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RECENT ADVANCES IN FIBER OPTICS COMPONENTS FOR HIGH SPEED DATA TRANSMISSION

Branko Leskovar*

Summary

The concept of guided lightwave communication along optical fibers has stimulated a major new technology over the past two decades. This technology profoundly impacts communication and instrumentation systems as well as computer interconnections and system architecture.

In this paper the state of the art of optical transmitters, low loss fiber waveguides, receivers and associated electronics components are reviewed and summarized for optical data transmission systems operating between 100 Mbit/s and 2.5 Gbit/s. Emphasis is placed on high speed data transmission subassemblies, such as time division multiplexers and demultiplexers, clock and data recovery circuits, as well as optical transmitters and receivers. In addition, the performance of candidate components of the wide band digital transmission systems intended for deployment in large detection systems for particle physics is discussed.

Introduction

Fiber optic links provide several major advantages over conventional electronic systems. These include immunity to electromagnetic interference, and low transmission losses for very high data rates. They also make possible thinner and lighter cables and are capable of providing long data transmission links operating in the gigahertz region.

Optical communication using fibers was made possible by the parallel development of low loss fibers, heterojunction lasers, light-emitting diodes, and sensitive photon detectors. The technology of this form of communication is advancing at a very rapid rate. As the short optical wavelength multimode fiber systems are being field-proven and used commercially, the technology is progressing towards single-mode fiber systems in the long-wavelength region. For example, significant advances have been made in the fabrication of low-loss and low-dispersion optical fibers. Losses of approximately 0.20 dB/km at 1300 nm have been achieved for single mode fibers with minimum dispersion at wavelengths near 1300 nm. Furthermore, the development of optical sources, and optical receivers, for long wavelength applications is also advancing rapidly. Several experimental transmission systems capable of operating at a 10 Gbit/s rate over a distance of 375 km employing in line erbium -doped fiber amplifiers and 20 Gbit/s over 100 km have been reported.^{1,2} Although these results were obtained under highly optimized experimental conditions they did give an indication of future capabilities. It should be pointed out however that at present practical high data rate optical transmission systems are operating only between 100 Mbit/s and 2.5 Gbit/s. There has been

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approximately a tenfold improvement in the system performance every three years and a corresponding decrease in the cost.

In addition to the requirements placed on the optoelectronic components of these systems, considerable attention has been paid to the associated logic circuit families with switching speeds in the microwave region. Such circuits are necessary for multiplexing and demultiplexing. These circuits have been implemented using both silicon and gallium arsenide (GaAs) technology. Devices based on GaAs technology have become available recently for applications in practical systems with a data rate capability of up to 2.5 Gbit/s. Although the major thrust for development of high data rate fiber optic systems has been for long distance communication links, the local data communication needs have given a new impetus for the development of advanced system components. The recent systems for local communication, such as computer interconnections, rf distributions in phased array radars and instrumentation for basic and applied research, required a high data rate capability.³⁻⁶

System Considerations

A simplified block diagram of a high speed point-to-point data transmission system is given in Fig. 1. The system consists of a number of data sources, a time division multiplexer, optical transmitter electronics, an interface and light source, an optical fiber transmission link, a light detector and interface, optical receiver electronics, a demultiplexer and a number of data destination points.

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Fig. 1 Simplified block diagram of a digital optical fiber transmission system.

Time Division Multiplexers and Demultiplexers

Various high-speed time division multiplexers and demultiplexers have been developed in recent years using large scale GaAs integration technology and optoelectronic metal - semiconductor - metal switches based on InP sampling elements. For example, a 16:1 ratio GaAs 4 Gbit/s multiplexer and 1:16 ratio 4.63 Gbit/s demultiplexer which operate from data rates of 5 Mbit/s in a multilayer ceramic package have recently been described.⁸ Also, InP optoelectronic switches and multiplexers with 8:1 ratio operating at a serial data rate of at least 2.5 Gbit/s have been extensively studied.⁹ Furthermore, devices based on silicon bipolar monolithic integrated circuits, using self-aligning polysilicon technology, with capability of operating up to 10 Gbit/s have been recently reported.¹⁰ However, it should be pointed out that these impressive results were obtained with experimental devices. At the present available devices have demonstrated conversion of parallel to serial data at rates up to 1.5 Gbit/s with the multiplexing (demultiplexing) ratio of 16:1 (1:16).⁷

These devices may incorporate threshold, clocking and resetting capability. Also the demultiplexer may contain on chip frame synchronization circuitry which simplifies an optical receiver design. The power dissipation of such multiplexer and demultiplexer is typically 0.95W and 1W, respectively.

Optical Transmitters

The optical transmitter typically consists of transmitter electronics, an interface and a light source. The transmitter electronics accept parallel input data and by using an appropriate encoding format converts the data into a serial stream. After conversion, electronics transmits the data through an interface and a light source to the optical fiber transmission link. The coding formats that satisfy the needs of clock recovery and DC balance are a tradeoff between coding circuitry complexity and bandwidth utilization. For high data transmission rates typical encoding formats are 4B/5B and 16B/20B. The combination of 4B/5B encoding and application of non-return to zero, inverts on ones (NRZI) data format results in frequent transitions on transmitter serial data output. In this case a duty cycle of 60%/40% is accomplished in the worst case. This is important for fiber optic transmission because it limits the DC offset voltage of the transmitter output. The frequent transitions on the incoming data stream to the optical receiver aid its phase-locked loop circuitry in maintaining synchronization with the transmitter.

Although the 4B/5B coding format has been widely accepted, particularly for the 100 Mbit/s Fiber Distributed Data Interface (FDDI), newer coding formats such as 16B/20B, have been recently implemented.¹² These formats are less complex to implement than 4B/5B coding and they are highly efficient.

The transmitter requires a reference clock of specified frequency, typically 20 MHz, for its phase-locked loop. This clock signal may be obtained from the host system or generated by a in-built crystal oscillator. The phase-locked loop circuit multiplies the reference clock and provides the timing reference for all internal clocking and control operations. The clocking and control circuit determines the operating frequency and controls the synchronization frame

insertion. The synchronization frame is inserted into the data path whenever there are no input data.

An input control circuit controls the input latch of the transmitter electronics. The input data are latched into the transmitter electronics on the rising edge of the strobe signal. The light source interface translates the logic level at the NRZI converter output into the drive current for the light source.

Light emitting diodes and semiconductor lasers are the most frequently employed light sources in optical systems. Light emitting diodes (LED's) offer the advantages of simple fabrication and operation as well as low cost, high reliability and good linearity and small temperature dependence of the light output. Semiconductor index-guided injection laser diodes offer high output power levels, efficiency and bit rate modulation capabilities as well as extremely narrow spectra and excellent mode stability of the emitted light. A summary of the typical characteristics of light emitting diodes and laser diodes for high speed data transmission is given in Table 1.

Table 1. Summary Characteristics of Light-Emitting and Laser Diodes for Optical Fiber Data Transmission

	Surface-Emitting LED	Edge-Emitting LED		Superluminescent Diode	Laser Diode
Optical Power ^a (μ W)	0.5 - 1.0	2.0 - 4.0	8.0 - 100 ^b	100 - 350	200 - 1500
Spectral Linewidth (nm)	40 - 170	100	60	30	0.5 - 3
Rise Time (ns)	2 - 3	2 - 3	2.0	1 - 2	0.04 - 0.3
Fall Time (ns)	2 - 7	2 - 3	2.0	1 - 2	0.05 - 0.3
Output Power Temperature Sensitivity (%/°C)	0.4	1.0	2.0	4.0	<1.0 ^c

^aOptical source was coupled to single-mode fiber.
Center wavelength $\approx$ 1300 nm.

^bOptical power was 20 μ W at 1550 nm.

^cObtained with automatic control of the output power level.

Using a light emitting diode, coupled to a 62.5 μ m-diameter core multimode fiber,¹³ presently available optical transmitters typically have the following characteristics: emission wavelength = 1300 nm, maximum data rate = 100 Mbit/s, average optical output power, while transmitting square wave = 32 μ W (-15 dbm), rise and fall time of the light pulse from 1 to 4 ns, and total power dissipation = 3.15 W.

Using an index-guided injection InGaAsP laser available optical transmitters typically have the following characteristics: emission wavelength = 1300 nm, maximum data rate capability = 1.0 Gbit/s, CW optical power = 1mW (0dBm), rise and fall time smaller than

330 ps, RMS spectra width smaller than 3nm, and total power dissipation = 8.5 W. The optical signal is coupled to 8 μm - diameter core single mode fiber. 11,14

Optical Fiber Waveguide

The basic transmission characteristics of the various types of optical fiber waveguide, such as attenuation, bandwidth and radiation induced attenuation, have been discussed elsewhere.^{4,15,16,17} Work is in progress establishing future standards for measuring the effects of steady state and transient ionizing radiation on optical fibers. Measurements performed on multimode and single mode practical optical fibers reveal that radiation dose rates and injected optical power levels significantly influence induced attenuation in silica core fibers. However, these parameters did not effect the response of germanium doped silica fibers as severely.

Radiation resistant optical fibers have recently become commercially available^{18,19}. Single mode Sumitomo fiber having a pure silica core and a fluorine doped cladding has been fabricated by the vapor axial deposition process. The fiber core diameter and cladding diameter was 8.5 μm and 125 μm , respectively. Depending upon the grade of the fiber, the preirradiation attenuation varies from 0.4 to 0.7 dB/km. Dispersion is smaller than 3.55 ps/nm/km for the wavelength range from 1285 to 1330 nm.

Measurements performed on this fiber exposing it to a ^{60}Co source have shown that the radiation-induced attenuation was 20 dB/km at a total dose of 7×10^4 Gy at a dose rate of 10^3 Gy/hour. The injected optical power level was 20mW at a wavelength of 1300 nm.

Similar measurements were performed on the fiber waveguider with the same geometry as given above but with germanium doped silica core and pure silica cladding. Under identical measuring conditions this fiber showed a radiation-induced attenuation of 20 dB/km at a total dose of 1.5×10^4 Gy and dose rate of 10^2 Gy/hour.

Furthermore, both fiber waveguides were irradiated with 14 MeV neutrons. The neutron induced attenuation of 20 dB/km was obtained after approximately 0.6 hours of irradiation for germanium doped core fiber. The attenuation increased up to 70 dB/km after 3.5 hours of irradiation (neutron fluence of 1.5×10^{14} n/cm²). However for pure silica core fiber the induced attenuation reached approximately 10 dB/km after the same irradiation time. Experimental results have clearly showed that a pure silica core fiber has significantly lower radiation sensitivity than a germanium doped silica core fiber for both γ -ray and neutron irradiation.

Optical Receivers

The optical receiver accepts serial optical data from the fiber transmission link, detect the optical signal, recovers clock and data and also performs a coding format conversion. Also the receiver assembles parallel words and transmits them to the demultiplexer.

The receiver consists of a photodetector, detector interface (usually low-noise preamplifier) and the optical receiver electronics.

The most useful photodetectors for optical fiber systems are the PIN diode and avalanche photodiode (APD). The APD is more sensitive than the PIN diode because of its internal avalanche gain. The receiver sensitivity, which is defined as the minimum optical power level required at the receiver input so that it will operate reliably with a bit error rate less than a desired value, depends also on preamplifier configuration and components used. Calculated values of the receiver sensitivity as a function of operating bit rate rate for a bit error rate (BER) of 10^{-9} and various preamplifier configurations are given in Fig 2.³ It can ben seen from this figure that the APD in combination with FET high impedance preamplifier provides the highest calculated receiver sensitivity.

Fig. 2 Calculated optical receiver sensitivity versus operating bit rate.

Fig. 3 Bit error rate as a function of average received optical power for practical optical receiver.

Experimental receiver sensitivity reported in literature are presently lower by at least 3 dB, from theoretical sensitivities at 1Gbit/s, because of lack of low noise long-wavelength APD's and imperfections of the received electronic circuitry.

For practical receivers using PIN photodiode and APD detector the bit error rate as a function of averaged optical power is shown in Fig. 3. These receivers employ GaAs IC transimpedance amplifiers with a gain of 18dB and bandwidth of 700MHz.⁷ Using an APD detector the input sensitivity is typically -35 dBm for BER = 10^{-9} , bit rate of 1.2 Gbit/s and feedback resistance value of 1K Ω . Using a typical PIN photodiode detector, the receiver sensitivity is approximately -27dBm for a bit rate of 1.1 Gbit/s and non-return to zero (NRZ) digital coding format.⁷

Receivers which employ GaAs transimpedance amplifier with a gain of 22dB and 1.9GHz bandwidth, and PIN photodiode detector have demonstrated the typical sensitivity of -24dBm for BER = 10^{-9} and bit rate of 2.5 Gbit/s (NRZ).

The receiver electronics contains a phase-locked loop circuit. This circuit typically multiplies the input reference clock signal by an appropriate factor to generate the timing reference signal for the receiver operation. The receiver can be operated with or without a local crystal oscillator. With a local oscillator the reference signal is obtained from a clock recovery circuit. Without the local oscillator the reference signal is obtained from the host system.

The clocking and control circuits coordinate the reconstruction of a parallel data word from the serial code word. However, it is necessary to acquire a synchronization signal before any data can be read. This is accomplished by providing a reference clock signal having the same frequency as the transmitter. Once the synchronization is achieved the data information is recovered from the serial input stream. Data are serially converted back to the appropriate format.

The strobe and status circuitry generates the following interface status signals: strobe, synchronization and error. Strobe pulses indicate when a new data word is present at the output latch. Synchronization indicates reception of the synchronization frame. Error is activated when the current output word is decoded from one or more invalid symbols. It remains activated until a new data word, decoded from ten valid symbols, is recorded on the output bus.

For multigigabit coherent systems a long time operation and the sensitivity depend on fluctuation in the state of polarization of the optical signal in the fiber, the system acquisition/locking functions and local oscillator laser stability. Long term operation of such systems can be accomplished by polarization diversity detection and an automatic frequency control circuit.²⁰ A 1.7 Gbit/s coherent system has demonstrated receiver sensitivities of -41.5 dBm and -40 dBm for the best and worst state of polarization of the incoming signal, and BER = 10^{-9} . Fig. 4 shows a typical bit error rate characteristics for the following states of polarization of the incoming signal: S-polarization, P-polarization and 45° linear polarization. The receiver sensitivity variation for various polarizations is smaller than 1.5 dB. The sensitivity penalty calculated from the theoretical limit is 7 dB.

For systems operating up to 100MBit/s, such as the Fiber Distributed Data Interface, the optical transmitter-receiver pairs have recently become available from numerous sources.^{13,14,21-25} The performance of these pairs fully meet the requirements of the FDDI Physical Layer Medium Dependent Standard. The optical transmitter typically uses a 1300nm InGaAsP LED, and a silicon bipolar IC interface. The LED has an integral etched lens that provides efficient coupling to a multimode fiber. The data input to the transmitter is differential 100K ECL compatible. For data rates up to 250 Mbit/s systems usually employ buried heterostructure laser diodes and single mode fibers.

Fig. 4 Bit-error-rate performance as a function of the state of polarization of the incoming optical signal.

The receiver employs a 1300 nm InGaAs PIN photodiode and custom made silicon bipolar integrated circuits. The preamplifier integrated circuit is mounted in the optical subassembly with the PIN detector to maximize the received sensitivity.

For systems operating up to 2.5Gbit/s, such as a Synchronous Optical Network (SONET), various GaAs integrated circuits have recently become available.²⁶ These IC's include 1.25 Gbit/s 8 channel multiplexers and demultipliers, 2.5 Gbit/s 4 channel multiplexers and demultiplexers as well as frame recovery circuits.

Conclusions

With respect to the detailed design of high-speed optical fiber networks for high speed data transmission in experimental research some subassemblies, for point-to-point communication, are commercially available. These subassemblies are transmitter-receiver pairs, based on gallium arsenide technology, and capable of operating up to 2.5 Gbit/s data rates.¹¹ In general, such pairs do not incorporate light sources, the photodetectors or associated electronics. To meet the data rates under discussion they would require interfacing with light emitters and photodetectors having an appropriate data rate capability.¹⁴ However, for data rates only up to 100 Mbit/s optical transmitter-receiver pairs have recently become available with incorporated light sources and photodetectors.

The detailed design of optical fiber networks for specific applications and the choice of technology used for their implementation requires further study. Some of these are the high-speed low power dissipation fiber optic subassemblies, wavelength division multiplexers and demultiplexers, radiation sensitivity of components and subassemblies and network reliability and failure modes.

High performance fiber optic subassemblies, such as time division multiplexers and demultiplexers, clock and data recovery circuits and optical transmitters and receivers typically require a significant amount of power for their operation. Design studies must be made of subassembly configurations and of integrated circuit technologies giving minimum power dissipation. In particular, studies are required on the design of these subassemblies based on the application of specific integrated circuits.

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