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Optically Interconnected Phased Arrays

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ABSTRACT

Phased-array antennas are required for many of NASA's future missions. They will provide agile electronic beam forming for communications and tracking in the range of 1 to 100 GHz. Such phased arrays are expected to use several hundred GaAs monolithic microwave integrated circuits (MMIC's) as transmitting and receiving elements. However, the interconnections of these elements by conventional coaxial cables and waveguides add weight, reduce flexibility, and increase electrical interference. Alternative interconnections based on optical fibers, optical processing, and holography are under evaluation as possible solutions. In this paper, current status of these techniques will be described. Since high-frequency optical components such as photodetectors, lasers, and modulators are key elements in these interconnections, their performance and limitations are discussed.

1. INTRODUCTION

Phased-array antennas based on GaAs monolithic microwave integrated circuits (MMIC's) are of interest as the next-generation antenna systems for communications and tracking applications in space missions. These missions include Mars Rover (Mars-to-Earth data relay), Mission Planet Earth (Earth radiometry with active array communication), and the Experimental Antenna System in advanced communication satellites. Phased arrays having hundreds of elements are becoming a reality with the maturity of GaAs MMIC technology. However, the current signal distribution methods (such as waveguides and coaxial cables) for phase and amplitude control signals and radiofrequency (RF) carrier signals to GaAs MMIC radiating elements suffer from high weight, mechanical inflexibility, and high loss. Optical techniques have the potential to overcome these limitations.[1] For example, optical fiber as a transmission medium is lightweight, small in physical size, mechanically flexible, highly resistant to electromagnetic interference (EMI) and electromagnetic pulses (EMP), and virtually without loss. Its loss is compared with microwave transmission media in Figure 1.

There are several approaches to optically controlled phased-array antennas, but most of them fall into two categories: one is based on the use of fiber optics and high-frequency optical components for signal distribution in phased arrays, and the other is based on the use of advanced optical processing techniques to achieve phase and amplitude changes in the microwave beam in phased-array antennas. Both of these approaches are discussed in detail in this paper.

From the components point of view, in the past several years, GaAs substrates have provided the basis for the development of monolithic microwave integrated circuit technology. Low-loss microstrip lines can be fabricated on this semi-insulating substrate. The high electron saturation velocity provides the essential microwave device technology. At the same time optical waveguides, lasers, and detectors can be fabricated on a GaAs substrate with convenient control of the composition and thickness of GaAlAs layers. The feasibility of fabricating a microwave and an optical integrated circuit on the same substrate provides an opportunity for monolithic integration of both optical and microwave functions in optically controlled phased-array antenna applications in space communications to provide low weight and reduced complexity in systems. The status of these components is discussed in the following section.

2. ARCHITECTURES FOR OPTICALLY INTERCONNECTED PHASED ARRAYS

The integration of MMIC's into microwave phased-array communications systems has identified optical interconnects as an enabling technology (Fig. 2). Two areas of development that are critical to the successful implementation of fiber are optical fiber architectures and integratable high-frequency optical components and devices on GaAs substrates. An analysis of potential architectures reveals that, at present, all of the possible architectures can be represented by following basic types for phase shifting from 0° to 360°. Other architectures are possible where 360° phase shift is not required.

2.1 Fiber-optic-based architecture

Control signal distribution is the least demanding architecture in terms of device technology development.[2] The typical configurations assume a central control unit from which element assignments are determined and transmitted (Fig. 3). Addressing schemes of this type result in element-by-element control signal distribution, which requires high serial bit rates to address large numbers of elements in demanding communications traffic scenarios.[3] An alternative design concept is to provide each element in the array with a minimal amount of processing capability, thereby distributing the system intelligence and easing addressing hardware constraints.

The lower frequency requirements of control signal architectures (<1 GHz) allow for a more timely development. However, many technology issues are common to all fiber architectures. These features include the integration of optical electronic integrated circuits with GaAs MMIC designs, fiber device interconnection, and device efficiency.

The RF signal distribution architectures are generally characterized by the point at which the communications data and the RF carrier are combined. In CPU-level designs, the communications data are impressed on the RF carrier before conversion to light. This type of architecture is the simplest conceptually, but is the most demanding on the optical requirements of the link, such as bandwidth, dynamic range, and noise figure.

A more realizable architecture at present is that of combining the communications data with the RF carrier at the transmit or receive MMIC module. The greatly reduced high-frequency RF bandwidths required lead to relaxed system specifications, but two fibers are needed instead of one, and components for mixing RF and data must be incorporated in the MMIC design.

2.2 Optical-processor-based architecture

A second type of architecture does not use controllable MMIC's as the devices necessary to create the appropriate phase and amplitude excitations for antenna beam formation.[4,5] Rather, this function is implemented in the optical domain (Fig. 4). Optical beam forming network (OBFN) architectures use holographic techniques to combine spatial and temporal information for antenna beam formation. By optically creating the desired antenna beam characteristics, the difficulty in producing nearly identical MMIC phase shifters and variable gain amplifiers is overcome.

The OBFN architectures have temporal device requirements similar to other fiber architectures, but have unique spatial device requirements. Temporal modulation, photodetection, and high-power light generation are common to all RF signal distribution architectures. Additionally, spatial modulation, spatial sampling, and optical signal combining devices are needed to completely develop OBFN architectures.

2.3 Holography-based architecture

Free space optical interconnections using a holographic optical element have been proposed for high-speed electronic circuits.[6] The feasibility of free space optical interconnection technique has not been fully assessed as applied to optically interconnected phased arrays.

3. OPTICAL MODULATION TECHNIQUES

While spatial modulation is unique to OBFN architectures, temporal modulation is common to all fiber architectures. Temporal modulation can be characterized by direct, indirect, and injection-locking techniques (Fig. 5). Injection locking differs from the other two techniques in that it does not directly support the RF carrier, but is used as a *reference* to synchronize free-running microwave oscillators at the desired frequency.

Conceptually, direct modulation is a straightforward technique.[7] The RF communications signal is used to directly modulate a laser diode. However, the optical link demands for a directly modulated link are significant. As with other microwave/millimeter transmission systems, direct links require large dynamic ranges, high center frequencies, wide bandwidths, and low noise levels. At present, modulation frequencies are limited to 30 to 40 GHz, largely because of the relaxation oscillation effects of laser diodes.

Relative intensity noise (RIN) effects, the primary noise source in optical links, result in modest bandwidths at reduced dynamic ranges. At frequencies above 8 GHz, direct modulation technique specifications such as threshold current and depth of modulation are usually traded off to achieve very reasonable link performance.

Indirect modulation techniques use external devices such as Mach-Zehnder interferometers together with laser sources to modulate optical carriers. The interferometric-type devices use phase modulation between the legs of the interferometer to generate an intensity-modulated optical signal. Most indirect modulation techniques use devices that operate at 1300 nm on substrates, like $LiNbO_3$, that until recently were incompatible with GaAs processing techniques. In interferometric devices, the RF communications signal is used to modulate the refractive index of one leg of the interferometer, which phase modulates the laser light and results in an intensity-modulated optical signal. Indirect modulators suffer from high insertion losses and therefore require significant optical power from the laser source. However, to achieve low noise in the optical carrier it is desirable to operate the laser at low power. The comparison of directly modulated and externally modulated RF fiber-optic links is performed by Stephens et al.[8]

Injection-locking techniques are the third major catagory of temporal modulators. This type of modulator differs from the others in that it supports the RF carrier indirectly. Optical injection locking is used to feed a synchronizing RF reference signal either directly or indirectly to a free-running microwave oscillator. The indirect technique uses a low-power continuous wave (CW) RF signal to modulate a laser source, and this optical synchronization signal is transmitted via fiber, detected and amplified, and fed to a free-running microwave oscillator.[9] The direct technique is similar except that the optical synchronization signal is applied directly to a photosensitive MESFET microwave oscillator without the need of predetection and amplification. The advantage of both techniques is the relaxed optical power constraint, and the synchronizing reference signal may be a subharmonic of the microwave oscillator frequency and use the nonlinear operational mode of the laser to generate the correct harmonic for injection locking. At present, injection locking is the only temporal modulation technique to be usable beyond 20 GHz.

4. SYSTEM COMPONENTS

The feasibility of several system architectures discussed in section 2 depends on the development of several key high-frequency optical components. The current capability of these components in terms of frequency or speed of operation is shown in Figure 6. More detailed discussions for each component are presented in the following subsections.

4.1 Optical integrated circuits

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 to the MMIC's will be connected to the baseband processor by an optical fiber, if feasible. It may be possible with multiplexing 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. The MMIC transmit and receive modules with optical integrated feed circuitry are shown in conceptual diagrams (Figs. 7 and 8, respectively).

Interfaces for phase and amplitude control of the MMIC receiver and MMIC 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. A variety of optical electronic integrated circuits (OEIC) have been demonstrated,[10] 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. A GaAs photoreceiver circuit operating up to 1 Gbit/sec and also employing a 1:16 demultiplex chip on a GaAs substrate tested with a clock speed up to 2.7 GHz has been demonstrated.[11] These operations are now being fully integrated to demonstrate the phase and amplitude control of GaAs MMIC's.

The OEIC's required for the RF signal interface require high bandwidth photodetectors. The status of such photodetectors is discussed in subsection 4.3. The direct optical control of phase shifting and gain functions of MMIC's is also a possibility that can further simplify the MMIC/optical interface. Optical control of microwave devices and circuits has been demonstrated;[12,13] however such techniques can provide switching but not sufficient phase shifting, and monolithic integration of such methods also has to be shown.

4.2 Laser sources

As discussed in section 3, the RF signal can be upconverted to an optical frequency by directly modulating the laser diode current and the modulated signal detected after transmission over a fiber-optic link.[14] Fully packaged commercial GaAlAs/GaAs can operate up to 10 GHz when biased to maximum output power. For GaInAs/InP lasers operating at 1.3 μm, modulation response up to 18 GHz has been demonstrated.[15] The direct modulation bandwidth of these lasers is limited to the relaxation oscillation frequency. Recently, in highly p-doped GaAs/GaAlAs multiple quantum well lasers, a relaxation oscillation frequency of up to 30 GHz has been observed.[16]

Direct modulation of the laser offers the advantages of small size, low coupling loss, and ease of operation. Relative intensity noise, nonlinearity, and power consumption remain major problem areas.

4.3 Photodetectors

Photodetectors in discrete form as well as integratable with GaAs MMIC's are required to demodulate microwave signals carried by an optical fiber up to 100 GHz. The optical wavelengths of 0.82 to 0.84 and 1.3 to 1.5 μm are of interest.

Photoconductors with interdigitated surface geometrics and fabricated on GaAs MESFET-like structures have been demonstrated up to 10-GHz bandwidths, and their performance in optical receivers has been evaluated.[17] Similiar photoconductors have also been studied based on heterostructures.[18] The gain bandwidth product in these photoconductors is limited by electrode spacing and saturated velocity of electrons in the GaAs or heterostructure layers.

A semi-transparent Schottky barrier photodiode designed and fabricated by Wang et al.[19] has been operated in excess of 20 GHz. By further reducing the active layer geometry to a 5-μm square, bandwidths have been demonstrated in excess of 100 GHz.[2] At 1.3 μm, GaInAs PIN photodiodes have been operated up to 30 GHz.[20]

Ease of integration with GaAs MMIC's, low noise, and high quantum efficiency remain the major criteria for the selection of photodetectors for phased-array applications.

4.4 Modulators

Indirect modulation techniques require the use of external modulators which take advantage of the electro-optic and electron absorption phenomena. So far, modulators based on electro-optics effects, such as Mach-Zehnder interferometric techniques, have shown bandwidths up to 17 GHz in $LiNbO_3$ substrates[21] and 20 GHz in GaAs substrates at 1.3-μm wavelength.[22] The advantage of GaAs is obvious, since it will allow integration with laser sources, detectors, and GaAs digital electronic circuitry.

The major advantages of modulation are low noise and separate optical and microwave signals. Additional weight, optical damage thresholds, and insertion loss remain major disadvantages.

5. CONCLUSIONS

Optical techniques have the potential to provide light weight and flexible interconnections for the GaAs MMIC phased-array antenna. As array element numbers and frequencies get higher, optical beam forming networks will become a necessity. However, at present, system tradeoffs are not clear, and only detailed architectures studies will point out when and what type of optical techniques will be applied to phased-array antennas. Parallel developments in high-frequency optical components will assure early breadboarding of optically interconnected phased arrays.

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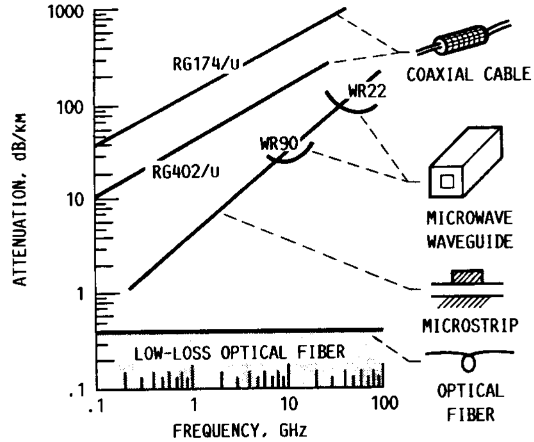

FIGURE 1. - COMPARISON OF ATTENUATION OF MICROWAVE TRANSMISSION LINES WITH OPTICAL FIBER.

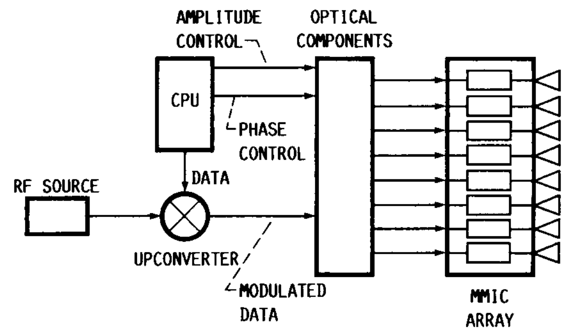

FIGURE 2. - GENERIC ARCHITECTURE FOR OPTIC-BASED PHASED ARRAY.

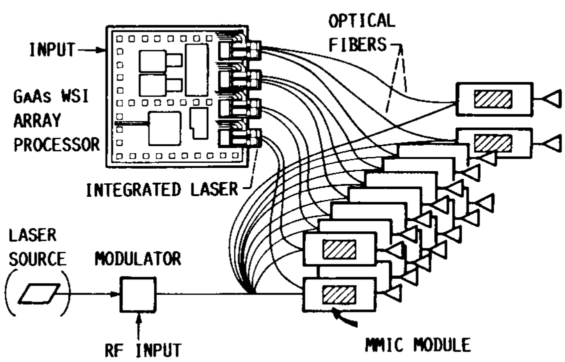

FIGURE 3. - OPTICALLY CONTROLLED AND FED MONOLITHIC INTEGRATED CIRCUITS FOR PHASED ARRAY ANTENNA.

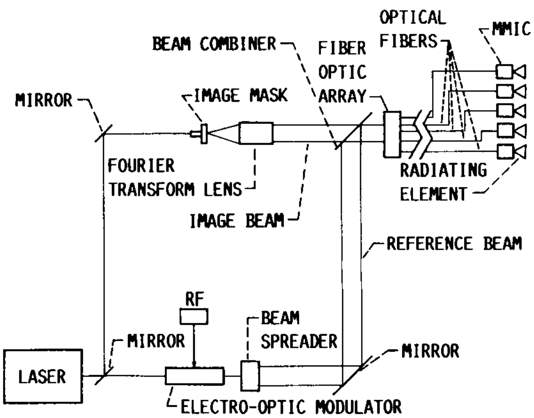

FIGURE 4. - OPTICALLY PROCESSED BEAM FORMING NETWORK.

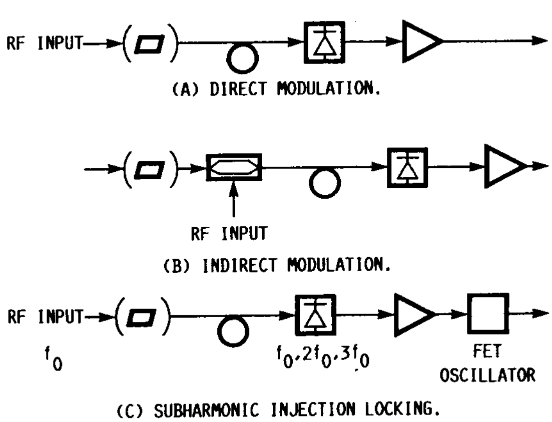

FIGURE 5. - VARIOUS SCHEMES FOR TRANSMISSION OF MICROWAVE SIGNAL VIA OPTICAL FIBER.

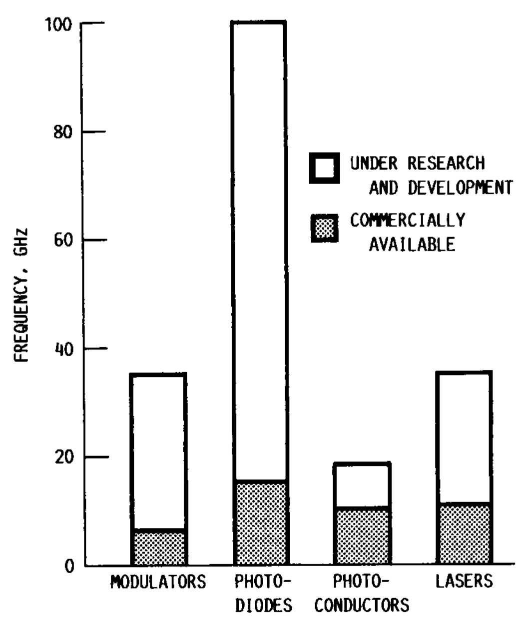

FIGURE 6. - PERFORMANCE OF CURRENT SOLID-STATE OPTICAL COMPONENTS COMPATIBLE WITH MMIC INTEGRATION TECHNIQUES.

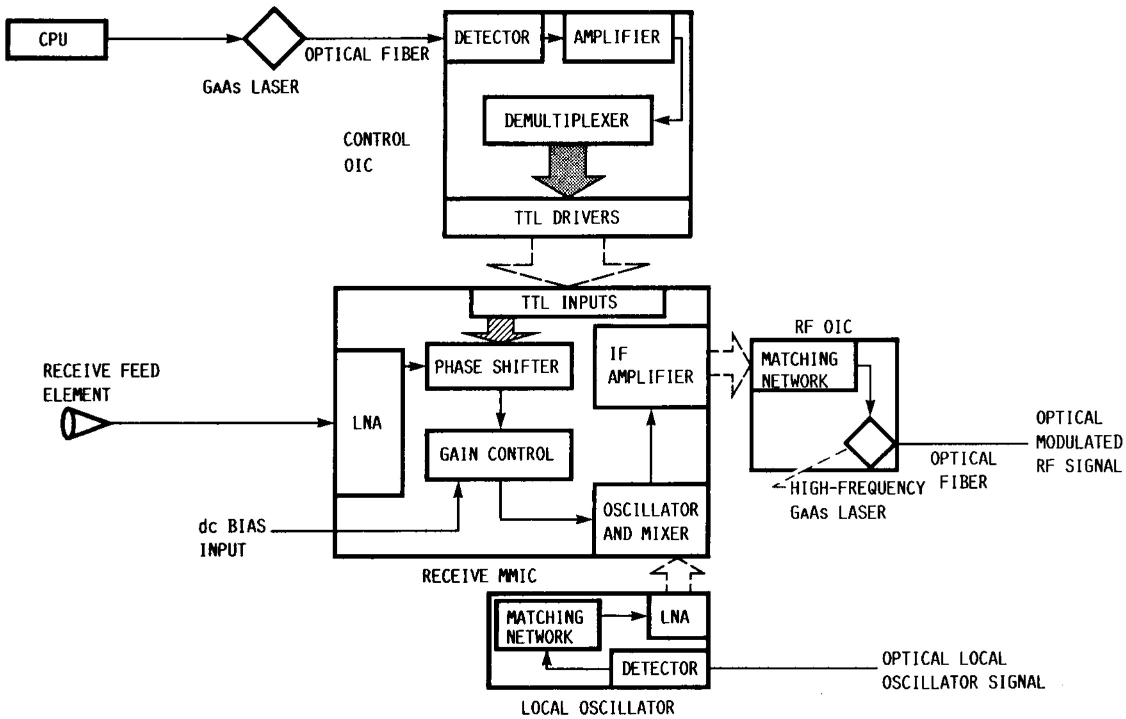

FIGURE 7. - BLOCK DIAGRAM OF RECEIVE MMIC WITH OPTICAL INTERCONNECTS.

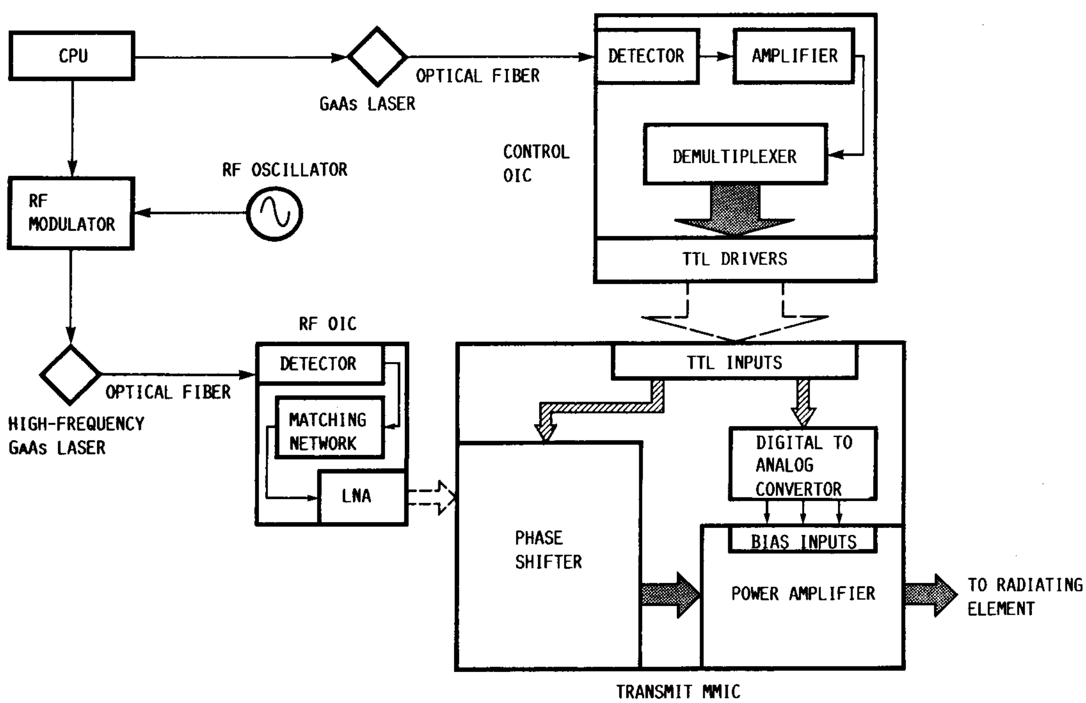

FIGURE 8. - BLOCK DIAGRAM OF TRANSMIT MMIC WITH OPTICAL INTERCONNECTS.

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