MILITARY AND AEROSPACE APPLICATIONS OF LIGHTWAVE TECHNOLOGY

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ABSTRACT

Examples of the use of lightwave circuits to partition aerospaceborne systems are presented. The role of lightwave technology in future radar, communication, and electronic warfare system architectures is discussed. Finally, the status of microwave bandwidth lightwave transmitter and receiver circuits operating between 1 to 20 GHz is summarized.

INTRODUCTION

The small size and improved reliability of solid state microwave bandwidth analog and digital equipment have enabled significant size reductions in systems, which in turn must now perform an ever-increasing variety of different complex functions, including self-diagnostics and built-in test. The parallel development of monolithic microwave integrated circuits (MMIC), gigabit logic circuitry, and optoelectronic integrated circuits (OEIC) interconnected by low loss, wide bandwidth, EMI free, fiber optic transmission lines will lead to new distributed system architectures with improved performance and reliability at reduced cost.

The wide availability of high bandwidth lightwave components and optical fibers developed by and for the telecommunications industry has enabled the military to develop similar digital links and networks for use in communications, command, and control (C^3) systems. However, as the robustness of lightwave components has improved, the DoD has also been able to demonstrate new distributed system concepts that range far beyond conventional telecommunications applications. The fiber optic guided missile (FOG-M) is currently in an advanced stage of development and is one of the first of these new distributed systems.

FIBER OPTIC GUIDED MISSILES (FOG-M)

In the FOG-M type systems (Figure 1), which have been under development by the Army since 1977, many miles of spooled fiber carried on board the missiles are payed out during the time of flight to enable simultaneous two-way communication between the missile and the launcher (1). FOG-M and a series of derivative missiles use optical wavelength division multiplexing (WDM) to provide full duplex communication between the missile and the launcher. Television/seeker video is transmitted down the fiber from the missile to the launcher on one optical carrier, while guidance and camera commands are transmitted up the fiber to the missile on a second optical carrier. Partitioning the FOG-M system with lightwave technology allows removal of a great deal of costly navigation, guidance, and signal processing equipment from the expendable missile, and placed instead at the reusable launcher, while also providing a jam free, over the horizon, man-in-the-loop capability.

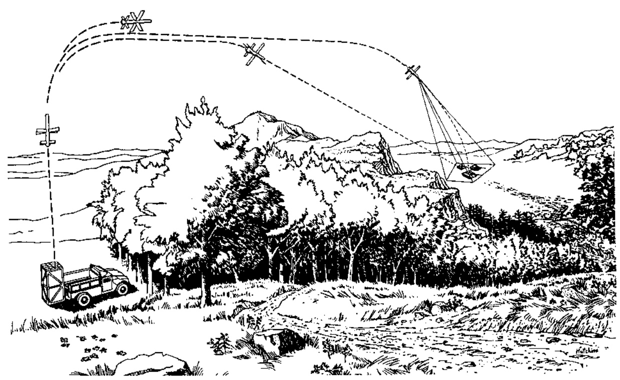

Figure 1.

Many kilometers of optical fiber carried onboard the FOG-M missile are payed out during flight to enable simultaneous two-way video and control communications between the missile and the launcher.

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AIRCRAFT APPLICATIONS

In the past, many fiber optic installations in aircraft have consisted of replacing low bandwidth wires and cables that interconnect electronic boxes with lightwave terminals and fiber optic cables. However, unless the EMI protection and/or size and weight reduction were crucial to the performance of the aircraft's mission, the added cost and complexity of the lightwave interconnect was difficult to justify.

One application avionics experts believe is well-matched to the capabilities of lightwave technology is that of multiwire data busses. Future avionic systems will require numerous parallel 8 to 16-wire data busses between sensors, processors, and displays operating at data rates from 1 to 100 Mb/s. One proposed military standard fiber optic bus is MIL-STD-1773, which has a protocol similar to the MIL-STD-1553 wire bus and that operates at 1 Mb/s data rates.

The recent rapid development of the protocol and of chip sets for the dual ring, fault tolerant, fiber distributed data interface (FDDI) standard operating at 100 Mb/s data rates could also accelerate the acceptance of fiber based aerospace-borne local area network architectures (2). The FDDI concept is being developed in the NASA Johnson Spaceflight Center data management system test bed for the space station (3).

In the past year, GaAs chip sets have become available for hybriding time division multiplexing (TDM) circuits suitable for multiplexing and demultiplexing as many as 10 parallel 100 Mb/s lines onto one serial link running at rates up to 1 Gb/s. Monolithic TDMs, some of which contain lightwave circuits on-chip, are now operating in the laboratory. Mating this high speed GaAs digital circuit technology with lightwave terminals (as shown in Figure 2) to replace 10 or more parallel coaxial cables in advanced sensor, processor, and display interconnects is an application that takes full advantage of the large bandwidth available with lightwave technology.

OPERATION AT MICROWAVE FREQUENCIES

Amplitude modulation of lightwave carriers with analog microwave waveforms between 1 and 20 GHz is being developed by both government and industry. Applications include delay lines for radar and communications, on and off gimbal links for SATCOM terminals, phase noise test sets, antenna remoting, and signal manifolds for phased array antennas. A typical application is shown in Figure 3, in which an X-band modulated, 3-mile-long fiber

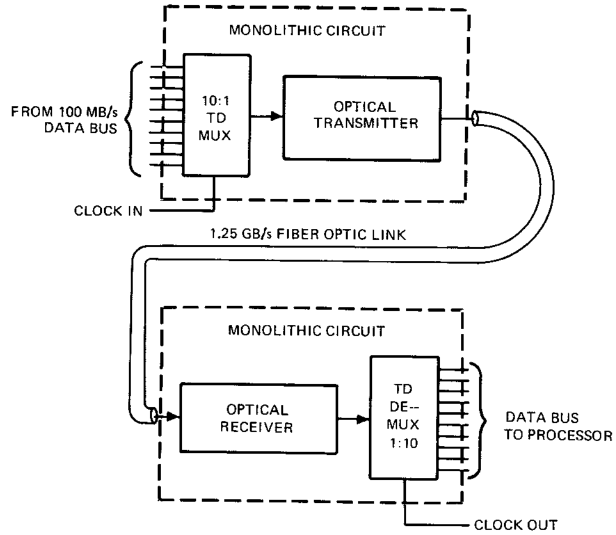

Figure 2.

GaAs time division multiplexer/demultiplexer circuits are being developed to combine a parallel wire data bus with a serial 1 Gb/s lightwave link.

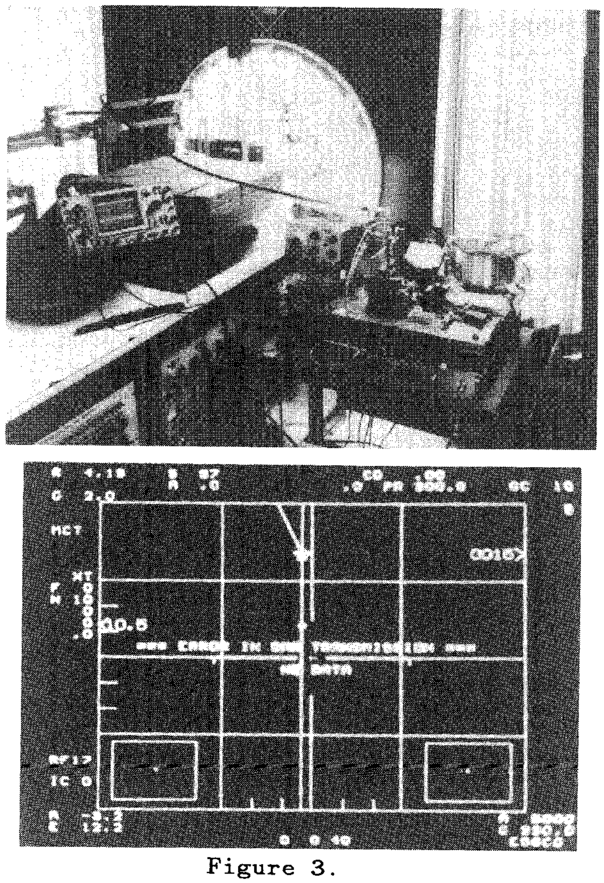

Figure 3.

Three-mile-range X-band fiber optic delay line incorporated into APG-65 radar and display showing high fidelity replica target.

optic delay line operating at 1.3 μm provides a high fidelity replica target for testing an APG-65 airborne pulse doppler radar (4). The Rome Air Development Center, the Air Force Avionics Laboratory, and the NASA Lewis Research Center have aggressively tackled the complex design required for the signal manifold in future active-aperture phased array antenna systems (5).

STATUS OF LIGHTWAVE TRANSMITTERS

Semiconductor lasers currently set the frequency, bandwidth, noise figure, and dynamic range limits for microwave modulated lightwave links. Depending on the application and on the microwave modulation frequency, one or the other of the two modulation techniques shown in Figure 4 is most often used. In Figure 4(a), the microwave analog waveform or gigabit per second digital signal is converted to amplitude modulated light by modulating the current through a laser diode. In the configuration shown in Figure 4(b), a cw diode laser and an external integrated optic amplitude modulator are used to produce modulated light.

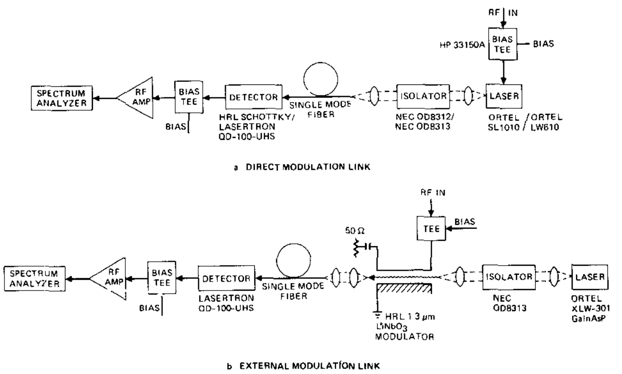

Figure 4.

The two standard microwave modulated fiberoptic link configurations: (a) laser current modulation; (b) cw laser and $LiNbO_3$ integrated optic modulator.

Links using current-modulated transmitters have several advantages, including using fewer parts, suffering less light attenuation, and requiring less modulator drive power (typically ~1 mW). The link dynamic range at the operating microwave frequency is set by the range between the laser output power and noise floor. Figure 5 shows the output power and noise levels of a state-of-the-art commercially available laser designed for microwave applications. Note that the output power and noise spectra have resonance effects that are a function of laser bias current.

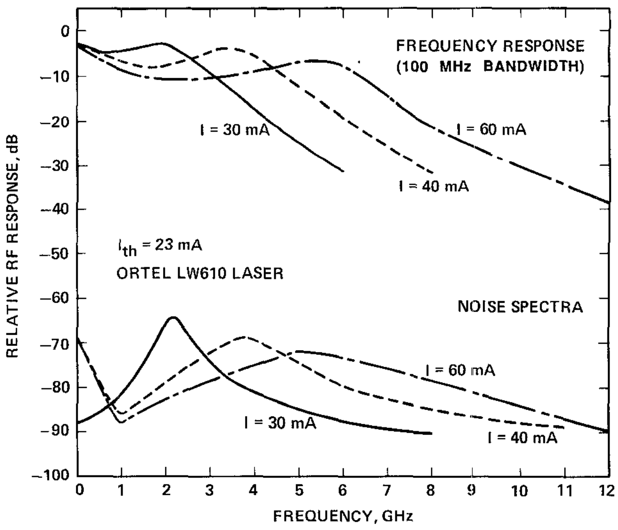

Figure 5.

Power output and noise levels for a commercially available microwave bandwidth semiconductor laser using a 100 MHz measurement bandwidth.

The frequency response of laser diodes under direct current modulation is influenced by both the intrinsic response of the laser chip and the parasitic circuit elements associated with the laser packaging.

For applications that require high dynamic ranges at frequencies above 10 GHz, external modulation is required. For example, the laser shown in Figure 5 can be operated at reduced current in a cw mode (zero frequency), reducing the noise floor by 10 to 15 dB below the resonance peaks, providing greater optical power and dynamic range (~85 dB) to the external integrated optic modulator. The two major disadvantages of the external modulator are an extra 6 to 10 dB of optical insertion loss and the required 100 mW of microwave drive power to the modulator at maximum signal levels. However, it must be remembered that unlike typical microwave circuits, the optical signal power and the optical noise power are equally attenuated through the optical circuits, and if correctly designed, the dynamic range will be preserved through the link while the noise figure is reduced by the amount of attenuation. As shown in Figure 6, the -3 dB frequency response of an integrated optic Mach-Zehnder traveling wave amplitude modulator extends beyond 17 GHz, with the roll off caused by a mismatch between the velocity of light in the waveguide and the microwave velocity of the coplanar stripline on the $LiNbO_3$ substrate (6).

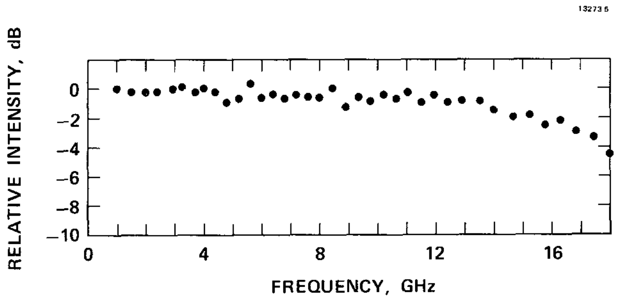

Figure 6.

Microwave frequency response of a $LiNbO_3$ based integrated optic traveling wave amplitude modulator.

STATUS OF LIGHTWAVE RECEIVERS

The receiver for a microwave modulated fiber optic link consists of a high speed photodetector and a low noise amplifier. The detector should have a flat response over the frequency range of interest and have as high an efficiency as possible. The amplifier should also have a flat response over the frequency range and a noise figure well below the received laser noise or thermal noise, whichever predominates.

GaAlAs photodiodes operating at 0.83 μm and InGaAs photodiodes operating at 1.3 μm with bandwidths of 20 GHz and quantum efficiencies as high as 70% have been fabricated and characterized. Based on a 1.5 μm depletion layer width, the frequency limitation caused by transit time effects is approximately 30 GHz. In normal operation with 50 Ω input impedance amplifiers, the bandwidth is determined by the RC time constant of the photodiode plus the parasitic C of the circuit and the amplifier input impedance R.

For links that are amplifier noise limited, it is desirable to design amplifiers with input impedances as large as possible, while still maintaining the $(RC)^{-1}$ bandwidth greater than the required link bandwidth. Tuned detector matching circuits are being developed in the laboratory to increase overall link efficiency and to center the receiver bandwidth at the appropriate microwave carrier frequency.

CONCLUSIONS

Laser current modulated transmitters are commercially available at 0.83 and 1.3 μm for modulation frequencies <10 GHz with dynamic ranges >125 dB/Hz. For frequencies from 1 to 20 GHz, $LiNbO_3$-based integrated optic modulators operating in the laboratory at 1.3 μm can provide dynamic ranges >130 dB/Hz. Reliable operation of lightwave transmitters throughout the military temperature range is a major challenge.

Optical receivers are commercially available at 0.83 and 1.3 μm with bandwidths to 10 GHz and dynamic range >130 dB/Hz. Laboratory receivers have operated to 20 GHz with similar performance.

The noise floor of the optical portion of lightwave links is typically set by laser noise at a noise figure of about 40 dB. The cascaded noise figure of the link, including input and output amplifiers, is set by the gain and noise figure of the input amplifier, by the noise floor of the laser diode, and by the attenuation encountered through the active and passive optical components in the link (5). With careful design, an overall total cascaded link noise figure only a few dB greater than the noise figure of the input amplifier is achievable today with commercially available components. Today's noise figures and dynamic range are suitable for many microwave system applications. We anticipate semiconductor laser power will increase 10 to 20 dB and laser noise will be reduced by 5 to 10 dB in the near future, providing even greater dynamic ranges and increased analog and digital applications.

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