DEMULTIPLEXING EQUIPMENT

During the past two decades, there has been rapid advancement in optical fiber communication technology. The reduction of single-mode fiber losses, the advent of fiber amplifiers, the improved optical receiver sensitivity, and the development of high-speed semiconductor laser diodes and fiber lasers have promoted the development of multiple access optical fiber networks. The multiple access networks are used to support communications of many users or channels simultaneously over a common network communication medium. When multiple users or channels are involved, there are two primary issues to be addressed. These two issues are how to address the contention that is inherent in sharing a single communication medium and how to synchronize all the users or channels of the network to resolve the contention. The existing optical multiple access networks include wavelength division multiple access (WDMA) networks, subcarrier multiple access (SCMA) networks, code division multiple access (CDMA) networks, and time division multiple access (TDMA) networks (1). On this subtopic we focus on the demultiplexing equipment for optical TDMA networks.

TDMA NETWORKS

The most common method of separating users or channels on a common digital communication medium is by ensuring that the signals are transmitted at different times. This technique is known as time division multiple access (TDMA). The optical fiber communication medium can support high aggregate data rate signal transmission, while the data rates are often lower at user channels. In this case, high-speed optical fiber transmission links can be shared by many lower-speed users. The cost of the high-speed link divided by the number of users can be significantly lower than the cost of an equivalent set of lower-speed links. To realize the high-speed link sharing, it is desired to divide a high-speed bit stream over a point-to-point communication link into a set of lower-speed bit streams, each with a predefined fixed bit rate. The technology for doing so is called time division multiplexing (TDM). The lower-speed bit streams to be multiplexed are called tributary streams. TDM techniques are used to interleave these tributary streams to obtain higher rate bit streams for the high-speed communication link. Figure 1 shows a schematic of a

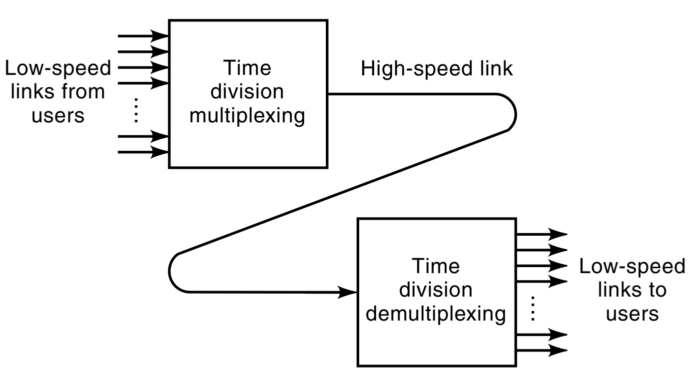

Figure 1. Schematic of time division multiplexing and demultiplexing to allow users or channels to share a high-speed communication link.

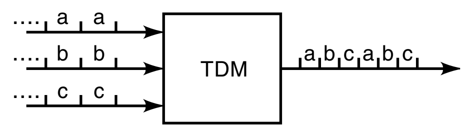

Figure 2. Interleaving of tributary data streams for the high-bit-rate data stream.

time division multiplexing system that allows many users or channels to share the high-speed communication link.

An example of TDM of three tributary bit streams is given in Fig. 2. Each tributary stream is divided into group of bits, known as time-slots. All input time-slots are interleaved to yield the output bit stream that has higher data rate than the input ones. The time-slot can contain one bit. The result of the TDMA is bit-interleaving. This approach requires only storage of one bit at each communication node at any time. It is attractive in terms of minimal memory space at each node. However, the requirement of bit-synchronization is difficult to achieve in high-bit-rate data streams in optical fiber networks. When the time-slot covers more than one bit, the TDMA is block-based interleaving. The block-based TDMA can be subdivided into two distinct classes: frame-based or packet-based. Here a frame on the high-speed output bit stream is defined as the collection of bits corresponding to one time-slot from each tributary bit stream. For the example of Fig. 2, one frame corresponds to time-slots a, b, and c. A packet, on the other hand, is an information group with variable size. It allows mixing of bit streams from different users that vary in bit rate and dynamically allocates the available bandwidth among these users. There can be different packet sizes in the networks. There are also additional overhead bits or headers added to each frame or packet to signal the beginning and ending of the data frame or data packet and to address the data frame or packet to be routed by the network switches. The additional overhead is useful for demultiplexers to ensure correct correspondence between input and output tributary bit streams and for network nodes to ensure correct routing the data streams.

Regardless of the types of TDMA used, whether bit- or block-based interleaving, the physical bit rate of the TDMA date stream is roughly equal to the number of users or nodes N connected to the network times the input–output data rate (B bit/s) at each node or user. The network must be able to process at the data rate of NB bit/s. Current optoelectronic transceivers can operate at up to 10 Gbit/s (2) and are commercially available from Ortel Corporation, for example. Current network capacity is limited by this data rate. Using higher-speed all-optical switches and demultiplexers, under research and development, the network capacity can be a lot higher.

The implementation of optical TDMA involves three important issues: (a) ranging, (b) synchronization, and (c) optical power leveling. Optical transceivers implementing these three functions are called burst-mode transceivers (3,4). Due to the varying propagation distances between the network nodes and the network controller, to avoid data block overlapping (collision), a technique to virtually equalize the connection distance from all nodes to the network controller is required. The ranging process is to insert a suitable electronic delay at each node so that all nodes appear at the same rela-

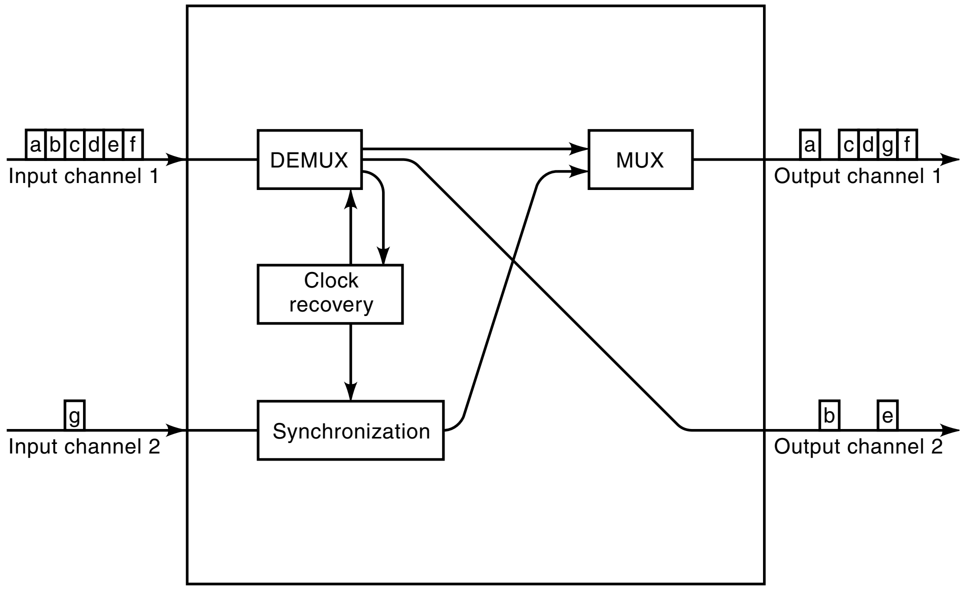

Figure 3. Operation principle of a demultiplexer (DEMUX) and a multiplexer (MUX) in a network node.

tive propagation distance from the network controller. Once ranging has been performed, quick recovery of the clock phase of each burst of data coming from different nodes is required. This synchronization process can be achieved using a phase-locked loop (5), an oversampling technique, or all-optical clock recovery (6–9). There are also variations of burst optical powers received at the network controller sent from different nodes. The receiver thus requires a large dynamic range to discriminate bits "0" and "1" as quickly as possible (3).

Within the optical TDMA network, there are both space and time switches. The different time channels on a particular input fiber should be capable of being linked to different output fibers (or space channels). The basic functions of multiplexer and demultiplexer are to perform insert-and-drop space switching and time-slot interchange switching. Figure 3 shows the basic operation of a multiplexer (MUX) and a demultiplexer (DEMUX) for a TDMA network node with two input channels and two output channels. A complex switching matrix can be formed by using a number of such basic MUX and DEMUX elements. The DEMUX performs the "drop" function by switching some data blocks from input channel 1 to output channel 2, while the MUX performs the "insert" function by adding the input data block from input channel 2 to the data channel from the DEMUX for output channel 1. Synchronization is important both for correct data block insertion (multiplexing) and for timely drop-out switching (demultiplexing). The "drop" and "insert" are for the whole time-slots which can be based on bits or blocks described above. The switching element must have a fast rise and fall time and have a high repetition rate capability. If the TDMA is bit-interleaved, the switch repetition rate is equivalent to the line rate (highest network data rate). If the TDMA is block-interleaved, the switch repetition rate can be lower than the line rate. If the block size is eight bits, for example, the switching speed can be one-eighth of the line rate. This relaxes greatly the switching speed requirement for the TDMA network and allows better utilization of the enormous capacity of the optical fiber links since present switching devices are mostly controlled by electronics. If the block size is even larger for packet or frame multiplexing and demultiplexing, the switching speed can be even lower.

OPTICAL SOURCES FOR TDMA NETWORKS

To implement the optical TDMA network, the optical sources must be stable and provide a train of short pulses in the return-to-zero (RZ) format. It must also be a low-duty cycle such as 1 : 5 at the highest network data rate or line rate. This is different from the electronic TDMA network, which uses lower repetition-rate pulses for tributary data streams and higher repetition-rate pulses for network lines. Optical TDMA uses same short pulses for tributary data streams and the network lines. The data rate of the tributary data stream is lower as a result of larger pulse-to-pulse separation, controlled by the tributary data stream modulator, while the network line rate is higher due to the TDM of many such tributary data streams.

When the user channel data rate is very low (tens of Mbit/s or below), the network can be implemented using electronic TDMA. The lower bit-rate channels can be electronic channels or optical fiber channels or both, while the time division multiplexed network lines use direct modulation of semiconductor lasers to generate several hundred Mbit/s to a few Gbit/s line rate. The multiplexing, demultiplexing, clock recovery, and synchronization are all handled electronically. Here, we focus on optical TDMA with a user channel data rate of several hundred Mbit/s and above and with a line rate of several Gbit/s to tens of Gbit/s.

To have such a pulse train at a high data rate such as 20 Gbit/s to 40 Gbit/s, it is not currently practical to use direct laser modulation. External modulation must be used. Narrow linewidth, which minimizes the pulse broadening of communicating light beams due to spectral dispersion in fiber, is a basic requirement to the laser sources.

A distributed feedback laser can be used as light source with electrical modulation using a high-quality sine wave for gain switching. The modulation results in short pulses (~80

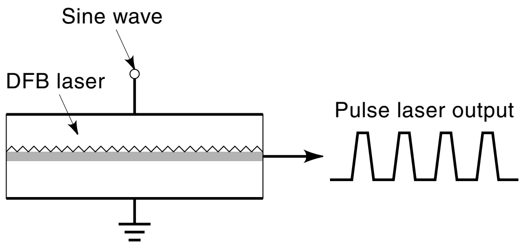

Figure 4. Schematic of a DFB laser driven by a sine wave to produce a pulse laser output.

ps pulse width) at a 10 Gbit/s repetition rate. The synchronization to form a burst mode transmitter can be easily done by a properly phase-controlled electrical driving signal. The pulses produced by this technique are, however, highly chirped. Appropriate spectral filtering and pulse compression of the output beam can improve the pulse quality for TDMA network systems. Figure 4 shows a schematic of a distributed feedback (DFB) laser driven by a sine wave for pulse laser output. The typical laser linewidth is several MHz for continuous-wave (CW) operation. Commercial producers of distributed feedback lasers include Philips Optoelectronics, Alcatel Optronics, Fujitsu Compound Semiconductor Inc., and Ortel Corporation.

A mode-locked fiber laser consists of a closed loop of fiber with part of the fiber loop being erbium-doped to allow optical pumping for optical gain [see Fig. 5(a)]. The pumping laser beam has different wavelengths as the fiber laser mode is coupled in and out of the fiber loop by wavelength division multiplexer (WDM) components. An optical isolator is used to control a single laser mode propagation direction in the loop, while a wavelength filter is used to select a particular laser longitudinal mode. Mode locking is performed by driving an intracavity electro-optic modulator (amplitude or phase modulator) with modulation signal period equal to an integer multiple of the cavity round-trip time. The fiber loop length can be stretched with a piezoelectric modulator to vary the cavity round-trip time and thus allow synchronization to the desired single modulation frequency. The periodic laser cavity perturbation by the modulation couples cavity modes and forces the laser to produce a continuous stream of ultrashort optical pulses. There are also other mode-locking configurations based on nonlinear interaction with high-power control pulses [see Fig. 5(b)]. High-power control pulses with different wavelengths are coupled again by wavelength division multiplexers into part of the fiber loop to perturb the fiber laser mode phase through nonlinear interaction that changes the fiber refractive index by the control pulse intensity. When the control pulse repetition rate is an integer multiple of the fiber laser mode round-trip time, the fiber laser is mode-locked and produces a continuous stream of ultrashort optical pulses. Active fiber stretching control is required to ensure pulsed laser output stability. A high-quality fiber laser with a pulse-width as low as 5 ps has already been demonstrated in the laboratory (10).

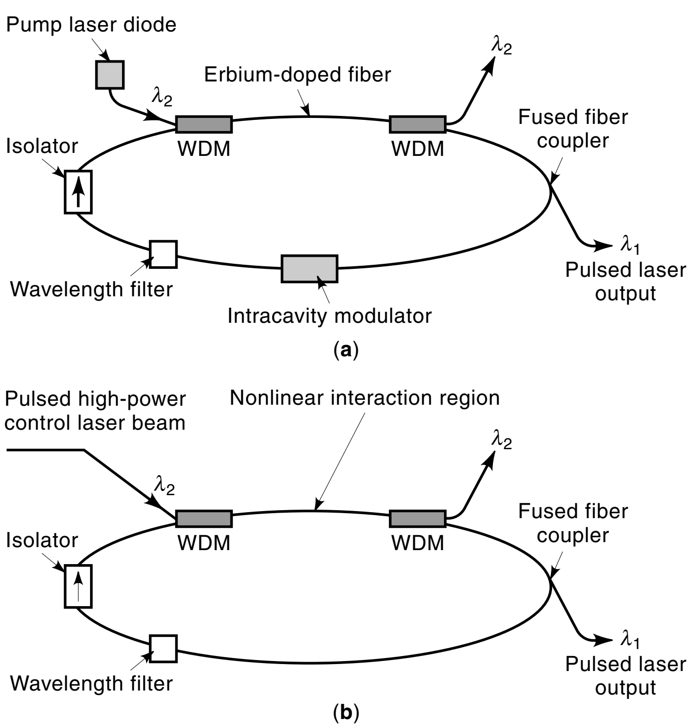

Figure 5. Mode-locked fiber laser used to produce pulsed laser output. (a) The fiber laser is modulated by an intracavity electro-optic modulator. (b) The fiber laser is modulated by a high-speed pulse train.

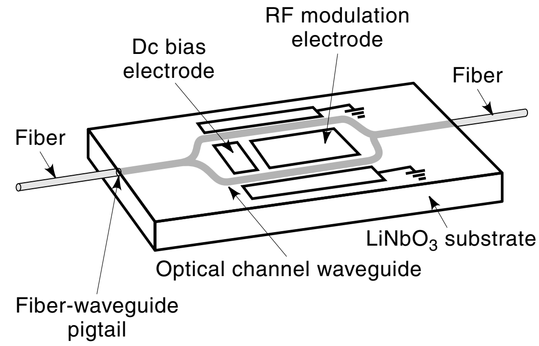

Figure 6. Schematic of a waveguide Mach–Zehnder electro-optic modulator. The modulator can use traveling-wave electrodes (not shown) for high-speed modulation.

An external cavity semiconductor laser can provide a very narrow linewidth of about 10^{-5} nm on CW operation. It is achieved by using an external cavity grating for laser linewidth control. A radio-frequency (RF) single-frequency driving signal is applied to the laser chip with optical round trip time in the cavity equal to the period of the RF drive signal. The resulting laser output is a train of short pulses with a pulse width of about 30 ps at 5 GHz modulation (11). An external cavity laser at CW operation is commercially available from New Focus in California and Photonetics in Germany. A mode-locked external cavity laser with short pulses is yet to be commercially developed.

External modulation of a CW semiconductor laser source can also produce short optical pulses for TDMA networks. This technique avoids active cavity control as required in mode-locked lasers. Wide bandwidth external modulators, including electro-optic modulators, electro-absorption modulators, or all-optical modulators, can be used. Figure 6 shows a waveguide Mach–Zehnder electro-optic modulator. It can be fiber-pigtailed for use as an ultra-high speed modulator. Modulation frequency as high as 50 GHz has already been demonstrated (12). On the commercial level, waveguide Mach–Zehnder electro-optic modulators have been fabricated on $LiNbO_3$ by United Technologies Photonics with a modulation bandwidth of about 18 GHz and a V_π of 14.5 V. Both phase and amplitude modulation can be integrated on a single device for different system needs. A semiconductor electro-absorption modulator based on a multiple-quantum-well structure (13) offers the advantage of monolithic integration with a semiconductor laser to form a compact picosecond pulse source chip. It also offers a lower drive voltage than do waveguide Mach–Zehnder modulator devices. Stable optical pulse trains with a narrow pulse width of 3.6 ps have been demonstrated (13). An all-optical modulator as shown in Figs. 13 and 14, to be discussed below, is currently under research investigation. The advantages of all-optical modulator are extremely fast, polarization insensitive, and elimination of optical to electrical conversion.

MULTIPLEXERS AND DEMULTIPLEXERS

The key elements of optical TDMA networks are the time division multiplexers and demultiplexers. The multiplexers may be passive, while the demultiplexers must be active. They are discussed as follows.

Passive Multiplexers

Pulsed digital data from a number of data channels can be multiplexed in principle by a passive star coupler. Figure 7 shows the schematic of the passive multiplexer. The timing of different data streams arriving at the output star coupler junction can be controlled by variable fiber delay lines by simply piezoelectric stretching the fiber lengths. The piezoelectric fiber-stretching device can be obtained from Canadian Instrumentation and Research Limited with piezoelectric modulation frequency of up to 100 kHz. There is no need for high-speed delay line variation since the synchronization can also be performed on the phase control of the electro-optic modulators which are used as on–off switches to the pulsed optical light beams to form the desired pulsed data streams on each input channel. The modulators can be waveguide electro-optic modulators or electro-absorption modulators, as described above. They are not used to shape the pulses. Therefore, there is no critical demand on modulator linearity. With a 10 GHz pulse repetition rate and a pulse width of 6 ps, 80 Gbit/s multiplexing has already been demonstrated for communication distance of 50 km (14). Passive multiplexers suffer from optical coupling loss from the fused fiber star coupler. Erbium-doped fiber amplifiers or semiconductor optical amplifiers with enough gain must be used to compensate for the optical power loss due to multiplexing.

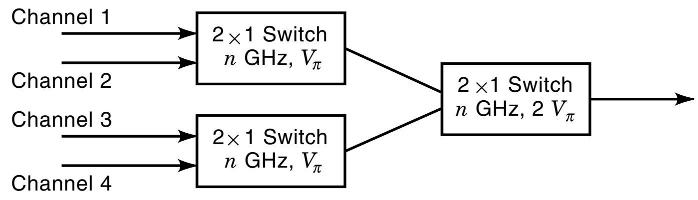

Figure 8. Active multiplexer formed by using several 2 × 1 switches.

Active Multiplexers

It is simple to implement passive optical multiplexers for the TDMA networks. Active multiplexers may provide additional functions to satisfy some particular network requirements. For example, when there is a need to provide simultaneous multiplexing and non-RZ to RZ optical format conversion, active multiplexers composed of several 2 × 1 waveguide electro-optic switches can be used (see Fig. 8) (15,16). The commercial 2 × 1 waveguide electro-optic switches are typically based on a Mach–Zehnder structure with a 3 dB directional coupler and are fabricated on $LiNbO_3$. Figure 9 shows the schematic of the 2 × 1 switch. The commercial vendors include New Focus and United Technologies Photonics. Because the cost of the 2 × 1 switches are significantly higher than passive fused fiber star couplers, passive multiplexers are, in general, more favorable than the active multiplexers. In addition, active switches introduce a significant insertion loss with typical values of 0 dB to 6 dB for a 2 × 1 switch.

Active Demultiplexers

Unlike the multiplexers that can be passive or active, the demultiplexers must be active since the drop-out switching from a single channel is time-sensitive. The timing can be con-

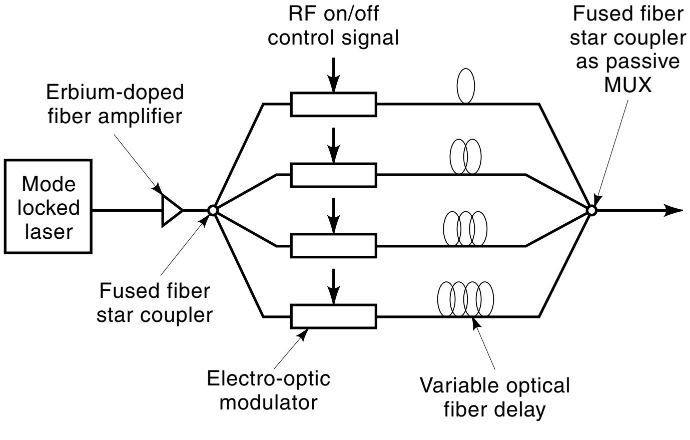

Figure 7. Schematic of a passive multiplexer formed by fiber star couplers, modulators, and variable optical fiber delay lines.

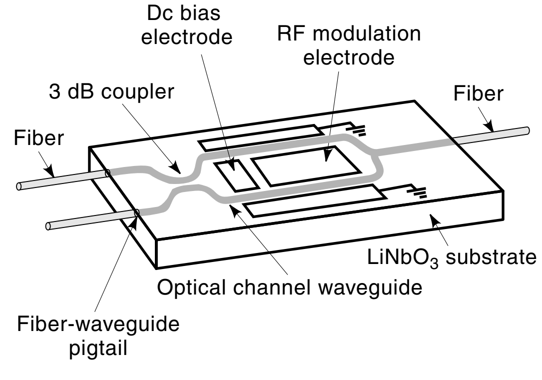

Figure 9. Schematic of a waveguide 2 × 1 switch with a Mach–Zehnder modulation section and a 3 dB directional coupling section.

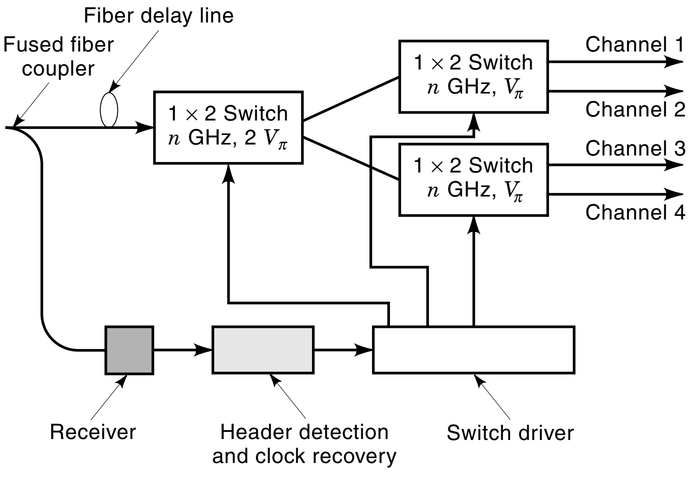

Figure 10. Active demultiplexer constructed by using several 1 × 2 switches.

trolled through a clock recovery circuit, while the drop-out switching (space switching) must be performed electro-optically or all-optically. One possible implementation is based on a number of cascaded 1 × 2 switches as shown in Fig. 10. This is a reverse configuration of active multiplexer shown in Fig. 8. The 1 × 2 switch is the same as the 2 × 1 switch but is used differently. For each demultiplexing step, the device can be implemented as in Fig. 10 with clock recovery and control. A small percentage of the optical data stream is taped out by a fused fiber coupler to a wide-band receiver that can be a *pin* photodetector with electronic amplifiers. Followed by clock recovery and header detection, a suitable electrical control signal is then applied to the 1 × 2 switch to perform the desired drop-out switching. Since the electrical processing for clock recovery and header detection is relatively slow and limited by the electronic devices, a suitable optical delay is required between the tap fiber coupler and the 1 × 2 switch to wait for the switching control signal. The optical delay can be implemented by a fiber delay line with piezoelectric fiber stretcher to allow delay time adjustment to synchronize with the switching control signal. The switch control signal is an on–off switching signal. It is not used for pulse shaping. The switching signal period must match with the data period of the drop-out channel. This period can be short for drop-out switching of a short time-slot such as a single bit and can be long for packet switching depending on the packet size.

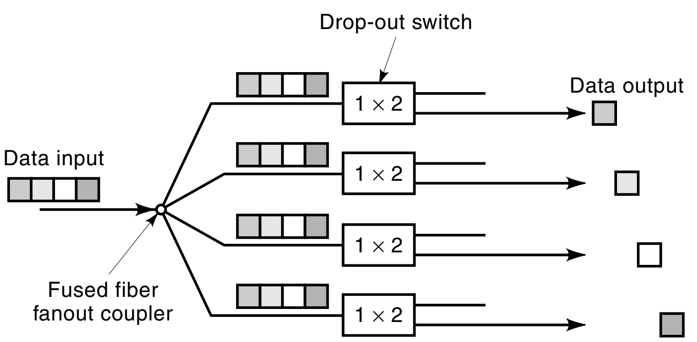

Figure 11. Active demultiplexer formed by using passive fiber fanouts and a number of 1 × 2 drop-out switches. Optical amplifiers are needed to compensate the power loss by the passive fiber fanouts.

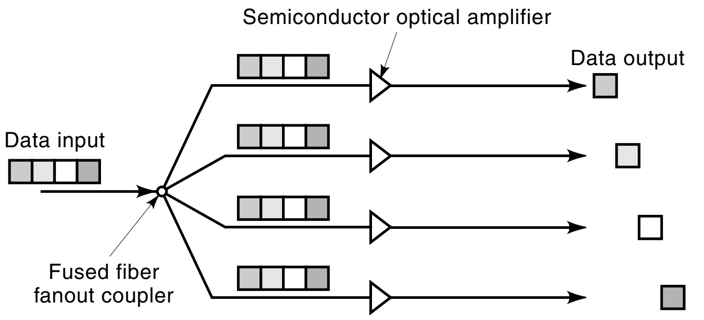

Figure 12. Active demultiplexer formed by using passive fiber fanouts and time-gated elimination and amplification of suitable time-slots by semiconductor optical amplifiers.

Another implementation of the active demultiplexer is based on a passive fanout combined with a number of parallel 1 × 2 drop-out switches. The schematic of this demultiplexer architecture for 1 to 4 demultiplexing is shown in Fig. 11. This type of demultiplexer implementation requires one additional 1 × 2 switch and suffers from the fanout optical power loss. Hence, erbium-doped fiber amplifiers or semiconductor optical amplifiers are required to compensate for this loss.

Semiconductor optical amplifiers (17) can also be used to implement active demultiplexers (see Fig. 12). It is based on passive fanouts and time gated elimination and amplification of suitable time-slots by the semiconductor optical amplifiers. The semiconductor optical amplifier is a InGaAsP device with about −30 dB loss when unbiased and about 10 dB gain when biased with ~100 mA current. It can be made polarization insensitive. This simple demultiplexer implementation is attractive. The semiconductor optical amplifiers are supplied from Alcatel Optronics, for example.

Switching Matrix

When we combine passive multiplexing and active demultiplexing based on semiconductor optical amplifiers, any complex multiplexer and demultiplexer switching matrix can be formed without much difficulty. To build a compact switching matrix, monolithic integration of fan-out components and optical amplifiers on a common substrate is required. Such a compact switching matrix is attractive in terms of minimizing fiber component packaging. Recently, monolithic integration of a 4 × 4 switch matrix has been successfully demonstrated with InGaAsP–InP optical amplifiers (18).

Ultrafast All-Optical Polarization Insensitive Switches and Demultiplexers

$LiNbO_3$-based 2 × 1, 1 × 2, and 2 × 2 switches are generally polarization-sensitive. There are significant losses when these switches are used in the randomly polarized optical fiber networks. Suitable electrical signals with voltage amplitudes are required for switching control. This needs optical to electrical signal conversion processing. For fast multiplexing and demultiplexing, it is preferred that the switching be performed all-optically based on the contents of the data stream header. To induce an all-optical interaction for switching, the medium must be nonlinear. In other words, the refractive index of the

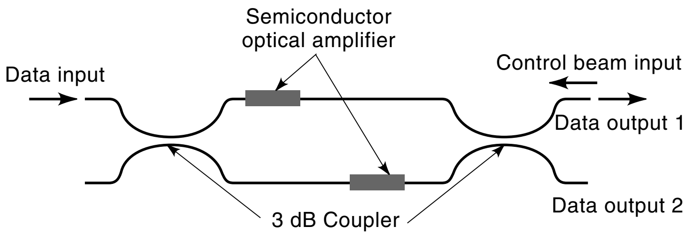

Figure 13. Schematic of an ultrafast, polarization insensitive, all-optical switching device based on the Mach–Zehnder structure (19).

medium depend on the light intensity propagating through the medium. Due to the variation of refractive index induced by light intensity, the light propagating phase is modulated. The phase modulation can be performed by the intensity of the same light beam. In this case it is called self-phase modulation. The phase modulation can also be performed by another beam and is known as cross-phase modulation.

Semiconductor optical amplifier medium is a good nonlinear optical medium. When the Mach–Zehnder device structure is used with two 3 dB couplers and two semiconductor optical amplifiers, as shown in Fig. 13, the counterpropagating control beam can modulate the propagation phases of the forward-propagating data streams in the two Mach–Zehnder arms. The uneven phase modulation on the two arms result in the selective coupling into either output channel 1 or output channel 2. Ultrahigh-speed all-optical switching with a switching window as small as 10 ps has been demonstrated (19). An 8 ps switching window has also been demonstrated on a symmetric Mach–Zehnder all-optical switch (20), and 40 Gbit/s demultiplexing using an all-optical clock recovery signal as a control beam on an all-optical Mach–Zehnder modulator has also been demonstrated (21).

Optical fiber is also a nonlinear medium but with a very small nonlinear Kerr coefficient. With a long fiber length the nonlinear effect in fiber can be significant to facilitate all-optical interaction and thus switching functions. Figure 14 shows a fiber loop mirror structure for all-optical demultiplexing (22). The input data stream uses optical carrier wavelength of λ_1 while the optical switching control source has carrier wavelength λ_2. Both wavelengths are centered near the 1.55 μm fiber communication wavelengths to minimize the group delay caused by fiber dispersion. The switching control source is amplified by an erbium-doped fiber amplifier to a power level high enough to effect strong non-linear interaction. The two wavelengths can be combined by a wavelength division multiplexer to a single fiber and launched into the fiber loop. The fiber coupler has a 50 : 50 coupling ratio for wavelength λ_1 and 100 : 0 for wavelength λ_2. The signal beams are now counterpropagating in the loop while the control beam is propagating in one direction in the loop as shown. When the signal beam pulses overlap with control beam pulses propagating in the control beam direction, these signal beam pulses experience a π phase shift. The interference of the counter-propagating signal beams at the fiber coupler can thus result in the "transmitting" of the signal beam to the output fiber or the "reflecting" of the signal beam back to the input fiber. The reflecting signal beam can be coupled out by another fiber coupler. The π phase shift can effectively switch the fiber loop from "transmitting" to "reflecting" or from "reflecting" to "transmitting" depending on the fiber loop setup controlled by a set of polarization controllers (22). In the "reflecting" mode the switching control signal sends the overlapping signal pulses to the output while the other pulses are reflected. In the "transmitting" mode the switched signal pulses are reflected. In either case the drop-out switching for the demultiplexer is demonstrated. The reverse operation by sending in "insert" pulses to overlap with the control pulses can result in multiplexing demonstration. The all-optical multiplexing and demultiplexing based on a fiber loop mirror and capable of 2.5 Gbit/s to 50 Gbit/s operation has been experimentally demonstrated (22–24).

TIME-SLOT INTERCHANGE SWITCH

Time-slot interchange is another basic function of the TDMA networks. It allows reconfiguration of the sequence of data time-slots, including frames and packets, in the network data streams. The basic function of the time-slot interchange is

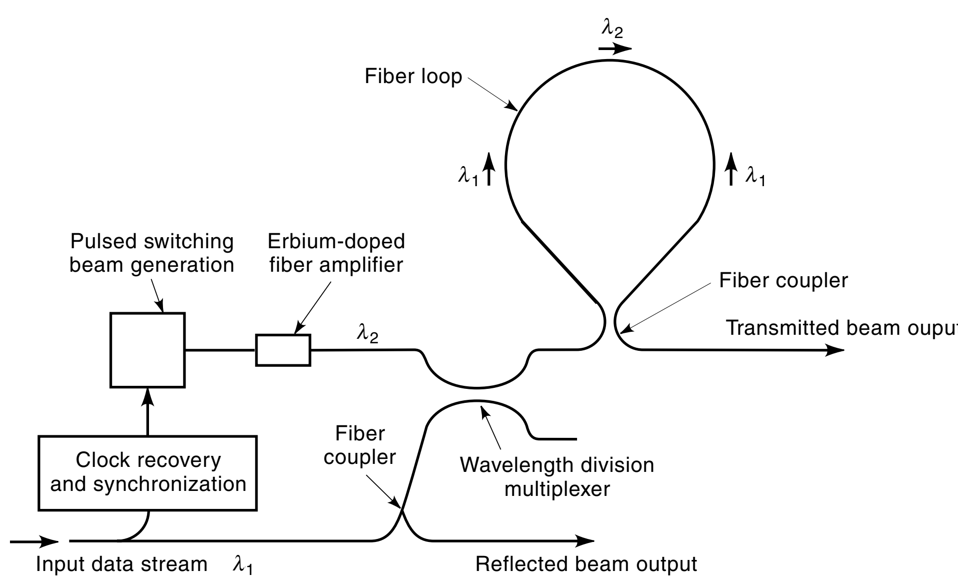

Figure 14. Schematic of a fiber loop structure for all-optical demultiplexing.

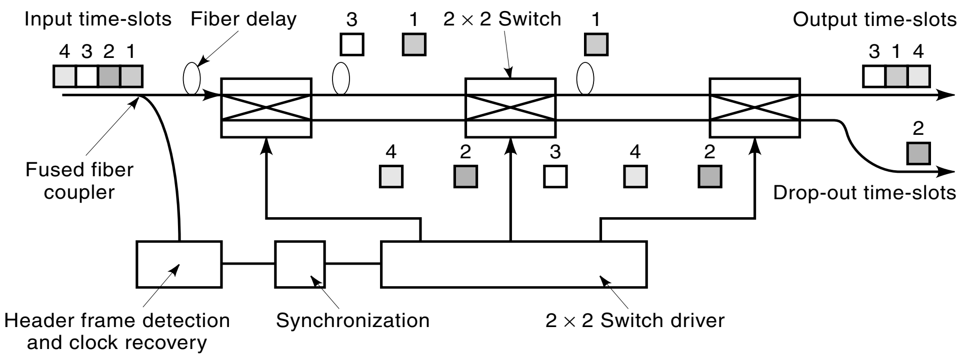

Figure 15. Time-slot interchange switch implementation using several 2 × 2 switches.

achieved by dropping a particular time-slot, implementing a suitable time delay using fiber delay lines, and inserting the time-slot back into the original data stream. The time-slot interchange can be used to resolve contention problems. The sequence of the time-slots in the data streams is now altered. The device implementation of the time-slot interchange switching can be accomplished by using several cascaded 2 × 2 switches with synchronization control and fiber delay. Figure 15 illustrates the operation function of a time-slot interchange switch for exchange four time-slot sequences. First, a fused fiber coupler is used to couple part of the data stream out for header detection and clock recovery for synchronization purposes. The synchronized switch-driver controls the "drop" and "insert" functions of the 2 × 2 switches. Fiber delay lines are used to synchronize the data time slots with the switching signal. For example, the time-slots 2 and 4 of the original time-slot sequence 1234 are switched out by the first 2 × 2 switch while the remaining time-slots are delayed by the subsequent fiber delay line. The delayed time-slot 3 is then switched out to join with the time-slots 2 and 4, and the remaining time-slot 1 experiences another delay. Then both time-slots 3 and 4 are switched back to the original data stream to yield the new time-slot sequence of 413. The time-slot 2 is dropped out by the time-slot interchange switch in this example. Both time-slot interchange and drop-out switching are demonstrated (25). The key component in time-slot interchangers is the 2 × 2 electro-optic switch that is similar to the 2 × 1 switch but contains two 3 dB directional couplers and thus two input and two output channels.

The main drawbacks of $LiNbO_3$-based 2 × 2 switches are their high insertion loss of about −4 dB to −6 dB. This limits the number of the 2 × 2 switches to be cascaded in the switching system. Another way to implement the time-slot interchange switch is the parallel approach shown in Fig. 16. It is based on passive fan-outs and time-gated elimination and amplification of the desired time-slots using semiconductor optical amplifiers. This approach requires lower drive voltage than the $LiNbO_3$-based switches. It can also facilitate "insert" multiplexing function along with the passive multiplexer described above. Current device development is focused on the combination of fan-out and the semiconductor amplifier arrays on an integrated substrate. This approach can significantly minimize the number of fibers to be packaged with the time-slot interchange switch unit.

CLOCK RECOVERY DEVICES

Clock recovery is an important part of the demultiplexer since it enables correct synchronization of the demultiplexing

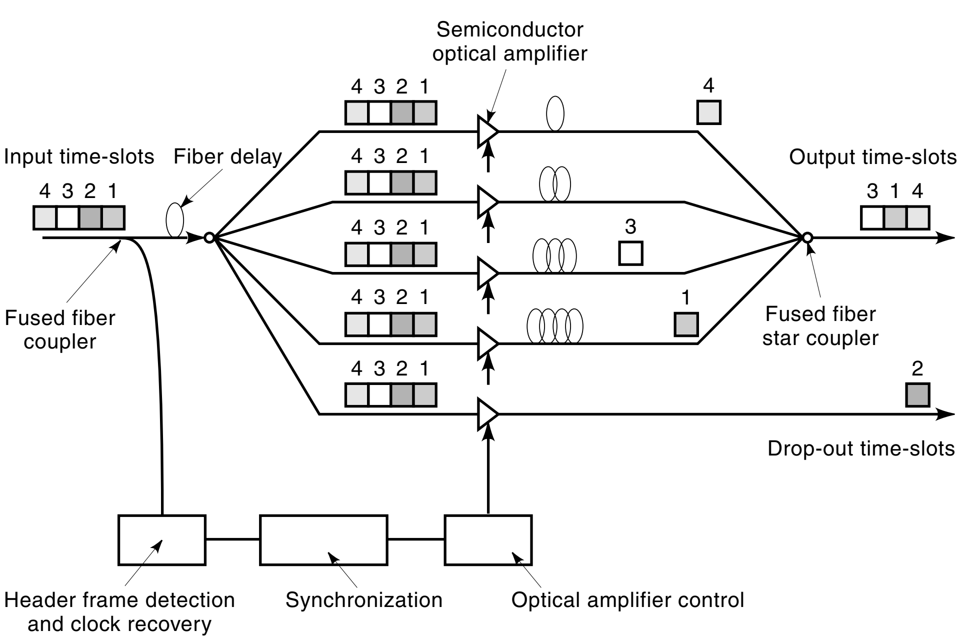

Figure 16. Implementation of time-slot interchange switch using passive fiber fan-outs, semiconductor optical amplifiers, and fiber delay lines.

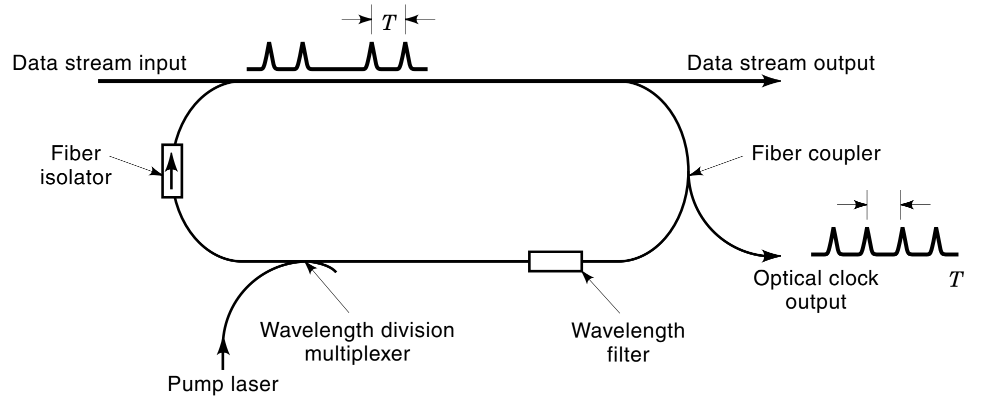

Figure 17. Schematic of an all-optical clock recovery based on a fiber laser loop and nonlinear interaction with the high-power input data stream.

switching and furthermore on multiplexing switching (see Fig. 3). There are two types of clock recovery, namely, electrical and optical clock recoveries. The electrical clock recovery as shown in Fig. 3 has no difference from those for any other transmission system with RZ data input. The optical clock recovery can be performed by mode-locked fiber laser and by self-pulsating diode laser. Recently, four-wave mixing technique has also been used for optical clock recovery (26).

Clock Recovery by Mode-Locked Fiber Laser

Pulsed optical data stream with sufficient power can be used to serve as the switching control pulses to control amplitude or phase of the laser mode in a fiber loop. In the configuration shown in Fig. 17 incoming data optical pulses propagating in part of the fiber loop provide a periodic phase perturbation of the laser cavity for mode locking (27). Fused fiber couplers are used to join the fiber loop with the data line. An erbium-doped fiber amplifier is used to ensure enough gain in the fiber loop. An optical isolator is used to control laser mode propagation direction in the loop while a fiber filter is used for laser mode wavelength selection since the fiber loop can support many resonant mode wavelengths when without a filter. Another fiber coupler is used for output coupling the resonant laser clock. Mode locking occurs when the data pulse period equals to an integer multiple of the laser round-trip time in the loop. In other words, data pulses with period T, $2T$, $3T$, and so on, can mode-lock the fiber laser at the period of T. All-optical clock recovery is thus achieved. A 40 Gbit/s optical clock recovery has been demonstrated (6).

Clock Recovery by Self-Pulsating Laser Diode

A self-pulsating laser diode consists of two contact sections: one is a forward biased semiconductor laser diode, while the other is a saturable absorber that is weakly biased. The saturable absorber section can act as a passive Q switch. The combination of laser gain and the saturable absorption results in a stable pulsation behavior. When a pulsed data stream is coupled into the self-pulsating laser diode, the self-pulsation may be locked on to the data pulses and produces high-quality optical clock pulses at its output. Using this method, a 5 Gbit/s optical clock recovery has been demonstrated (8,28). The speed of the self-pulsating laser diode using a saturable absorber is limited by the carrier lifetime in the absorber. With a two-section DFB laser, as shown in Fig. 18, about 18 GHz optical clock recovery has been demonstrated (9). The self-pulsating mechanism in this case is achieved by dispersive self-Q-switching. Optical clock recovery using self-pulsating laser diode is attractive because the input optical data pulse can be relatively low power and the whole device is small.

HEADER DETECTION AND PACKET SWITCHING

Headers or framing bits have typically been inserted to the data streams to signal the beginning and ending of the data frame or data packet and the address the data to be routed. Buffering of the incoming data frames or packets with the same destination address is required for contention resolution. An optical switch must be able to recognize the header information to effect the data frame or packet switching.

The header address can be coded in time or in wavelength. For a time-encoded header, the header detection can be accomplished by specific optical delay lines and by setting the photodetector array to be activated by the first header bit that experiences the longest delay, and then by comparing with the address code of that particular node. If the header address code matches with that of the node, the 2×2 switch as shown in Fig. 19 is activated to switch the data frame or packet to this node for further processing. If the header address does not match with that of the node, the switch is not activated. So the data frame or packet continue propagation to the next network node. New data frame or packet can also be inserted from the node to the network using the 2×2 switch with the addition of an optical header.

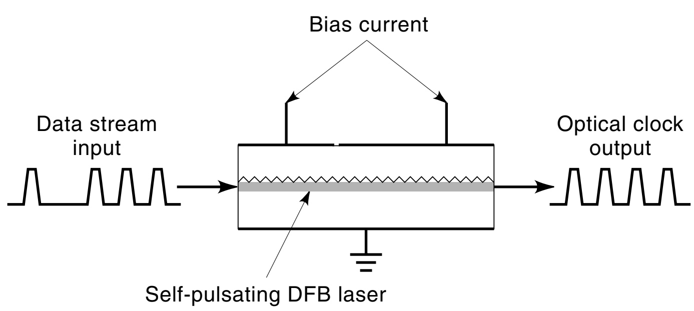

Figure 18. Two-section self-pulsating DFB laser for all-optical clock recovery.

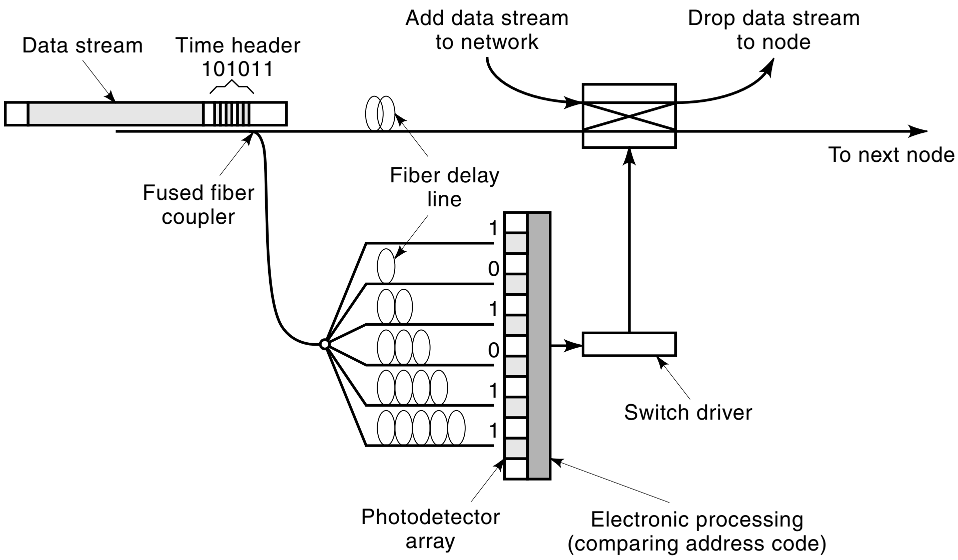

Figure 19. Example of time-encoded header detection for TDMA network switching.

For a wavelength encoded header, as shown in Fig. 20, the header can be overlapped with the data frame or packet (16). The wavelength multiplexing of the header and data stream in the same time window allows better utilization of the fiber capacity per given time-slot. Group delay due to different data and header wavelengths must be compensated for by introducing a transmission delay between the header and the data depending on the known routing length from network node to network node. The detection of the wavelength header can be done by using a passive wide-band fused fiber coupler with a narrow-band wavelength filter, such as a fiber grating device (29). At each node there is a specific wavelength filter. When the wavelength header passes through the filter, a switching signal is sent to activate the 2×2 switching and thus switching the data frame or packet to this node for further processing. The wavelength header length in time scale is slightly longer than the data frame or packet length so that the switch will remain open during the data transmit time to allow the whole data frame or packet to be switched to the node. When the wavelength header does not pass through the fiber filter, the switch is not activated and the whole data frame or packet passes through the node to the next node. A new data frame or packet can also be added to the network communication with the addition of a wavelength header.

The time-encoded header detection is typically performed by electronics. Fiber and semiconductor-based optical logic gates are in the earlier development stage. The wavelength addressed header detection is relatively simple and the switching control can be faster than the time-encoded header detection.

SUMMARY

Optical TDMA networks require timely "drop" and "insert" data streams. The "insert" switching is performed by the multiplexer, while the "drop" switching is performed by the demultiplexer. The data stream sequences can be altered by a time-slot interchange switch. The switching pulse period is controlled by the clock recovered by either electronic or all-optical means. The system timing is achieved by the header detection and synchronization. When the TDMA networks are block-interleaved, the switching data rate can be significantly lower than the line rate. In this case, the synchronization control can be done by electronics. For faster TDMA switching, the synchronization should be based on the all-optical clock recovery technique described above.

Currently, most commercial TDMA networks have line rates of a few Gbit/s or lower. They are basically electronic

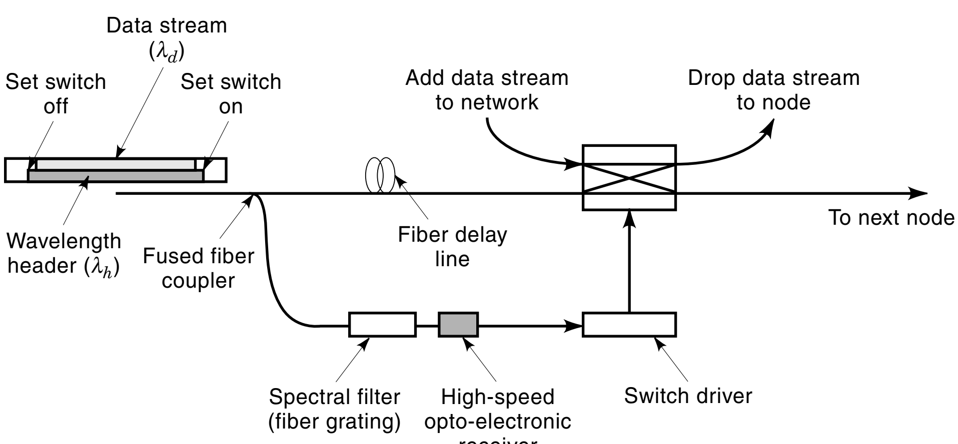

Figure 20. Detection of wavelength-encoded headers for TDMA network switching.

TDMA networks with input and output channels being optical fiber channels or a combination of fiber and electronic channels. The input and output fiber channels use opto-electronic transceivers. The multiplexing, demultiplexing, time-slot interchange switching, clock recovery, and synchronization are all handled by electronics. Audio, video, and data can be time division multiplexed to yield multimedia TDMA networks. Higher data rate optical TDMA networks are currently in the infancy of the development. They have the potential to offer a significantly faster data rate and allow better utilization of the enormous capacity of the optical fiber communication. It is the future of the TDMA networks.

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MICHAEL R. WANG
University of Miami