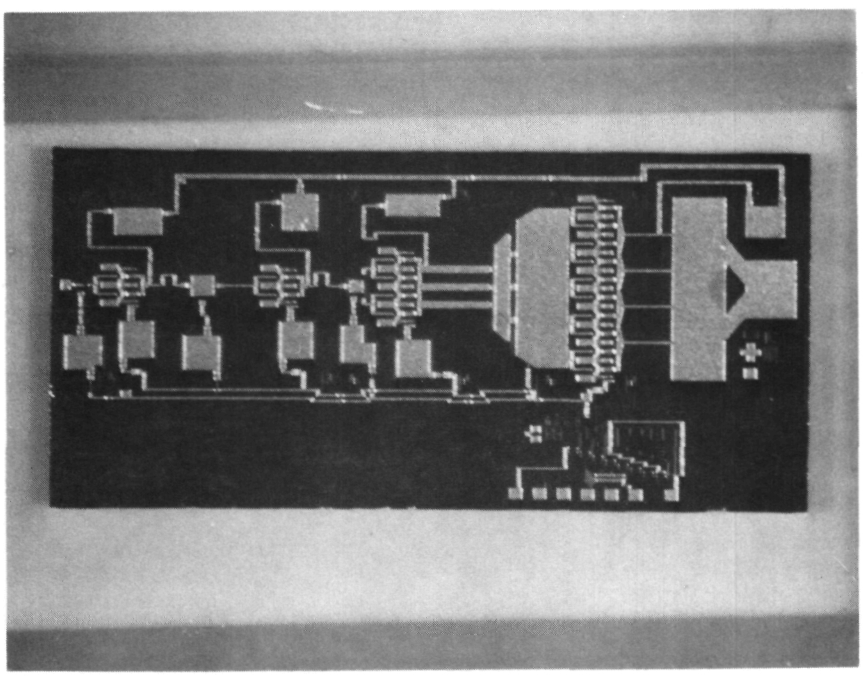
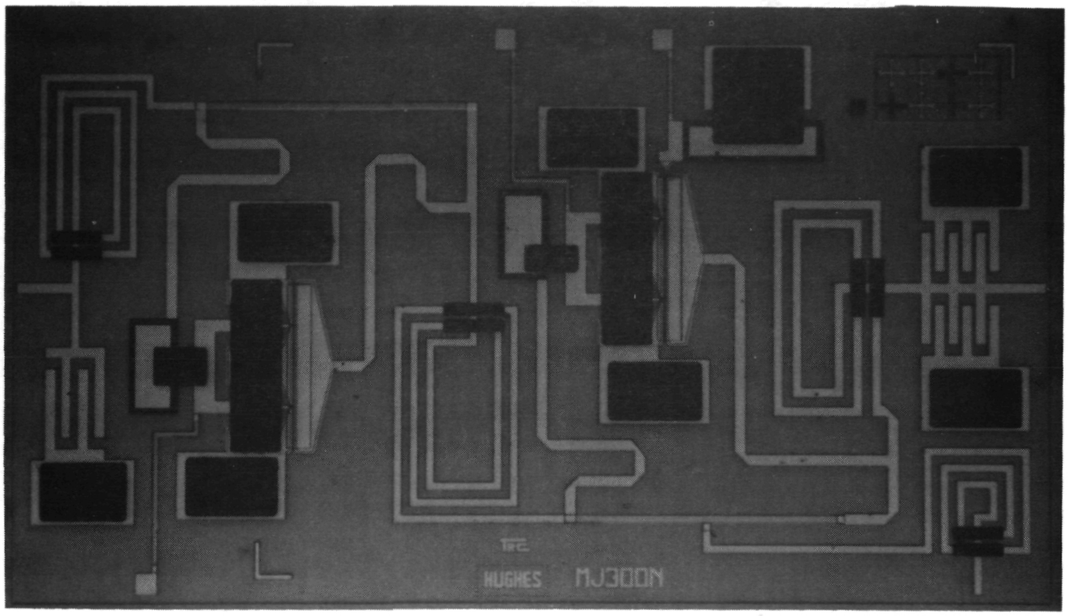


Figure 2. - 20-GHz variable power amplifier.

INPUT
FROM
MIXER



OUTPUT IN
2 TO 6 GHz

Figure 3. - Intermediate-frequency amplifier for 30-GHz MMIC receive module (1.9 by 1.1 mm).

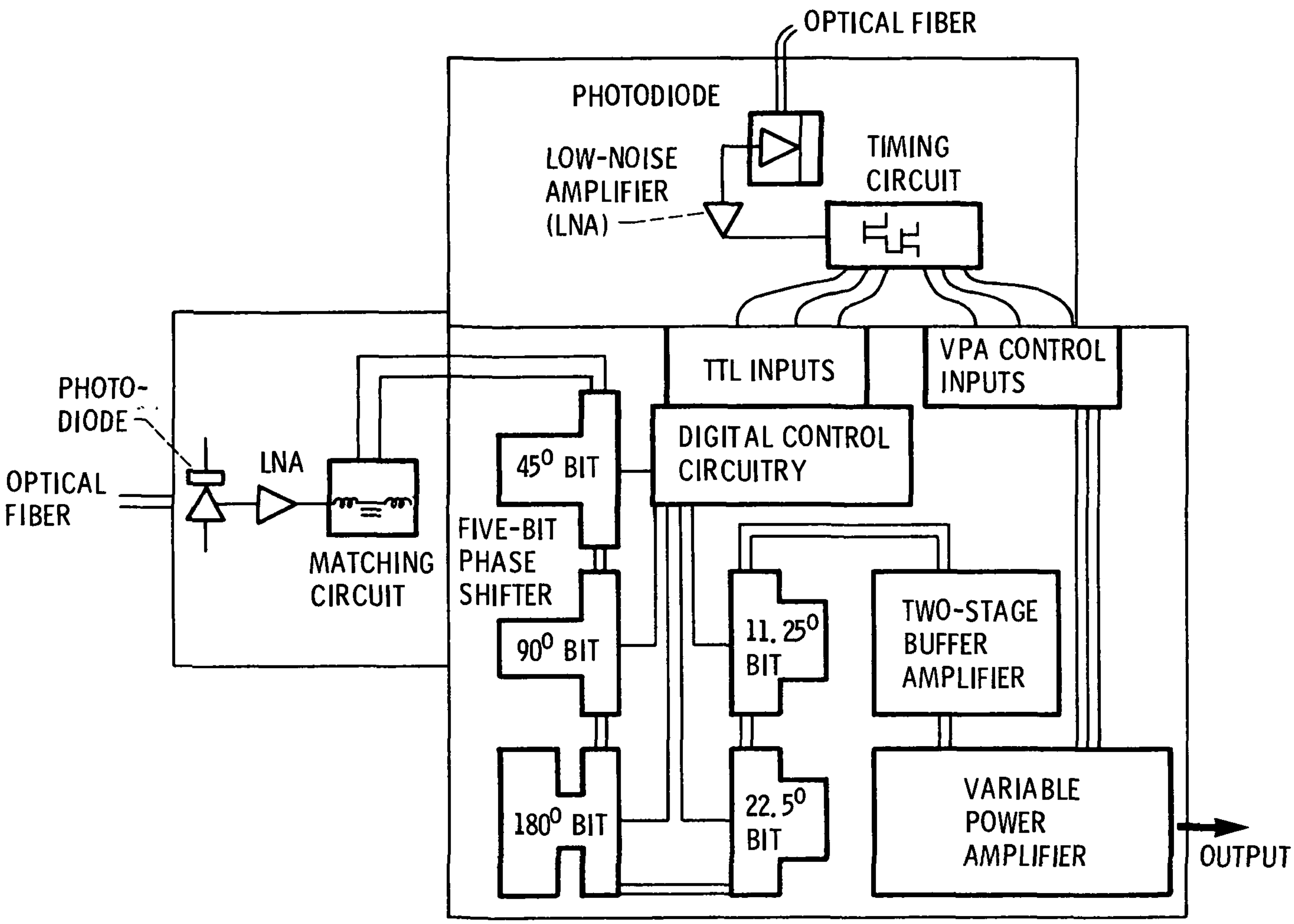


Figure 4. - Optical integrated interface circuits to MMIC transmit module.

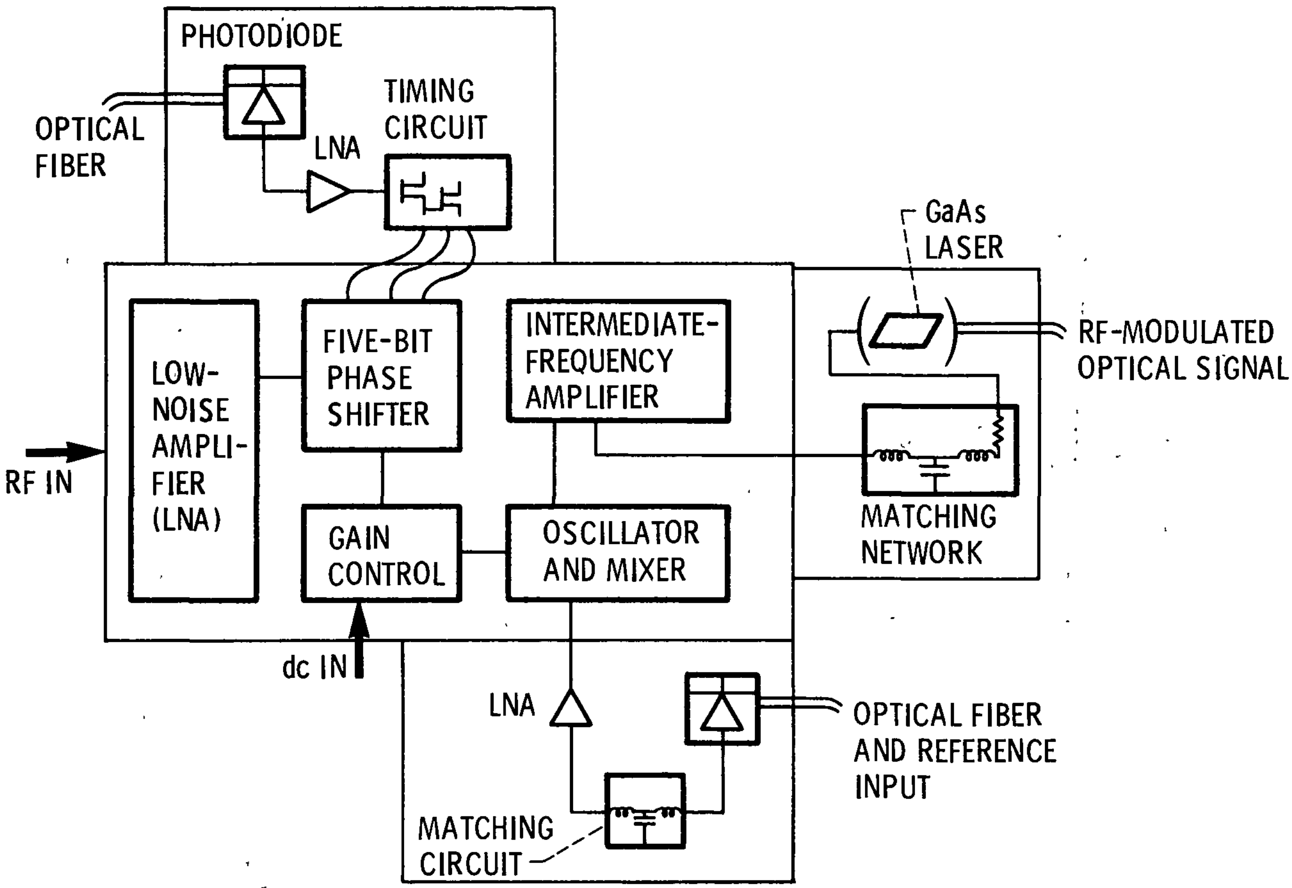


Figure 5. - Optical integrated interface circuits to MMIC receive module.

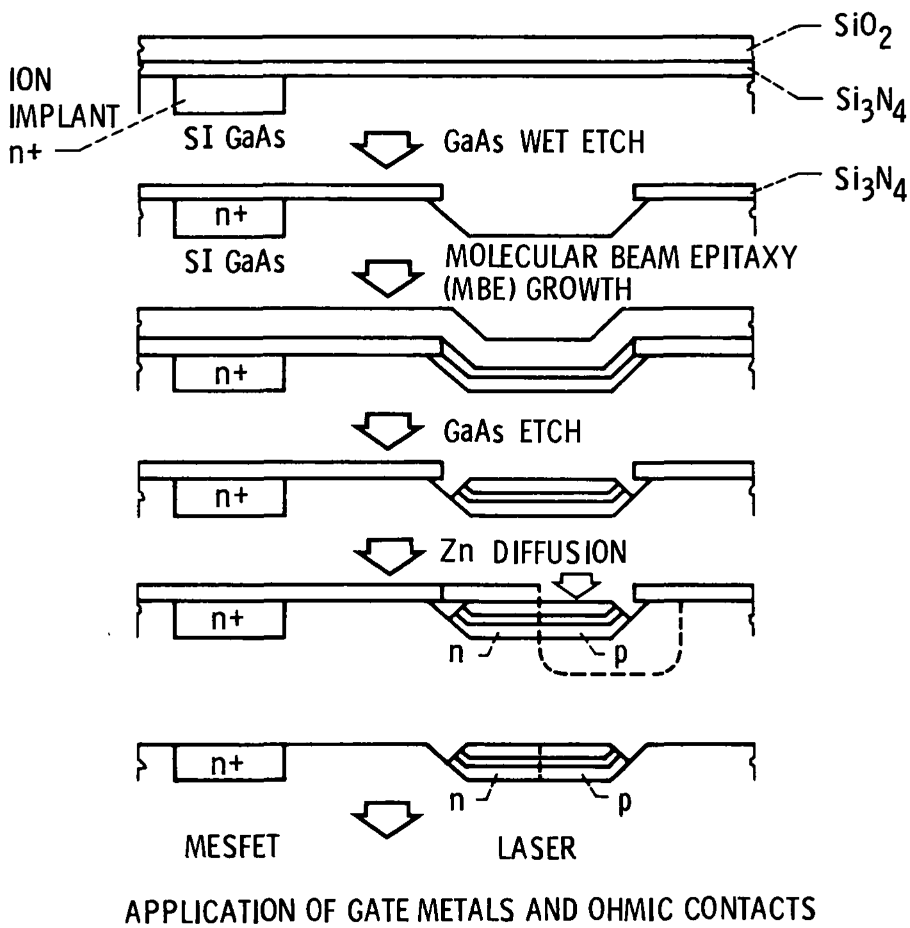


Figure 6. - Monolithic opto electronic circuit fabrication process.

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