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Optical Techniques to Feed and Control GaAs MMIC Modules for Phased Array Antenna Applications

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OPTICAL TECHNIQUES TO FEED AND CONTROL GaAs MMIC MODULES FOR PHASED ARRAY ANTENNA APPLICATIONS

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Abstract

A complex signal distribution system is required to feed and control GaAs monolithic microwave integrated circuits (MMICs) for phased array antenna applications above 20 GHz. Each MMIC module will require one or more RF lines, one or more bias voltage lines, and digital lines to provide a minimum of 10 bits of combined phase and gain control information. In a closely spaced array, the routing of these multiple lines presents difficult topology problems as well as a high probability of signal interference. To overcome GaAs MMIC phased array signal distribution problems, optical fibers interconnected to monolithically integrated optical components with GaAs MMIC array elements are proposed as a solution. System architecture considerations using optical fibers are described. The analog and digital optical links to respectively feed and control MMIC elements are analyzed. It is concluded that a fiber optic network will reduce weight and complexity, and increase reliability and performance, but higher power will be required.

Introduction

In an effort to achieve rapid beam reconfigurability and steering in future space communications systems, the use of phased array antennas, either directly radiating or in feed systems, has been under investigation.[1] Prompting this move is the increased ability of GaAs monolithic microwave integrated circuits (MMICs) to provide lightweight, low loss beam forming networks with the necessary variable amplitude and phase shifting capabilities.[2] Unfortunately the conventional cabling used to furnish bias and control signals to MMICs results in a complex signal distribution network. Fiber optic technology offers promise to improve signal distribution for GaAs MMIC phased arrays.

While other optical techniques for providing phase and amplitude excitation of phased arrays exist,[3-5] a natural extension is to retrofit the MMICs with optical integrated circuits (OICs) to exploit the advantages of optical interconnection for a signal distribution network. This is feasible since MMICs and OICs can be monolithically integrated on a single GaAs chip.

On a systems level, optical control of MMICs offers advantages in the following areas. Current MMIC arrays use complex and expensive mounting fixtures. These fixtures adapt the MMIC to a waveguide environment by providing an interface between the MMIC and the external RF and control signal sources. Even though small (approximately 3 x 1 x 1 in. at 30 GHz), the fixtures are bulky and limit array spacing to a minimum of approximately two times the wavelength. An experimental MMIC phased array antenna, using conventional signal distribution techniques, is shown in Fig. 1.

Control signal connection to the fixture is achieved with multiconductor cable or by specialized flexible printed circuit boards. Standard connectors normally used with this cable are ill-suited because space is limited. Instead, special clamping connectors or custom printed circuit board adapters are used to access the fixtures; this limits the interelement clearance needed to the printed circuit board or ribbon cable thickness (approx. 1/16 in.).

These limitations can be overcome with the use of an optical fiber interconnection network. A single multiplexed optical fiber could be used to transmit RF and control signals, eliminating the complex mounting fixtures and waveguide hardware. By interfacing to a microstrip environment rather than waveguide, array spacings of as little as $\lambda/2$ could be achieved, where λ is the operating wavelength. The additional benefits of low weight, minimum cross-talk, flexibility and immunity to electromagnetic interference are also offered by fiber optic signal distribution techniques. The disadvantages are the power required for electrical to optical conversion or vice-versa and the dynamic range limitations of optical components.

In this paper, we discuss the system design considerations for GaAs MMIC based phased array antennas and various optical techniques for its signal distribution. The RF optical link for analog signal transmission and digital optical link for phase and gain control of MMICs are also presented. Associated optical components required to achieve the signal distribution network are highlighted.

System Design Considerations

The system design presented is applicable to planar arrays used either as feeds to a reflector based antenna system or as a direct radiating array. Each array element needs optical connections for RF and control/data signals. It is desirable to have all these signals on a single multimode fiber, however, state-of-the-art RF modulation techniques require specialized optical components and therefore independent cabling. A conceptual diagram of the optical distribution network for an MMIC based phased array is shown in Fig. 2.

The heart of each array element is an MMIC transmit or receive module possessing a 5-bit variable phase shifter, a 4 or 5 bit variable power amplifier, and an integral D/A converter to provide the required analog bias voltages. Characteristics of MMICs being developed for 20 to 30 GHz communications satellites are discussed below:

GaAs MMIC for 20 to 30 GHz System

NASA Lewis Research Center has a substantial, on-going program to develop MMIC circuits in the 20 and 30 GHz frequency bands primarily for phased array antenna applications. The features of these MMICs which will play a key role in the optical signal distribution network development are:

Variable Phase Shifter (VPS)

The VPS module functions include 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 and a three-stage power amplifier completes the module. Each submodule requires a minimum of five connections for phase shifting and several bias connections. More detailed information on this VPS module is given elsewhere.[6]

Variable Power Amplifier (VPA)

These can be electronically switched to any one of five output power levels: 500, 125, 50, 12.5, and 0 mW. The efficiency is to vary from 15 percent at the 500 mW level to 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 x 6.45 mm GaAs chip.[7] 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 changed over a large dynamic range (20 to 40 dB). Over this range the amplifier has a minimum transmission phase shift (approx. 5°), and FET input/output impedances are essentially constant providing constant shape of the gain-frequency response curve. A mounted VPA is shown in Fig. 3. Notice the number of connections required for gain control.

30 GHz Monolithic Receive Module

This module combines five separate receiver functions on a single GaAs chip. The separate receiver submodule developments include a low noise amplifier, an amplifier with gain control, a phase shifter with controls, a mixer and an IF amplifier. This 30 GHz receive module development is in an early stage with two of the 4 yr scheduled for this effort having been completed.

A number of advances in this receive module technology have been made under NASA contract. Hughes has fabricated a two-stage low noise amplifier with 13 dB gain and 6.5 dB noise figure. An IF amplifier with an output frequency range of 2 to 6 GHz, and an analog phase shifter and mixer have also been fabricated.

Honeywell has also made advances in the fabrication of a 30 GHz 5 bit phase shifter for the receive module; this is described elsewhere.[8] The phase shifter uses 30 GHz, 0.25 μm dual gate FETs. 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. This phase shifter requires five TTL-compatible electrical connections. A packaged phase shifter submodule with its connections is shown in Fig. 4.

From the above discussion of MMIC characteristics, it is evident that MMICs need several digital and RF connections for their operation. Optical distribution techniques which can minimize the complexity of these connections are outlined below:

Optical Signal Distribution Techniques

As a solution to the MMIC phased array signal distribution problem, the use of fiber optic technology may provide an answer. Optical fiber can be used to transmit both analog and digital signals. Other advantages include small size, lightweight, mechanical flexibility and large bandwidth. Optical wavelength division multiplexing techniques, which allow distribution of diverse signals simultaneously on a single fiber, will futher reduce the signal distribution complexity. Since short links are involved in GaAs MMIC phased array signal distribution, the shorter 8500 to 9000 A wavelength will suffice. Also, GaAs-based devices required to provide the interface operate in this region. Several GaAs optical integrated circuits such as a photodiode preamplifier and a laser/field effect transistor have been demonstrated. These circuits, if integrated with GaAs MMICs, can simplify the optical interface to the MMICs.

Two possibilities for control/data signal distribution to the array modules exist. An individually modulated laser diode can be multiplexed to be the feed for all the elements. However, in large arrays this could limit how rapidly the beam could be steered due the overall length of the addressing time. Alternatively, for an array with N elements, N laser diodes could be used to distribute the signals in parallel. A combination of both distribution methods using a modulated laser diode for each column or row is also a viable option.

A trade-off between message size and bit-rate will ultimately determine which distribution scheme is optimum. Increased amplitude and phase quantization or chip complexity requires larger message lengths and the longer the message, the higher the bit-rate. Given a fixed bit-rate, parallel signal distribution could be used to produce the desired speed.

Wavelength or time multiplexing techniques can be used for control of phase and gain functions of MMICs. Rapidly altering the phase excitation of each array element to produce rapid beam steering is achieved by using an array processor to download control/data signals to the individual modules as dictated by the controller. [Synchronized data transmission of the control/data signals is used to transfer information from the array processor to each module.]

Wavelength division multiplexing (WDM) takes advantage of the characteristic of optical fiber that much of the available spectral transmission band is not used. By using sources that produce many spectral bands within the overall fiber bandwidth, simultaneous transmission of many optical signals over the same fiber can be accomplished leading to multiple transmission channels[9] (as shown in Fig. 5). This technique, however, requires optical sources capable of producing multiple stable bands separated by a few tens of nanometers, crosstalk levels between -20 and -30 dB, and optical power sufficient to support N multiple channels as well as the insertion loss of the WDM components.

RF transmission requires that an identical signal be fed to all modules in parallel, which necessitates the need for an optical data bus (see Fig. 6). An optical data bus configured from transmitting star couplers seems to be a likely candidate. This type of coupler features a high efficiency, but suffers from the limitation that the number of input and output ports is fixed by initial design and is not expandable once chosen. The overall array size is then limited not only by the coupling efficiency of the star coupler, but more importantly, by the optical transmitter power output and/or receiver sensitivity.

The balance equation for this type of link is given by:

$$P_S - P_R = L_S + 2\alpha_f L + 4L_C + L_{SP} + \text{SYSTEM MARGIN (20 to 50 percent)} \quad (1)$$

where,

P_S source power, dBm

P_R receiver sensitivity, dBm

L_S insertion loss of the coupler,

$$10 \log \frac{\sum_{j=1}^{N} P_J}{P_i}$$

P_J the output power from each port

P_i the input power to the coupler

α_f fiber attention per foot

L total fiber length of link, ft

L_C connector loss

L_{SP} splitting factor, 10 log N (N = number of coupler ports)

Optical Components and Link Considerations for GaAs MMICs Phased Array Signal Distribution

Signal distribution for GaAs MMIC phased arrays via optical fibers can be achieved by using integrated optoelectronic circuits on GaAs to provide an interface for the fiber to the MMICs and the array processor. Such circuits, required for GaAs MMIC receive and transmit modules and array processor, are shown in Figs. 7 and 8.

Interfaces for phase and amplitude control of the receiver and transmitter are digital. Input RF to the transmitter, local oscillator frequency to the receiver and output from the receiver can be modulated on the optical fiber. Considerations for both digital and RF optical fiber links for MMICs are discussed below.

RF Signal Distribution Considerations

Direct, or indirect optical intensity modulation techniques can be used for distribution of the RF signal to the MMIC depending on the frequency limitation of the various optical components used in either technique. Direct intensity modulation of lasers and indirect modulation of lasers via modulators are shown in Figs. 9 and 10, respectively.

Direct laser modulation (using GaAs/GaAlAs semiconductor laser) has been demonstrated up to 8 GHz[10] and is being extended to even higher frequencies.[11] However, the highest modulation frequency achievable with this technique is limited due to fundamental reasons.[11]

The insertion loss parameters for the RF link have been obtained by Stephens, et al.[12] and are given below:

$$\text{Insertion loss} = \left[E_m \frac{R_L}{R_S} (\eta_L R_D \alpha_0)^2 \right]^{-1} \quad (2)$$

where R_L and R_S are source and load impedances, η_L is the laser efficiency, R_D is the detector responsivity, α_0 is optical losses, and E_m is matching circuit losses. When the detected optical power is low, detector and amplifier noise usually dominates.

The conclusion regarding fiber optic signal distribution manifolds is therefore that the required S/N ratios for RF signal distribution in a phased array may be obtained, but that the number of output ports is severely limited, typically to about six from a single laser of the usual 10 mW output power.

External modulation has been demonstrated at frequencies up to 17 GHz. By using $LiNbO_3$ crystals[13] the frequency range can be further extended by various improvements. The threshold for optical power damage and the efficiency for integrated optical modulators is low. If such modulators are designed on GaAs they offer the possibility of monolithic integration.

The trade-offs to be made in considering whether a fiber optic distribution network is a viable replacement for a conventional distribution network, lies chiefly in considerations of loss and stability. In addition, fiber optic networks can carry multiple signals as well.

It has been calculated, that by using optimized values of the parameters in Eq. (1), the intrinsic insertion loss of the electrical-optical conversion could be reduced to a minimum of 10 dB.

The overall S/N for a single optical fiber link depends on the photodetector shot and thermal noise together with thermal noise associated with the amplifier following the photodetector, and the laser intensity noise. For a signal transmission at gigahertz frequencies, laser noise is generally dominant.

If such RF-optical fiber links are viable, lasers and photodetectors can be monolithically integrated to reduce weight, power cost, and circuit parasitics. For a MMIC phased array signal distribution network, a number of OICs will be required. For example, for the input RF signal and local oscillator reference signals for MMIC modules using intensity modulation, the following GaAs optical integrated circuits are needed: a high frequency external modulator on GaAs with high efficiency and a high optical damage threshold; a wide band integrated photodetector and preamplifier for demodulation of the signal, and an integrated laser. In addition, a high power integrated laser capable of being directly or indirectly modulated at high frequencies with an integrated driver is needed.

To carry the IF signal from the receive module to the on-board processing system, an integrated laser and low frequency driver with extremely linear performance, and an integrated very low noise photodetector and preamplifier on GaAs substrate are needed.

Optical Interface to Digitally Controlled MMICs

Phase and amplitude control of GaAs MMICs can be achieved via a single fiber interconnect to an array processor rather than the several electrical connections needed currently. Such an interconnect will require the monolithic integration of optical components (laser, photo diode, etc.) with GaAs MMICs and array processing chips. The recent developments in optoelectronic integrated circuit (OEICs) technology make this feasible,[14] although their compatibility with MMIC fabrication processes have yet to be determined. NASA Lewis has taken the initiative to integrate a photoreceiver with a MMIC.[15] If the results are successful, subsequent OEICs will be required to develop an optical interface to MMICs and an array processor as shown in Figs. 7 and 2, respectively.

The direct optical control of phase shifting and gain functions of MMICs is also a possibility which can further simplify the MMIC/optical interface. Optical control of microwave devices and circuits has been demonstrated.[16,17] However, such techniques can provide switching but not sufficient phase shifting, and monolithic integration of such methods also has to be shown.

Conclusions

Optical techniques offer several advantages for the signal distribution network for GaAs MMIC based phased array antennas. Optical interfacing to digitally controlled phase and gain functions of MMICs via single fiber and optoelectronic integrated circuits is achievable. Microwave signals in some cases can be brought on via optical fibers to MMICs. However, the feasibility of these techniques depends upon the development of monolithic integration of optical components with MMIC and digital circuits. Optical distribution links with optoelectronic integrated circuits as interfaces will provide further advantages for on-board optical processing and intersatellite links for further space communication systems.

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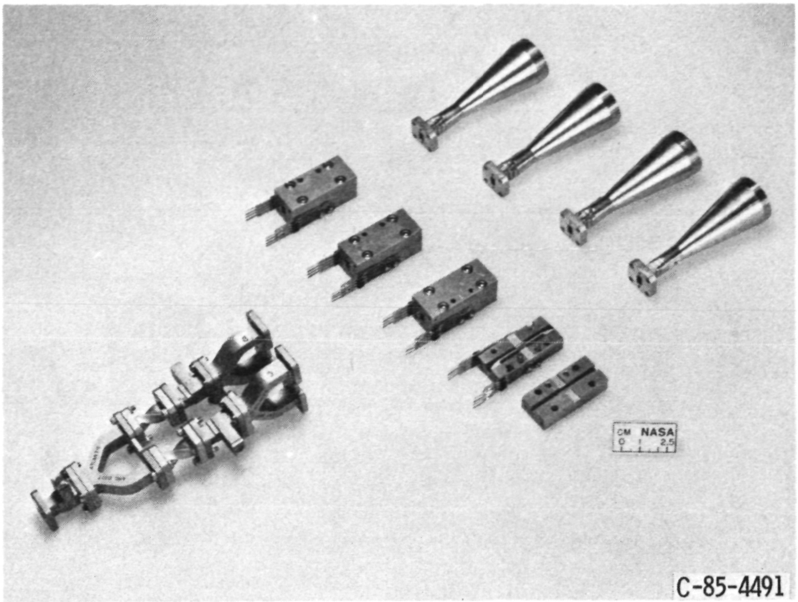

Figure 1. - Experimental four horn hybrid monolithic integrated circuit phased array feed system.

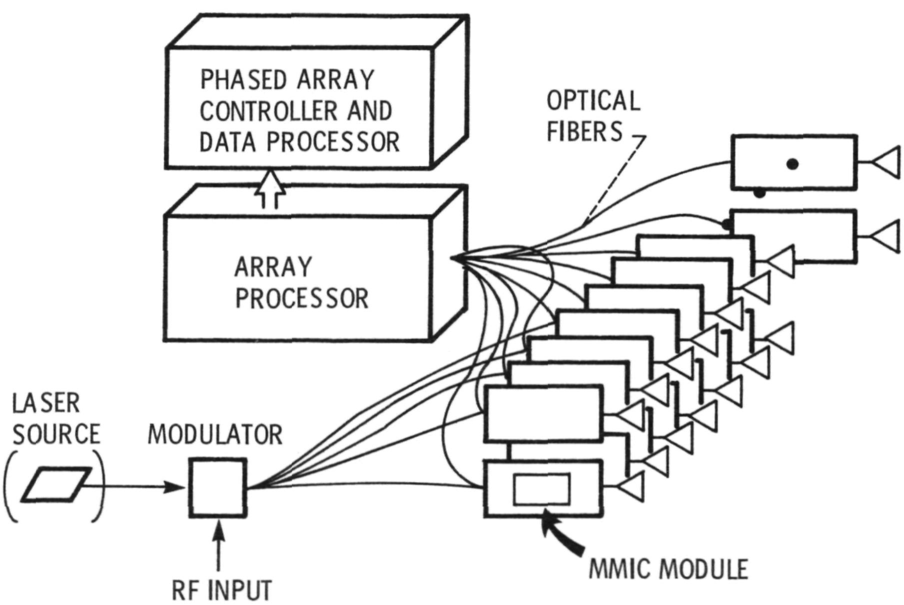

Figure 2. - Conceptual diagram of optically fed and controlled GaAs Monolithic microwave integrated circuit (MMIC) based phased array.

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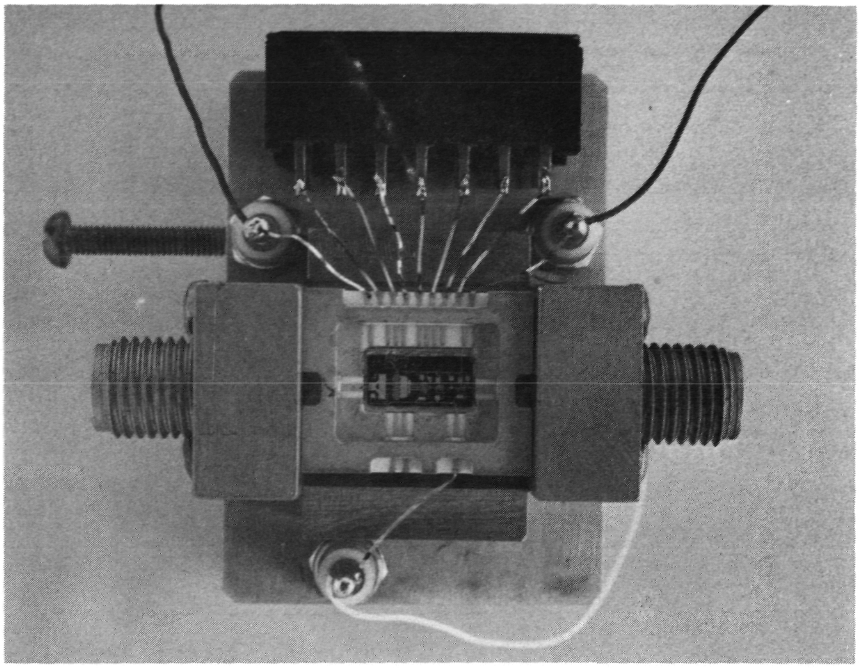

Figure 3. - MMIC variable power amplifier (VPA) module in a test fixture.

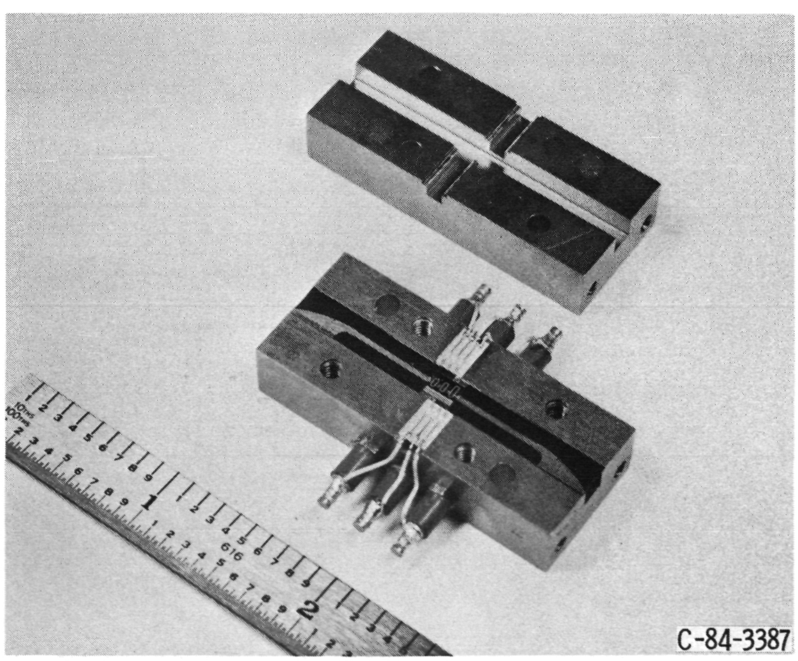

Figure 4. - MMIC variable phase shifter (VPS) module in a test fixture.

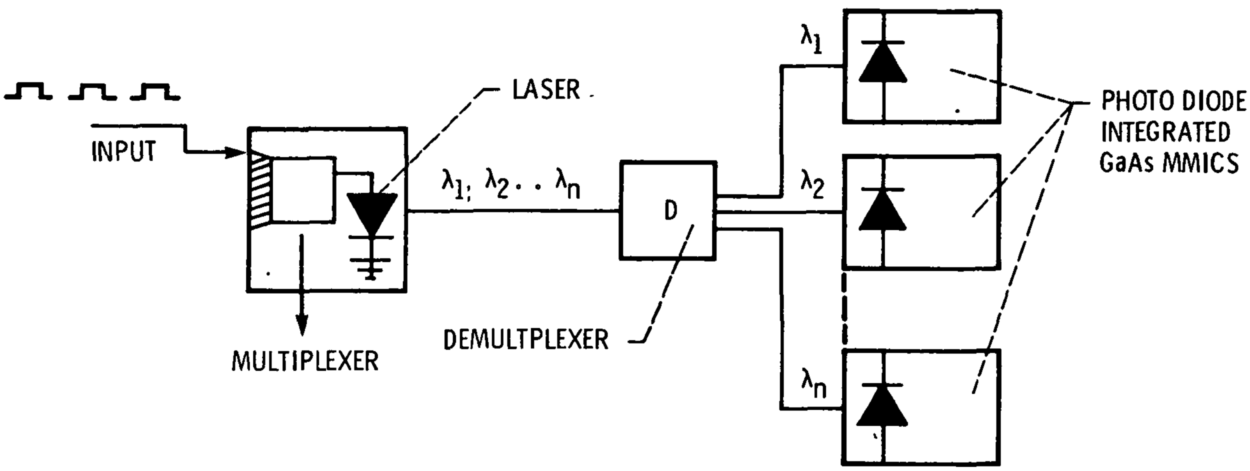

Figure 5. - Optical wavelength division multiplexing (WDM) technique for digital signal distribution.

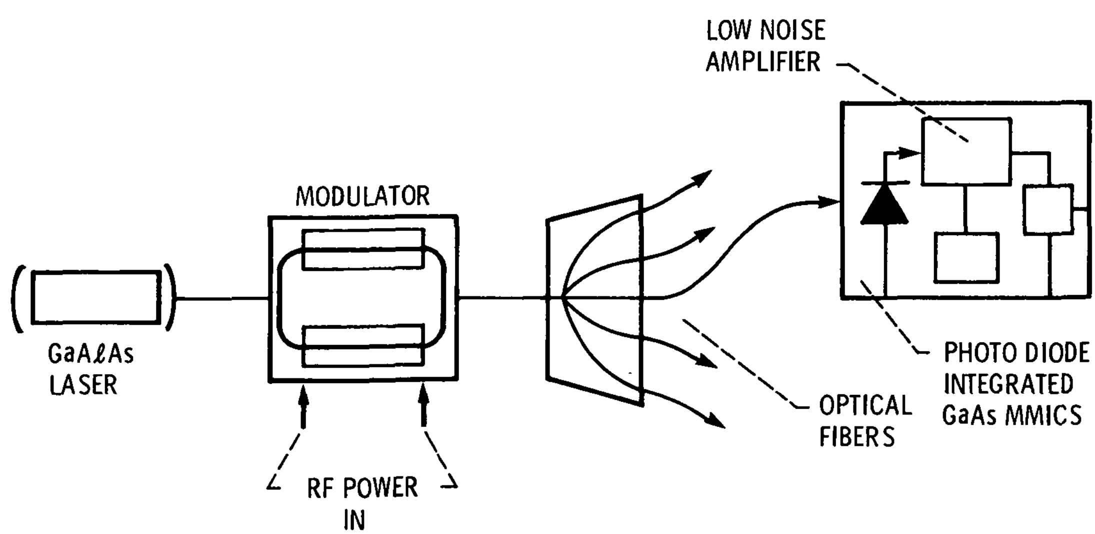

Figure 6. - Optical signal distribution network for MMIC module RF signals.

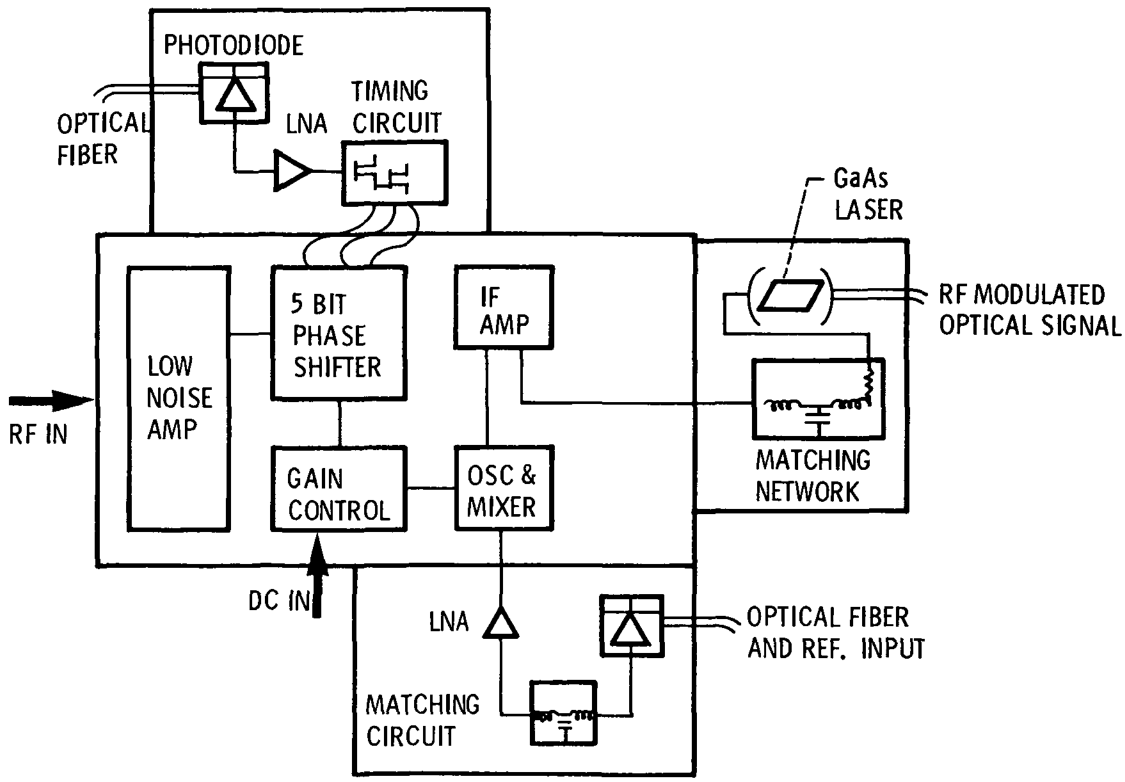

Figure 7. - Optical integrated circuits interfaced with MMIC receive module for optical fiber interconnections.

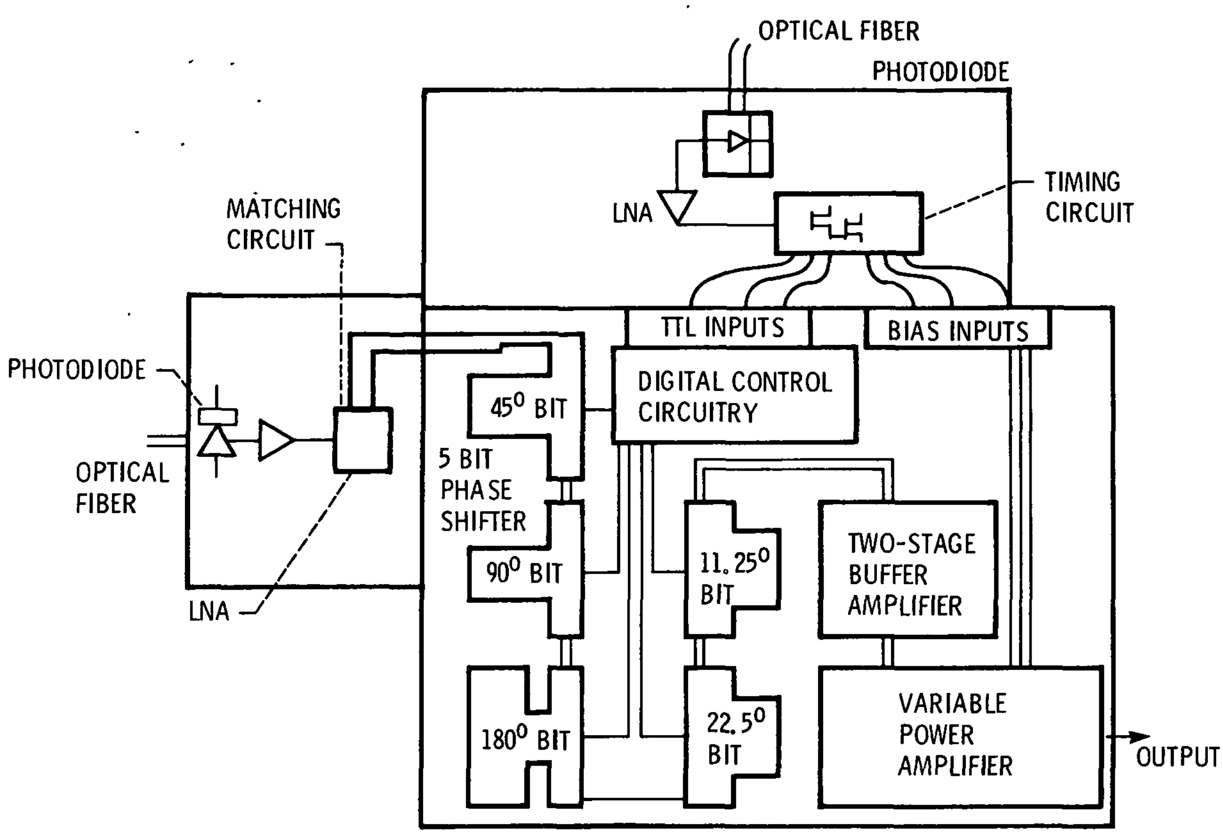

Figure 8. - Optical integrated circuits interfaced with MMIC transmit module for optical fiber interconnections.

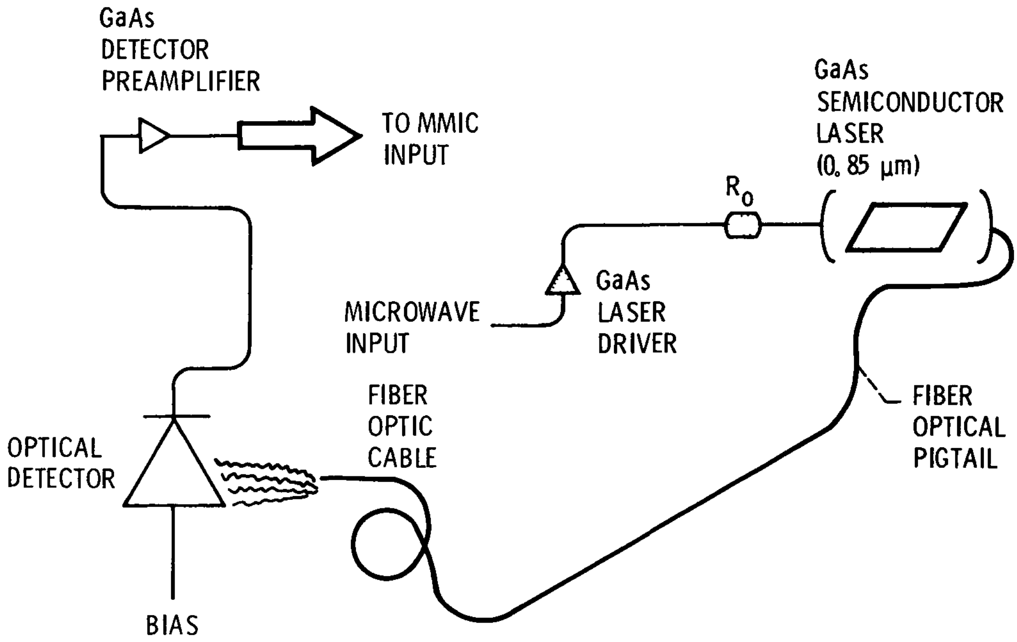

Figure 9. - Direct laser modulation techniques using GaAs components.

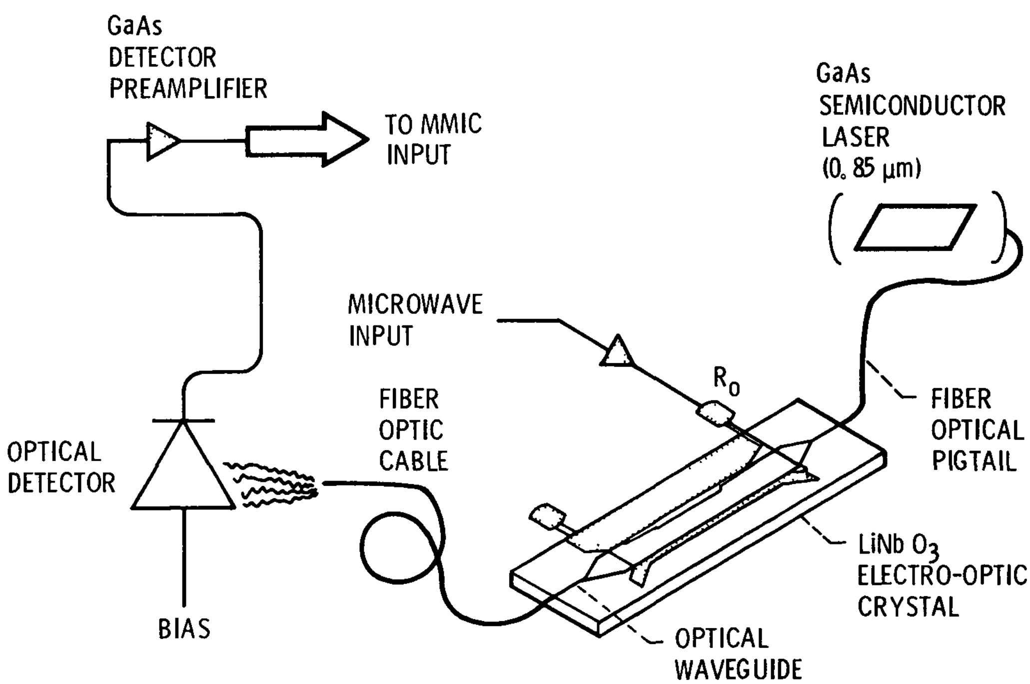

Figure 10. - Indirect laser modulation techniques using GaAs components.

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