Technology and Design Considerations for a Very-High-Speed Fiber-Optic Data Bus

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Abstract—The technology for very-high-speed fiber-optic data transmission is reviewed, and an assessment is made of the data rate limitations for a ring bus. Maximum data rates for single-channel transmission are estimated to be in the five-ten Gbit/s range, but bus capacity can be increased to 100 Gbits/s or higher with parallel interconnections or carrier-frequency multiplexing. A recirculating fiber loop is proposed as a buffer between the high data rate bus and terminals which operate at relatively low speeds. A bus terminal design based on this concept is suggested.

I. INTRODUCTION

As the technology of electronic data processing continues to advance at a phenomenal rate, the limitations of present data communications systems become more and more apparent. The evolution of VLSI chips with higher switching speeds, lower power consumption, and greater circuit densities are making possible new generations of computers which, though physically smaller than their predecessors, have faster central processing units and larger memories. Input-output data rates for state-of-the-art computers are also steadily increasing. This trend could accelerate over the next few years with the advent of gallium arsenide integrated circuit technology, which can provide higher speed and lower power dissipation than the traditional silicon circuits. Furthermore, with continuing advances in analog-to-digital conversion technology, the quantity of digital data which is available from sensors continues to increase rapidly. All of these factors lead to requirements for higher and higher communication data rates in information processing systems.

Coaxial cables and twisted wire pairs are still the primary media for data communications, just as they were decades ago. Data rates for these electrical transmission lines are limited to a few Mbits/s for lengths of 1 km. These relatively low data rates are not adequate to meet the requirements of many of our modern information processing systems.

The new technology which is capable of overcoming these limitations is fiber-optics communication. Since the first low-loss (20 dB/km) fibers were produced ten years ago [1], an optical communication industry based on the use of semiconductor light sources, photodetectors, and silica fibers has evolved. Fibers with losses as low as 0.2 dB/km have been produced [2], with losses of 0.5 dB/km routinely achieved in production. Experimental links have been operated at data rates as high as 2 Gbits/s over transmission line lengths in excess of 40 km [3]. Fiber optics is just beginning to make an impact in data processing, but lower costs and requirements for larger transmission capacity will combine to make the technology cost effective for an increasing number of civilian and military computer systems in the years ahead.

Data rates of state-of-the-art optical transmitters and receivers are limited to a few Gbits/s, yet much higher rates could be effectively utilized in future military systems. One example of such a system is the local computer network illustrated in Fig. 1, in which the terminals communicate with one another in a burst transmission mode. Applications for such a distributed network include multisensor correlation, image processing, artificial intelligence, weather prediction, and display networks. Very high processing rates are needed for these applications. Some algorithms and architectures will also require very high bus data capacities to fully utilize the computational power of a large number of interconnected processors.

This paper addresses the technology, design, and performance limitations for a very-high-speed fiber-optic bus of the type illustrated in Fig. 1. The state-of-the-art and future prospects in high-speed fiber-optic data transmission are discussed, followed by a treatment of bus design and architectural issues. Some conclusions regarding the ultimate performance of such a system are indicated.

II. TECHNOLOGY FOR HIGH DATA RATE FIBER-OPTIC SYSTEMS

A great deal of research and development effort has been expended during the past decade on components and systems for optical fiber communications. Since the great majority of commercial and military applications require bandwidths less than 100 MHz, only a relatively small part of this effort has been concerned with reaching high bandwidths. However, there is an increasing interest in wide-band fiber-optics technology, and some impressive results have recently been reported. This section summarizes the state-of-the-art in components and systems for high data rate fiber communications. Included in the survey are transmitters, receivers, and fibers, as well as systems demonstrated to date. Future prospects are also discussed.

A. Transmitters

A number of digital optical transmitters have been developed for operation at data rates in the 1.0–2.3 Gbit/s range. Most of these experimental transmitters have utilized an injection laser diode as the optical source, directly modulated by varying the driving current. The first demonstration of one...
Gbit/s modulation was reported in 1973 [4]. The laser was a stripe-geometry Ga_xAl_{1-x}As double-heterostructure diode, and the driver was a silicon emitter-coupled logic circuit. A similar experiment was performed shortly thereafter using a Trapatt diode as the laser driver [5]. Digital modulation of injection lasers at rates as high as 2.3 Gbits/s using a Gunn diode as the driver was also reported in 1973 [6].

These early experiments demonstrated the feasibility of direct modulation of semiconductor lasers at high speeds. However, practical transmitters and repeaters for optical communications require more sophisticated electronics for shaping input electrical pulses and providing sufficient amplitude from low-level input signals to drive the laser. More recent work has concentrated on development of the circuitry needed to drive these capabilities by the transmission of pseudorandom bit sequences. One such experiment utilized a GaAs FET as the driver for a GaAlAs laser [7]. In another experiment, a transferred electron logic device (TELD), a planar Gunn-effect device used as a current switch, was the pulse shaping and driving element in a 1.5 Gbit/s transmitter [8].

The highest data rate yet reported, 8 Gbits/s, was obtained in a GaAlAs laser driven by a stepped-recovery diode and multiplexing circuit [9]. Finally, a transmitter incorporating an InGaAsP double-heterostructure laser was operated at a 2 Gbit/s data rate [3]. The quaternary InGaAsP laser is of particular interest for long distance high data rate systems because it can be designed for an emission wavelength in the 1.2-1.5 μm range where the dispersion and losses of doped silica fibers are lowest. Both loss and dispersion are substantially higher in the 0.8-0.9 μm region where the GaAlAs lasers operate most efficiently.

An alternative to direct modulation of semiconductor lasers is the use of a CW laser with an external modulator. A bandwidth of one GHz was demonstrated several years ago in a LiTaO_3 optical waveguide modulator [10]. More recently, a bandwidth of 1 GHz was demonstrated several years ago in a LiNbO_3 waveguide modulator [11]. A traveling wave configuration in which the modulating signal is carried on a coplanar transmission line was used. This modulator was driven from an oscillator and the pulse response was not investigated.

It should also be mentioned that a 1 Gbit/s transmitter using a mode-locked Nd:YAG laser and a LiTaO_3 bulk modulator has been developed for space communications [12]. However, that transmitter is not viewed as practical for fiber-optic applications, inasmuch as the electrical power required for the modulator alone was about 50 W.

**B. Receivers**

A number of solid state optical receivers have been demonstrated to operate at rates in excess of 1 Gbit/s. Most of these were developed to be compatible with optical transmitters for use in link transmission experiments. The receivers have all incorporated semiconductor p-i-n photodiodes or avalanche photodiodes (APD's) as the optical sensor. The APD is desirable because its inherent internal gain improves the signal-to-noise ratio for a given optical power input and also reduces the gain required from the electronic amplifier.

APD's fabricated in the elemental semiconductor materials Si [13] and Ge [14] have shown a response equivalent to digital data rates greater than 2 Gbits/s. The decreasing optical absorption of Si at longer wavelengths limits its spectral region for efficient operation to wavelengths less than about 1.1 μm. On the other hand, although the quantum efficiency of Ge is high at longer wavelengths, noise due to the high dark current can limit its sensitivity. APD's fabricated from compound semiconductors such as GaAlAs for wavelengths less than 0.9 μm and GaAlAsSb and InGaAsP at wavelengths in the 1.0-1.6 μm range have much lower dark current than Ge and an extremely fast response, equivalent to about 5 Gbits/s [15].

A high-speed digital receiver contains not only the photodetector but also an amplifier and a threshold circuit to restore a clean digital waveform. One such receiver used a Si APD and bipolar Si amplifiers and threshold circuitry and operated at 1.6 Gbits/s [16], and another with a Ge APD and a tunnel diode comparator as the threshold circuit operated at 2 Gbits/s [3]. A 5 Gbit/s receiver using a Si APD with GaAs preamplifier and demultiplexing circuits has also been reported [17].

**C. Fibers, Connectors, and Splicers**

The attenuation in optical fibers has dropped dramatically over the past decade. Prior to 1970, the lowest fiber losses were in the neighborhood of 1000 dB/km. In 1970 the first "low-loss" fiber, with an attenuation of 20 dB/km, was reported [1]. A loss figure of only 0.2 dB/km has been achieved in doped silica single-mode fibers at a wavelength of 1.5 μm [2]. This is close to the "Rayleigh limit" of loss resulting from the scattering of light from frozen-in refractive index inhomogeneities. At the wavelength of 0.82 μm, where GaAlAs lasers have best performance, and 1.3 μm, where InGaAsP lasers emit efficiently, the losses are 2.4 and 0.5 dB/km, respectively.

The data rate capacity of single-mode fiber has been determined in experiments on pulse propagation in the fibers. At a wavelength of 0.85 μm, the dispersion is about 8 ps per km of fiber length per Å of source spectral width [18]. At the zero dispersion wavelength near 1.3 μm [18], [19], maximum data rates are well above 100 Gbit-km/s [20]. The limitation for an externally modulated single-mode laser stems not from the inherent linewidth of the source but from the spectral broadening introduced by the modulating signal.

Splicing is needed for field installation and repair of the fiber cables. Fusion splicing of single-mode fibers with an electric arc has been demonstrated to produce losses consistently.
TABLE I  
RESULTS OF SINGLE-MODE TRANSMISSION EXPERIMENTS

<table>
<thead>
<tr>
<th>Data Rate</th>
<th>Ref. 24 Mbit/s</th>
<th>2 Gbit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>7.3 km</td>
<td>44 km</td>
</tr>
<tr>
<td>Laser Material</td>
<td>GaAlAs</td>
<td>InGaAsP</td>
</tr>
<tr>
<td>Emission Wavelength, λ₀</td>
<td>0.85 μm</td>
<td>1.30 μm</td>
</tr>
<tr>
<td>Spectral Width</td>
<td>~ 1 Å</td>
<td>~ 15 Å</td>
</tr>
<tr>
<td>Dispersion at λ₀</td>
<td>9 ps/Å-km</td>
<td>~ 0.2 ps/Å-km</td>
</tr>
<tr>
<td>Total Dispersion</td>
<td>65 ps</td>
<td>130 ps</td>
</tr>
<tr>
<td>Power Coupled Into Fiber</td>
<td>-0.5 dBm</td>
<td>-1.2 dBm</td>
</tr>
<tr>
<td>Photodetector Type</td>
<td>SI APD</td>
<td>Ge APD</td>
</tr>
<tr>
<td>Received Power, 10⁻⁹ error rate</td>
<td>-26 dBm</td>
<td>-29.4 dBm</td>
</tr>
<tr>
<td>Allowable Loss, 10⁻⁹ error rate</td>
<td>25.5 dB</td>
<td>26.2 dB</td>
</tr>
<tr>
<td>Total Fiber Loss</td>
<td>24.3 dB</td>
<td>25.3 dB</td>
</tr>
</tbody>
</table>

less than 0.5 dB [21], although careful alignment of the fibers is needed due to the small (~4-10 μm) diameters of the fiber cores. It is also important that good uniformity of fiber diameter as well as core concentricity be maintained for consistently good results with this type of splice.

Demountable connectors for single-mode fibers have long been a critical problem, due to the mechanical tolerances (~1 μm) required to achieve low optical loss. However, connectors using mating plugs and a sleeve with ballbearing arrays to force alignment have demonstrated insertion losses consistently less than 0.7 dB [22]. As with the low-loss splice, it is important to maintain diameter uniformity and core concentricity for the mating fiber ends.

**D. Systems Experiments**

Extensive development of single-mode components at Nippon Telegraph and Telephone has recently culminated in some impressive demonstrations of point-to-point data transmission over single-mode fibers. One of these experiments used a CW LiNdP₄O₁₂ laser emitting at a wavelength of 1.05 μm and a LiNbO₃ waveguide modulator to transmit data over a 4 km length of fiber at an 800 Mbit/s rate [23]. The results of two other experiments which utilized directly modulated semiconductor lasers at data rates of 800 Mbits/s [24] and, more recently, 2 Gbit/s [3], are summarized in Table 1.

A recent fiber communication experiment achieved a data rate of 5 Gbits/s over 500 m of single-mode fiber [17]. The transmitter contained a GaAs MESFET driving a transverse-junction-stripe (TJS) GaAlAs laser diode. A Si APD with MESFET amplifier was used in the receiver, which required ~18 dBm of optical power for a 10⁻⁹ bit error rate. The margin for signal attenuation in the fiber was about 10 dB. The data rate in this experiment was limited to 5 Gbits/s by the photodetector response time.

**E. Future Prospects**

It appears rather obvious that optical transmitters and receivers which operate at data rates of 20 Gbits/s or more are not only possible, but can be demonstrated in the next few years. However, when factors such as the optical power budget and the speed of digital electronic circuitry are taken into account, the data rate limitation for a time-division-multiplexed point-to-point link will probably be considerably lower than this value; say, around 10 Gbits/s. And when the extra complexities of interfacing a large number of processors with a high-speed bus are considered, the limiting data rate drops again, perhaps to 5 Gbits/s.

One way to circumvent this limitation is to use parallel fiber channels to interconnect the bus terminals. This is certainly a straightforward way to increase the bus data capacity, but it also increases the amount of fiber and number of interconnections in proportion to the data rate. This would have undesirable consequences for system cost and reliability. Synchronization of timing between channels might also be a problem in such a system.

A more elegant solution, and probably in the long run more desirable, is the use of carrier frequency-division multiplexing (CFDM) (also termed “color multiplexing” and “wavelength multiplexing”). This approach will require laser oscillators operating at different stable frequencies and couplers for combining and separating the frequency channels, as illustrated in Fig. 2. This puts a much greater burden on the terminal device technology but maintains a minimum number of fibers and interconnections. Monolithic integration of transmitters, receivers, and multiplexers could ultimately lead to cost and performance advantages with this approach.

In CFDM systems, the transmitters could make use of distributed Bragg mirrors to stabilize the laser frequencies at predetermined values, as in Fig. 2(a). In this case, gratings with very short periods are needed. The period is given by \( m \lambda/
2n, where \( \lambda \) is the free-space wavelength, \( n \) is the effective refractive index of the lasing mode, and \( m \) is the grating order. It is generally believed that first-order gratings \( (m = 1) \) are required for lasers with low-threshold current because of optical coupling to radiation modes for higher \( m \) values. This means that the grating period must be about 1200 \( \text{Å} \) for GaAlAs lasers operating at a wavelength near 0.82 \( \mu \text{m} \) and 2000 \( \text{Å} \) for an InGaAsP laser operating near 1.3 \( \mu \text{m} \). Furthermore, the grating period must be constant to approximately one part in 10,000 over a distance of the order of 1 mm. Gratings with similar periods and tolerances are needed for the wavelength-selective couplers for combining or separating the channels.

Lasers with distributed Bragg mirrors have been operated at room temperature on a pulsed basis at wavelengths near 0.9 \( \mu \text{m} \) [25] and 1.3 \( \mu \text{m} \) [26], and it has been shown that the spectrum remains stable in such a laser (in this case, operating at 1.53 \( \mu \text{m} \)) when modulated at a frequency of 1 GHz [27]. Although contradirectional frequency-selective couplers of the type illustrated in Fig. 2(b) have not yet been fabricated, calculations show that center-to-center wavelength spacings of 6 \( \text{Å} \) could be achieved in a length of less than 0.5 mm for a center wavelength near 0.8 \( \mu \text{m} \) [28]. (A short coupling length is important to minimize the total coupler length, and, hence, the optical propagation loss, in a multifrequency coupler). This means that 20 frequency channels could be accommodated in a lasing material with an effective width of 120 \( \text{Å} \) for the gain spectrum.

The “ultimate” in high-speed terminals would have the optical and electronic components integrated on a single substrate to minimize stray capacitance, inductance, and impedance mismatch problems. Some simple integrated optoelectronic circuits have been demonstrated on both GaAs [29]-[31] and InP [32], [33] substrates. It is still not clear which of these substrate materials would be the best choice. Electronic device technology is much further advanced in GaAs, but the longer wavelength lasers fabricated on InP substrates can take advantage of much lower fiber loss and dispersion. Furthermore, for frequency multiplexing the longer grating period required for the InP-based components gives a big advantage in terms of ease of fabrication and potential device yield. Regardless of which substrate is chosen, years of effort will be needed to develop device processing techniques capable of producing monolithic terminals for the frequency-multiplexed bus.

### III. BUS DESIGN

The concept of a ring bus for connecting microprocessor terminals in a local network is illustrated in Fig. 1. It is assumed in the design that the data rate for the main bus is much higher than the input-output rates for the processors which interface with the bus. This means that data buffers must be provided at the terminals. Conventional electronic shift registers are limited in transfer rate to a few hundred MHz, and at these rates the capacity is limited to a few tens of bits and electrical power dissipation is high. For interfacing an optical bus operating at data rates of several Gbits/s, large improvements in transfer rate, data capacity, and power dissipation per bit are needed. Access speeds and readout timing problems would also appear to eliminate semiconductor random access memories as a candidate for the data buffer. It seems clear that this application calls for a new type of data buffer.

The recirculating fiber-optic shift register would appear to be the ideal data buffer for this application. The data capacity and transfer rates for a fiber loop are extremely high, as illustrated in Fig. 3. For example, for a data transfer rate of 5 Gbits/s, the capacity of a 10 km loop (with a
propagation time of 50 \mu s) is 250 kbits. It is evident that such a loop could be operated in any of the three wavelength regions represented in Fig. 3. If carrier-frequency multiplexing is used, the data capacity indicated in Fig. 3 is multiplied by the number of carrier frequencies. Another feature of the fiber-optic buffer is that it is readily interfaced with the bus via an optical switch.

A design for a bus terminal in which fiber-optic loops are used as data buffers is illustrated schematically in Fig. 4. An input loop is provided for injecting data onto the bus, and an output loop is provided for removing data from the bus. Each loop is provided with a digital repeater so that data can be recirculated indefinitely, and each loop is connected to the main bus via a 2 \times 2 electrooptic switch [34] of the type illustrated schematically in Fig. 5. Data are injected into the input loop from a signal generator by means of a directional coupler, and are removed from the output loop and directed to an optical receiver by means of another electrooptic switch.

The switches which connect the main bus to the buffer loops can be relatively slow, with turn on and turn off times of several bit intervals. However, the switch for removing single bits from the output buffer loop must be turned on and off quickly.

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**Fig. 4.** Ring bus terminal.

**Fig. 5.** Electrooptic switch for interfacing between the main bus and a fiber buffer loop.
off in a fraction of the bit interval. Switches in LiNbO$_3$ with 10-90 percent rise and fall times of 110 ps have been reported [35]. These would be adequate for single-channel data rates of the order of 2-3 Gbits/s; and faster switching speeds are possible. Similar switches can also be made on GaAs or InP substrates, although lengths of the order of 1 cm are necessary in those materials to obtain switching voltages in the 10 V range. For such a design to operate at high speeds, a traveling wave configuration [11] would be needed to match the phases of the optical wave and the modulating microwave signal.

In order to introduce data into the input loop at a low rate, the signal pulses must be generated at a much lower rate than the clock rate for the bus. For example, if the input loop contains $N$ bits with a total delay of $Nt$ s, the clock period for the signal generator might be $(N + 1)t$ s. This would correspond to adding one bit to the data stream each time it circulates completely around the loop, as illustrated in Fig. 6. If $N$ were 1000, then the data bus rate would be 1001 times the buffer input rate. The input rate could be slowed even further if desired, by making the clock period for the signal generator equal to $(pN + 1)t$, where $p$ is an integer. In this case, one bit would be inserted into the loop for each $p$ times the data circulate around the loop.

While data are being injected into the input loop, the electrooptic switch is in the "straight-through" state so that the loop is, in effect, disconnected from the bus. When data are to be injected into the bus, the switch is changed to the "crossover" state. After the desired data have been transferred from the bus. The switch is then returned to the "straight-through" state.

For removing data from the bus, the switch connecting the output loop to the bus is changed to the "crossover" state. After the desired data have been transferred from the main bus and the output loop is only partially activated. In this case, some of the light passes on to the next downstream repeater on the main bus and part circulates in the output loop. The electrooptic switches can easily be operated in this manner by applying only a fraction of the voltage required for complete switching. When a data packet returns to the originating terminal, it is necessary to remove it from the bus to prevent it from circulating indefinitely. This is accomplished by setting the switch to divert all of the main bus signal into the output loop. With the repeater power in the output loop turned off, the packet would then be eliminated from the system.

Clock synchronization is an important feature of the bus design. It is envisioned that a master clock for all of the terminals could be provided by a single centrally located mode-locked laser connected to the terminals via fiber-optic lines independent of the main bus. Adjustment of timing to initialize the bit interval (to within a few ps) would be needed in the data output loop. This could be accomplished by adjusting the switch activation time relative to the clock pulse until maximum output (corresponding to proper bit interval adjustment) is obtained. A similar adjustment might also be needed in the repeater.

The preceding discussion of bus design refers to a single-carrier-frequency bus system in which a fiber carries only one information channel at any given time. However, the same principles can be applied to the case in which multiple carrier frequencies are used to increase the data capacity of the fiber. As indicated previously, the multifrequency system will require lasers operating at different precisely determined wavelengths and frequency-selective couplers matched to the laser frequencies. An indication of how two of the key bus components, the signal generator and repeater, might be configured for multifrequency operation is given in Figs. 7 and 8.

**IV. CONCLUSIONS**

Although single-channel data rates in fiber-optic systems will be limited to 5-10 Gbits/s, carrier-frequency multiplex-
Fig. 7. Signal generator for parallel frequency channels, using multifrequency lasers and a frequency-selective coupler for combining the channels.

Fig. 8. Multifrequency optical repeater chip.

ing can provide much higher transmission rates over single-mode fibers. In order for such large capacities to be useful, some sort of buffer to interface relatively low data rate terminals with the high-speed bus is needed. Recirculating fiber-optic memories with optical switches for interfacing with the main bus line would appear to be the solution. The key element of a terminal in the "ultimate" bus system might be an optoelectronic integrated circuit with frequency-stabilized lasers, frequency-selective couplers, optical switches, photodetectors, and electronic amplifiers and logic circuits fabricated on a GaAs or InP substrate. Such a system should be capable of data rates in the vicinity of 100 Gbits/s. There appear to be no fundamental barriers to the realization of the required circuits, but considerable improvement in optoelectronic device fabrication techniques will be needed.

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REFERENCES


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