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# Optically Controlled Phased-Array Antenna Technology for Space Communication Systems

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# Optically controlled phased-array technology for space communication systems

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## ABSTRACT

Using MMICs in phased-array applications above 20 GHz requires complex RF and control signal distribution systems. Conventional waveguide, coaxial cable, and microstrip methods are undesirable due to their high weight, high loss, limited mechanical flexibility and large volume.

An attractive alternative to these transmission media, for RF and control signal distribution in MMIC phased array antennas, is optical fiber. Presented are potential system architectures and their associated characteristics. The status of high frequency optoelectronic components needed to realize the potential system architectures is also discussed. It is concluded that an optical fiber network will reduce weight and complexity, and increase reliability and performance, but may require higher power.

## 1. INTRODUCTION

The successful development of GaAs monolithic microwave integrated circuits (MMIC) at mm-wave frequencies has transitioned to the integration of MMIC devices into microwave systems, particularly phased array antennas. Phased arrays having hundreds of elements are becoming a reality with the maturation of this technology. However, conventional signal distribution methods for control and RF functions are not amenable to phased array applications. Waveguide, coaxial cable, and microstrip transmission lines suffer from high weight, mechanical inflexibility, and high loss. Fiber optic transmission lines have the potential to overcome these limitations.<sup>1</sup> Fiber is lightweight, small in physical size, mechanically flexible, highly EMI and EMP resistant and virtually lossless.

With the benefits of optical fiber systems becoming more promising, many technology issues remain to be addressed before fiber technology is mature enough for use in space communication systems. Much research has been initiated to make high frequency fiber optics realizable for microwave phased array antenna systems. As part of its overall goals, NASA has identified several missions requiring high frequency fiber optic technology. These missions include Mars Rover (Mars to Earth data relay), Mission Planet Earth (Earth radiometry with active array compensation), and the Experimental Antenna System, (prototype reflector based antennas using phased array feeds). This paper attempts to show the types of architectures that are possible and the devices required to implement microwave phased array antenna systems.

## 2. OPTICAL SYSTEM ARCHITECTURES FOR MICROWAVE PHASED ARRAYS

The integration of MMICs into microwave phased array communications systems has identified fiber optic interconnections as an enabling technology. Two areas of development that are critical to the successful implementation of fiber are optical fiber architectures and integratable optoelectronic devices on GaAs substrates. An analysis of potential architectures reveals that, at present, all of the possible architectures can be represented by three basic types.

Control signal distribution is the least demanding architecture in terms of device technology development.<sup>2</sup> The typical configurations assume a central control unit from which element assignments are determined and transmitted. 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.<sup>3</sup> 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.

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The lower frequency requirements of control signal architectures (<1 GHz) allow for a more timely development of these architectures. However, many technology issues are common to all fiber architectures. These features include the integration of Opto-Electronic Integrated Circuits (OEICs) with GaAs MMIC designs, fiber device interconnection, and device efficiency. Even at lower frequencies, efficient OEIC design and implementation is a challenge.

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 is 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.

A third type of architecture does not use controllable MMICs as the devices necessary to create the appropriate phase and amplitude excitations for antenna beam formation, rather, this function is implemented in the optical domain. Optical Beam Forming Network (OBFN) architectures use holographic techniques to combine spatial as well as temporal information for antenna beam formation.<sup>4,5</sup> By optically creating the desired antenna beam characteristics, the difficulty in producing nearly identical MMIC phase shifters and variable gain amplifiers is overcome.

OBFN architectures have similar temporal device requirements 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.

### 3. OPTICAL MODULATION TECHNIQUES

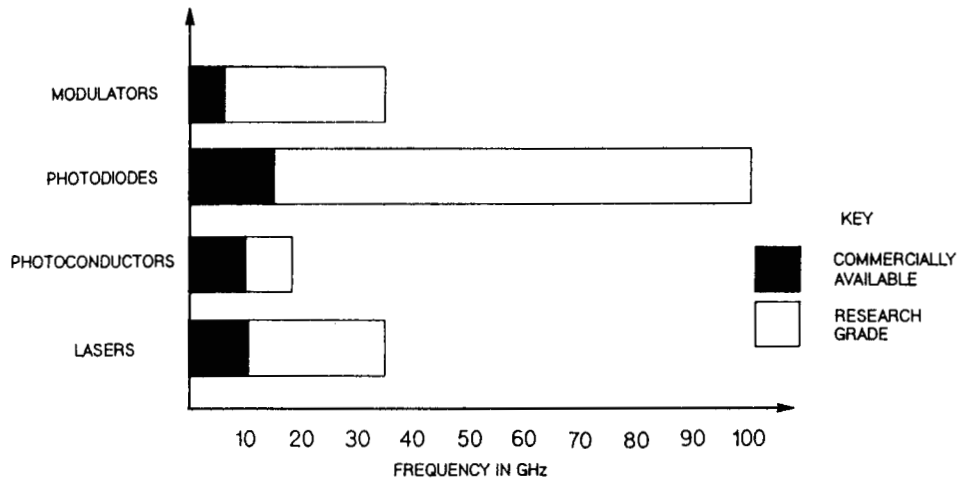
While spatial modulation is unique to OBFN architectures, temporal modulation is common to all fiber architectures. Temporal modulation can be characterized by direct, indirect, and injection locking techniques. Injection locking differs from the other two techniques in that it does not directly support 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.<sup>6</sup> 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 mm-microwave transmission systems, direct links require large dynamic ranges, high center frequencies, wide bandwidths, and low noise levels. At present, modulation frequencies are limited to the upper teens of GHz, limited largely by 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 along with laser sources to modulate optical carriers. Most indirect modulation techniques use devices that operate at 1300 nm on substrates, like LiNiO<sub>3</sub>, 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. Ironically however, to achieve low noise in the optical carrier it is desirable to operate the laser at low power.

Injection locking techniques are the third major category of temporal modulators. This type of modulation 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 CW sub-harmonic 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.<sup>7</sup> The direct technique is similar except the optical synchronization signal is applied directly to a photoreactive MESFET microwave oscillator without the need of predetection and amplification. The advantage of both techniques is the

relaxed optical power constraint and that the synchronizing reference signal may be a sub-harmonic of the microwave oscillator frequency and use the non-linear operational mode of the laser to generate the correct harmonic for injection locking. At present, injection locking techniques have been the only temporal modulation technique to be usable beyond 20 GHz.



**FIGURE 1. - PERFORMANCE OF CURRENT SOLID STATE OPTICAL COMPONENTS COMPATIBLE WITH MMIC INTEGRATION TECHNIQUES**

4. SYSTEM COMPONENTS

The feasibility of several system architectures discussed earlier 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 Fig. 1. More detailed discussions for each component are presented below:

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 MMICs 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  $\mu\text{m}$  wavelength transmission.

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 opto-electronic integrated circuits (OEIC) has been demonstrated,<sup>8</sup> although their compatibility with MMIC fabrication processes has yet to be determined. The OEICs required for the RF signal interface require high bandwidth photodetectors. The status of such photodetectors is discussed in Section 4.3

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 Gbits/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.<sup>9</sup> These operations are now being fully integrated to demonstrate the phase and amplitude control of GaAs MMICs.

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,<sup>10,11</sup> 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 earlier, the RF signal can be up-converted to an optical frequency by directly modulating the laser diode current and the modulated signal detected after transmission over a fiber optic link.<sup>12</sup> 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  $\mu\text{m}$ , modulation response up to 15 GHz has been demonstrated.<sup>(13)</sup> 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.<sup>14</sup> Direct modulation of the laser offers the advantages of small size, low coupling loss, and ease of operation. RIN, non-linearity and power consumption remain major problem areas.

#### 4.3. PHOTODETECTORS

Photodetectors in discrete form as well as integrable with GaAs MMICs are required to demodulate microwave signals carried by an optical fiber up to 100 GHz. The optical wavelength of 0.82 to 0.84  $\mu\text{m}$  and 1.3 to 1.5  $\mu\text{m}$  are of interest. A semi-transparent Schottky barrier photodiode designed and fabricated by Wang et al.<sup>17</sup> has been operated in excess of 20 GHz. By further reducing the active layer geometry to a 5  $\mu\text{m}$  square, bandwidths have been demonstrated in excess of 100 GHz. At 1.3  $\mu\text{m}$ , GaInAs PIN photodiodes have been operated up to 30 GHz.<sup>18</sup> Ease of integration with GaAs MMICs, low noise, and high quantum efficiency remain the major criteria for the selection of photodetectors for phased array applications.

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.<sup>15</sup> Similiar photoconductors have also been studied on heterostructures.<sup>16</sup> The gain bandwidth product in these photoconductors is limited by electrode spacing and saturated velocity of electrons in the GaAs or heterostructure layers.

#### 4.4. MODULATORS

Indirect modulation techniques require the use of external modulators which take advantage of the electro-optic and electron absorption phenomenon. So far, modulators based on the electro-optics effect such as Mach-Zehnder interferometric techniques, have shown bandwidths up to 17 GHz in LiTaO<sub>3</sub> substrates<sup>19</sup> and 20 GHz in GaAs substrates at 1.3  $\mu\text{m}$  wave length.<sup>20</sup> The advantage of GaAs is obvious, as it will allow integration with laser sources, detectors and GaAs digital electronic circuitry. Other major advantages of indirect modulation are low noise along with isolated optical and microwave inputs. Additional weight, optical damage thresholds and insertion loss remain the major disadvantages.

#### CONCLUSIONS

Several potential architectures for optically controlling and feeding high frequency GaAs MMIC devices used in microwave phased-array antennas have been presented. The specifications and characteristics for the opto-electronic devices required to implement these architectures have also been discussed. It is concluded that a substantial effort in the research and development of this technology is needed to produce opto-electronic devices and architectures for use at mm-wave microwave frequencies above 20 GHz. Additionally, without fiber optic links for feeding and controlling microwave phased-arrays, large phased-arrays at mm-wave frequencies may never be enabled.

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