A High-Speed Optical Star Network Using TDMA and All-Optical Demultiplexing Techniques

Liam P. Barry, Philippe Guignard, Jean Debeau, Remi Boittin, and Martine Bernard

Abstract— **The authors demonstrate the use of time-division multiplexing (TDM) to realize a high capacity optical star network. The fundamental element of the demonstration network is a 10 ps, wavelength tunable, low jitter, pulse source. Electrical data is encoded onto three optical pulse trains, and the resultant low duty cycle optical data channels are multiplexed together using 25 ps fiber delay lines. This gives an overall network capacity of 40 Gb/s. A nonlinear optical loop mirror (NOLM) is used to carry out the demultiplexing at the station receiver. The channel to be switched out can be selected by adjusting the phase of the electrical signal used to generate the control pulses for the NOLM. By using external injection into a gain-switched distributed feedBack (DFB) laser we are able to obtain very low jitter control pulses of 4-ps duration (rms jitter < 1 ps) after compression of the highly chirped gain switched pulses in normal dispersive fiber. This enables us to achieve excellent eye openings for the three demultiplexed channels. The difficulty in obtaining complete switching of the signal pulses is presented. This is shown to be due to deformation of the control pulse in the NOLM (caused by the soliton effect compression).**

The use of optical time-division multiplexing (OTDM) with all-optical switching devices is shown to be an excellent method to allow us to exploit as efficiently as possible the available fiber bandwidth, and to achieve very high bit-rate optical networks.

I. Introduction

As THE requirement for broadband multimedia and interactive services increases, so will the necessity to have networks which can handle very high capacities. The use of optical fiber networks is very attractive due to the large inherent fiber bandwidth which can support very high capacity transmission. However, the capacity of optical systems is limited by the speed at which the light can be modulated electronically at the transmitter, and thus the available fiber bandwidth is under-exploited. To overcome this electronic limitation it is necessary to use optical concurrency or multiplexing techniques which offer the possibility of very large capacity networks in which the fiber bandwidth is more fully exploited. The majority of research in this area has been focused on the wavelength-division multiplexing (WDM) technique [1], [2]. An alternative technique to WDM is that of optical time-division multiplexing (OTDM), in which the fiber bandwidth is shared between the network stations in the temporal domain [3].

It is the application of this OTDM technique in an optical star network which is considered in this article. First, we give a brief discussion of the use of OTDM in an optical star network and present the main elements which are required to realize such a network. Then, we present the experimental network operating at 40 Gb/s, and explain the operation of its three main elements: i) the pulse source, ii) the multiplexer, and iii) the demultiplexer. After this, we consider the control of such an optical star network, and we finish with a discussion and a brief conclusion.

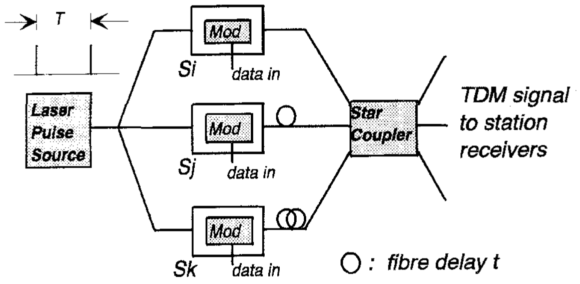

Fig. 1. Application of OTDM to an optical star network.

II. OTDM Star Networks

The basic principle of OTDM networks is to increase the overall network capacity by multiplexing together a number of low bit-rate channels in the time domain. The transmission side of a OTDM star network is shown in Fig. 1. A central source of narrow optical pulses is distributed to all the station transmitters where data (usually in the form of NRZ electrical data) is encoded onto the optical pulse stream using electrooptic modulators. Thus, at the modulator output, we have a RZ optical data stream. The presence (absence) of an optical pulse in a bit slot represents a one (zero). The optical pulse width, τ, is usually very narrow compared with that of the fundamental bit slot, T. Thus, we can consider dividing the fundamental bit slot up into a number of narrow bit slots of width t, into which the low duty cycle optical data from each station can be inserted. The overall capacity which can be achieved using this technique is the inverse of the narrow bit slot width, t, which is the spacing between two adjacent multiplexed channels. This is basically determined by the pulse width, as t must be large enough so that there is no overlapping of adjacent channels, which would result in crosstalk.

After the electrical data has been encoded onto the optical pulse stream, it is necessary to put the data from each station into its respective bit slot. This is normally carried out by using fixed optical delay lines which ensure that the data from a particular station is always assigned to the same bit slot. Each

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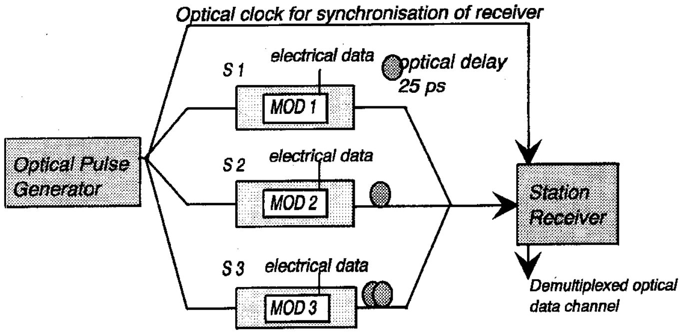


Fig. 2. Experimental setup for TDMA optical star network.

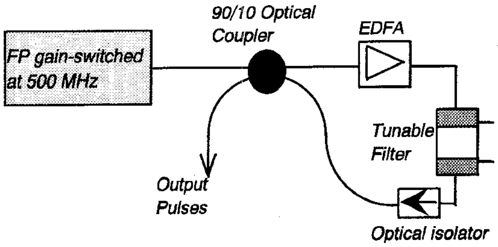


Fig. 3. Optical clock generation using self-injection locking of gain-switched Fabry–Perot (FP) laser.

station of the network will, therefore, have periodic access to the network in the time domain. This is called fixed assignment time-division multiple access (TDMA) [4].

The multiplexed data is then sent to all the station receivers by using a central star coupler. The task of the receiver is to switch out its required data channel from the incoming multiplexed signal. In order to do this, the receiver must be able to switch the overall capacity of the system. If very narrow time bit slots are used, then the overall capacity of the OTDM system may become very large. As electronic or opto-electronic switching cannot be used for switching of very high bit-rate signals (>20 Gb/s), it is necessary to use all-optical switching techniques based on optical nonlinearities. As non-resonant optical nonlinearities have femtosecond response times, they can be used to achieve ultra-fast optical switching. The all-optical switching device used in our experimental network, the NOLM, is based on the optical nonlinearity in fiber. The operation of this device is described in detail in [5] and [6].

III. EXPERIMENTAL TDMA STAR NETWORK

The experimental setup used to demonstrate a TDMA star network is shown in Fig. 2. The fundamental element of the network is the source of narrow optical pulses generated at a low to medium repetition rate (500 MHz). The pulse stream is split into four ways at a 1 × 4 passive optical coupler, with one way being sent directly to the optical receiver, and the other three ways sent to three electrooptic modulators. The modulators represent three station transmitters of the network. Electrical data is encoded onto each of the pulse trains at the modulators, and the three data channels are then delayed to their assigned bit slots using fixed fiber delay lines before being recombined in an optical 4 × 1 coupler (only three of the inputs are used) to create the OTDM signal. The multiplexed signal is then sent to a station receiver (along with the optical clock signal), where either of the three data channels may be demultiplexed out using a NOLM.

The system can be divided into three separate parts: 1) optical clock source, 2) modulation and multiplexing of the channels, 3) station receiver. Each of these will now be discussed in more detail.

A. Optical Clock Source

The optical pulse source used is similar to that presented in [7]. Fig. 3 represents the basic experimental setup. A high-speed Fabry–Perot (FP) laser with a central wavelength of 1534 nm, and a mode spacing of 1 nm, is gain switched at 500 MHz using electrical pulses generated from an electrical comb generator (HP 33 004A). This results in 13 ps optical pulses, at a 500 MHz repetition rate, which have a multimoded spectrum. However, for high-speed OTDM systems, we require not only that the pulses be as narrow as possible, but also that their optical spectrum be as narrow as possible (i.e., transform-limited pulses). This ensures that pulse broadening due to dispersion is a minimum, which is vital in preventing crosstalk between adjacent channels as the high bit-rate multiplexed signal is distributed along optical fiber. By using the setup shown in Fig. 3, we produce pulses which are close to the transform limit by using self-injection locking of the gain-switched FP laser, as described in [7] and [8].

The resulting output pulse is shown in Fig. 4. The deconvolved optical pulse width is 9.5 ps and its associated spectral width is 43 GHz. This gives us a time bandwidth product ($\Delta t \Delta v$) of 0.41, which is close to that for transform limited Gaussian pulses (0.44). The output pulse stream is discretely wavelength tunable (1528–1544 nm) by tuning the optical filter in the feedback loop to the longitudinal modes of the FP laser [7], [8]. Over the tuning range, the time-bandwidth product varies between 0.4 and 0.48. This property of wavelength tunability is important for obtaining the optimum operation of the NOLM used at the station receiver [9].

Another very important property of this optical pulse source is the very low jitter on the output pulses. The jitter was measured to be 1.4 ps rms using the oscilloscope, but as the oscilloscope has an inherent jitter of about 1.1 ps, we can deduce that the actual jitter on the pulses is less than 1 ps.

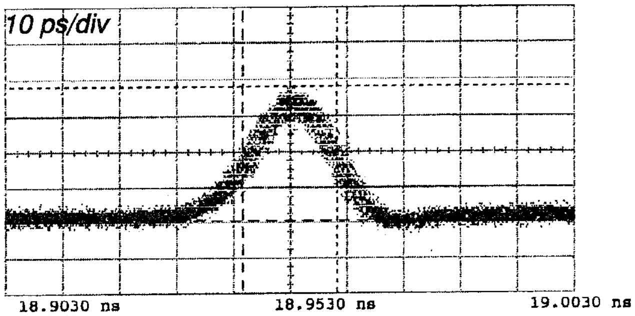


Fig. 4. Low jitter output pulse (nonaveraged) from optical pulse source.

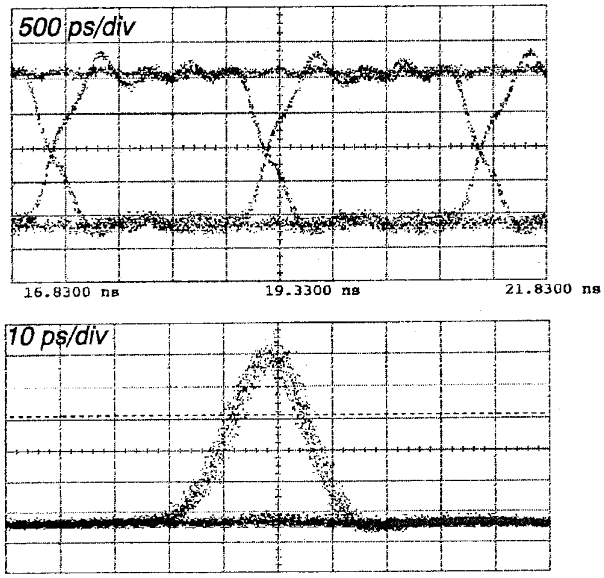


Fig. 5. Eye diagram of 500 Mb/s electrical data **from the** PRBS generator and resultant eye diagram of optical pulse data at modulator output.

It is important to have low jitter pulses in OTDM systems where adjacent channels are placed very close to each other. A significant amount of pulse jitter may result in data from one bit slot straying temporarily into an adjacent bit slot, and this will lead to channel cross talk. To overcome this crosstalk, it would be necessary to increase the channel spacing to accommodate for the pulse jitter, but this clearly would reduce the overall capacity. Such low jitter pulses as we generate here cannot be obtained from directly gain-switched DFB laser diodes due to their high turn on time jitter (TOJ) of the order of 2–3 ps [10]. However, by using self-injection (also known as self-seeding) techniques with a gain-switched FP laser, not only can we achieve wavelength tunable pulses, but we can also obtain low pulse jitter [11].

The average output pulse power from our source is 1 dBm (1.26 mW), and as the pulse width is 9.5 ps and the period of our clock pulses is 2 ns (500 MHz repetition rate), the peak pulse power can be calculated to be around 24.2 dBm (265 mW). We are able to produce such high power pulses due to the optical amplifier in the feedback loop. Due to this high output pulse power, it is not necessary to have another EDFA, before the 1 × 4 optical coupler, to overcome the losses which will be incurred in the optical couplers and in the electrooptic modulators of the network demonstrator.

B. Modulation and Multiplexing

After the optical pulse train is split at the 1 × 4 optical coupler, one of the four pulse trains is sent directly to the network receiver, and the other three ways are sent to electrooptic modulators (Mach–Zehnder $LiNbO_3$ intensity modulators) representing three station transmitters. The modulators used do not need to have an excessively high bandwidth, as they are operating at the data rate of the electrical NRZ signal (500 Mb/s). The three modulators have 3 dB electrical bandwidths of 2.5 GHz and have extinction ratios of greater than 20 dB with a switching voltage of 2.5 V.

The electrical data applied to the modulators is obtained from a pseudo-random binary sequence (PRBS) generator. This generator is synchronized to the electrical clock source used in the generation of the optical pulse stream. Thus, the electrical data from the generator is synchronized to the optical pulses from the pulse source. The electrical data is split in three using electrical couplers, and applied to each of the three electrooptic modulators. In order to simulate the application of three different data signals to each of the modulators, the electrical data signals are passed through different lengths of cable before being applied to the modulators.

It is vital that the electrical data stream and the optical clock to the modulators are not only synchronized, but also have a particular phase relationship. The phase relationship is important because we need the optical pulse to arrive at the modulator when the electrical data is either in a high, or a low state, and not in a transitional state (as this would seriously degrade the resulting eye diagram). Fig. 5 shows the eye diagram of the 500 Mb/s data applied to the modulator. We can see that the signal has a risetime and a fall time of around 500 ps. To ensure that the optical pulse train does not arrive at the modulator during a transition, the lengths of electrical cable used to apply the electrical data signal to the modulators are carefully chosen. The resulting eye diagram of one of the optical pulse data channels at 500 Mb/s is also shown in Fig. 5.

To achieve our multiplexed signal, the three optical data channels are assigned to three successive 25 ps bit slots (leading to an overall capacity of 40 Gb/s) by using fixed fiber delay lines between the output of each modulator and the recombining coupler. The fiber delay lines are fabricated by cutting the required optical fiber lengths with a high precision diamond cleaver. Using this method, we are able to cut the fiber to a precision of about 0.2 mm (which corresponds to a time precision of 1 ps). When the three data channels are recombined together with a 4 × 1 coupler after passing their respective fiber delay lines, the resulting eye diagram of the multiplexed data signal is as shown in Fig. 6. From this, we can see the excellent eye opening for the three time multiplexed channels. The slight overlap between the channels is due to the limited response time of the photodetector and the oscilloscope (overall response time of approximately 15 ps) used to display the eye diagram. The multiplexed data stream is then sent to the network receiver.

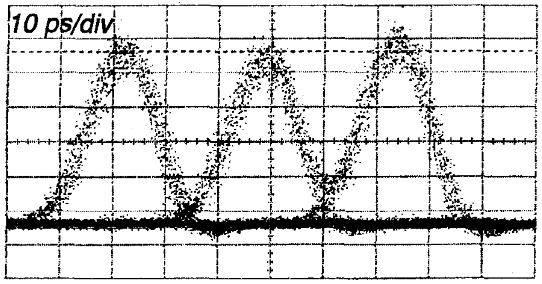


Fig. 6. Eye diagram of optical data channels multiplexed together with 25 ps delays between adjacent channels.

C. The Station Receiver

The experimental setup for the station receiver is shown in Fig. 7. The inputs to the receiver are the multiplexed data stream and the optical clock signal (which is required for correct synchronization of the receiver). As we are using a star configuration network, the optical clock must be distributed to all the stations. By using a 1 × 2 coupler at the station input the clock can be sent to both the transmitter and the receiver. In our network, for experimental purposes, one of the outputs from the 1 × 4 coupler after the optical clock generator is used to send the optical clock to the receiver. The receiver consists of three main sections: a) recovery of an electrical clock from the optical clock, b) the generation and phase control of the high power control pulse, and c) demultiplexing in the NOLM.

1) Electrical Clock Recovery: The optical clock sent to the receiver is used to regenerate an electrical clock signal. To recover the electrical clock we use a low bandwidth pin diode and a low Q electrical filter. When the optical clock is detected by the pin diode the resulting spectrum of the electrical signal is a comb of frequencies at multiples of the pulse repetition frequency (as expected for the spectrum for a stream of pulses). The electrical bandpass filter selects out the fundamental component at 500 MHz. As the electrical clock signal is recovered directly from the low jitter optical pulse stream at the clock rate, and not from the multiplexed data stream, we are able to use a low Q filter ($Q = 20$) and still recover a very low jitter clock signal at 500 MHz, as shown in Fig. 8 (the jitter of the recovered electrical clock is deduced to be <1 ps from the oscilloscope trace).

2) Phase Control and Generation of Optical Control Pulse: The recovered electrical clock signal then passes a variable phase adjuster which allows the phase of the 500 MHz clock to be varied by up to 200 ps. After this, the electrical clock is amplified to obtain an RF power of almost 30 dBm before being fed into a 500-MHz electrical comb generator to obtain electrical pulses of 80 ps duration with high peak voltages (15 V). These electrical pulses are used to gain-switch a DFB laser diode (central wavelength of 1552 nm). This produces optical pulses which have a width of 16 ps. In order to improve the switching speed of the NOLM, we need to narrow the optical control pulses. Compression of the highly chirped gain-switched DFB pulses can be achieved by passing the pulses through normal dispersion fiber [12]. However due to the reduction in the side mode suppression ratio (SMSR) of gain-switched DFB lasers, the compressed pulse may not be suitable for use as the control pulse in the NOLM.

The SMSR reduction is caused by extremely large fluctuations in the electron density under gain-switching conditions, which results in the laser side modes being strongly excited [13]. This problem can clearly be seen from the optical spectrum of the output pulses from the gain-switched DFB laser, Fig. 9. From this, it can be seen that the SMSR, which is almost 40 dB with the laser in CW operation biased at 30 mA, is reduced to only 15 dB under gain-switched conditions. This large degradation in the laser SMSR means that the energy in the laser side modes is nonnegligible, and this results in two major problems when we try to compress the pulse in highly normal dispersive fiber.

1) First, as the DFB laser used has a mode spacing of about 1.8 nm and the compression fiber which we use is highly dispersive ($D = -20$ ps/km · nm), the laser modes will propagate at different velocities which will lead to satellite pulse formation [14].
2) Second, the competition between the modes results in the spectral distribution being time dependent, thus power is constantly being transferred between the modes. This results in a large amount of jitter on the compressed pulse.

These two problems can clearly be seen in Fig. 10, which displays the output after the gain switched pulse has propagated through 700 m of the highly dispersion shifted fiber. This pulse is clearly unsuitable for use as the control in the NOLM.

These problems have been overcome in our experiment by using low-level injection from a tunable, CW, low linewidth source into the gain switched DFB laser in order to increase its SMSR. We inject 50 μW of power at a wavelength of 1551.8 nm into the laser. This external injection causes an initial excitation well above the spontaneous emission level for the central DFB mode. This suppresses the gain in the side modes of the DFB and results in a far higher SMSR (29 dB) for the gain-switched laser. When this gain-switched pulse is now compressed using the highly normal dispersive fiber, the former problems of satellite pulse formation and jitter are eliminated. By compressing the pulse using various lengths of the compression fiber the optimum length required for maximum compression is found to be 700 m. The resulting compressed pulse monitored using our 34 GHz photodiode and 50 GHz oscilloscope is shown in Fig. 11. There are no satellite pulses and the jitter is measured to be only 1.5 ps rms using the oscilloscope.

The resulting compressed pulse width measured using the oscilloscope is 14.4 ps, which is approximately the combined response time of the photodetector and the oscilloscope. Thus, to examine the pulse width accurately, it is necessary to use an autocorrelator. The autocorrelation pulse trace (Fig. 11) has a width of 6 ps, and assuming a Gaussian-shaped pulse, the actual pulse width is about 4 ps. This pulse is then amplified using a high power EDFA before being coupled into the NOLM as the control pulse.

3) NOLM Demultiplexing: The NOLM that we use consists of a 3-dB optical coupler with its output ports joined

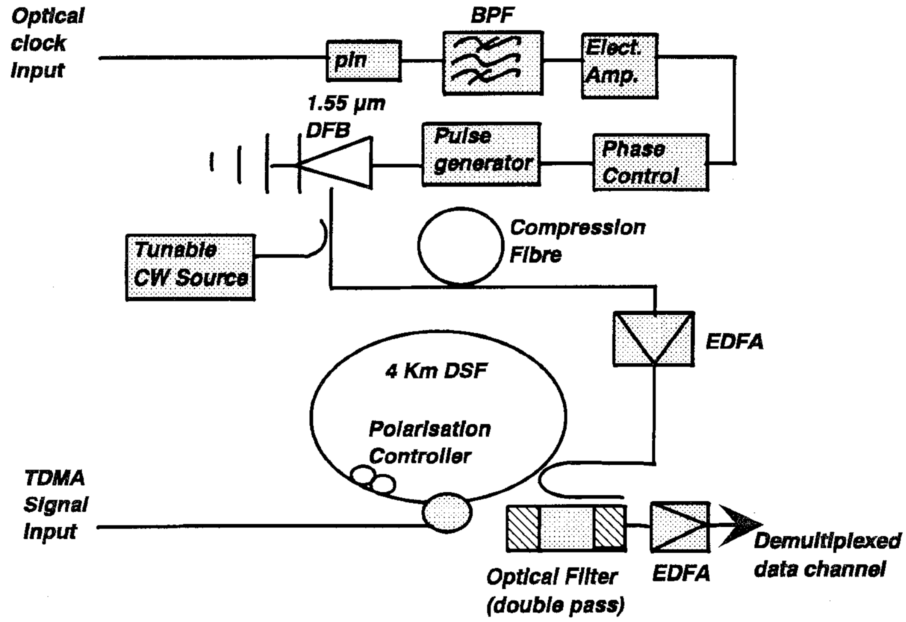


Fig. 7. Experimental setup for network receiver consisting of electrical clock recovery, generation and phase control of control pulse, and demultiplexing with the NOLM.

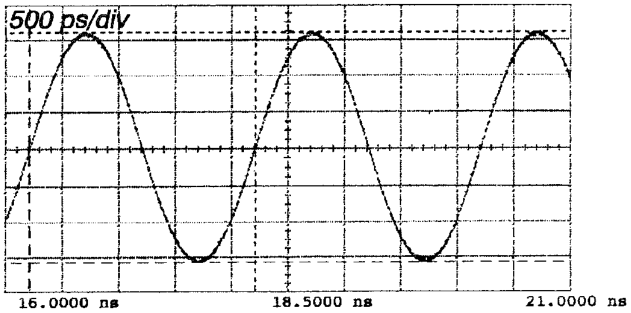


Fig. 8. Recovered 500 MHz electrical clock signal (nonaveraged).

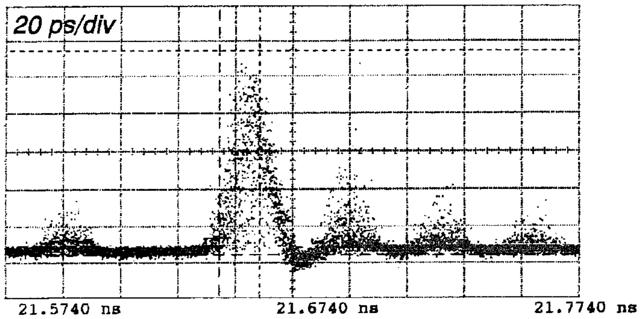


Fig. 10. Gain-switched pulse from DFB after propagation through 700 m of dispersion shifted fiber ($D = 20$ ps/km · nm).

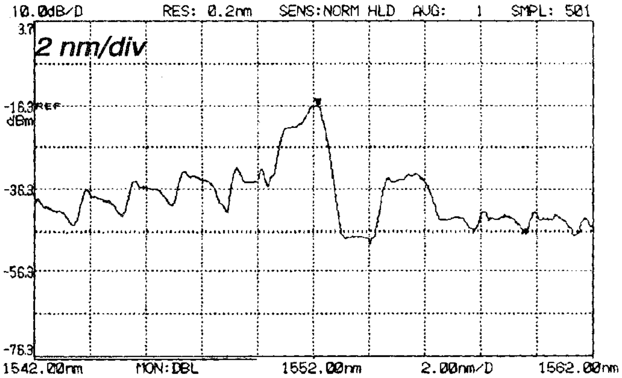
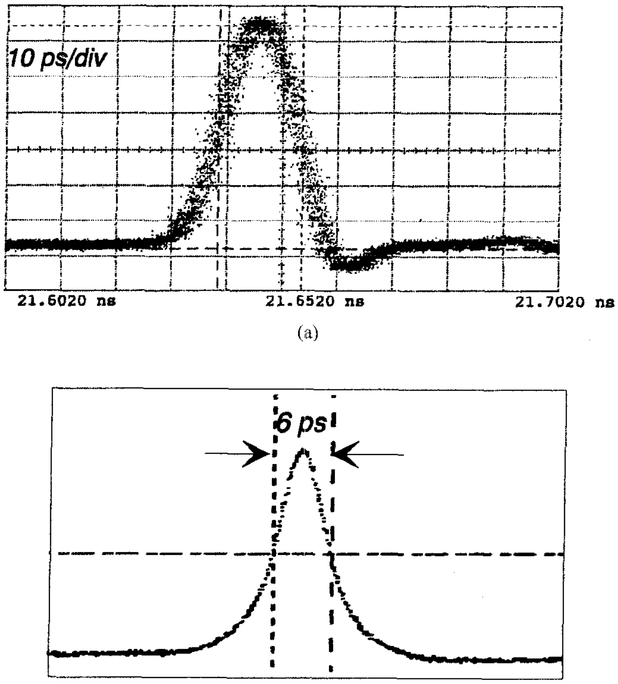


Fig. 9. Optical spectrum of gain-switched DFB laser diode.

together using 4 km of DSF and a polarization controller. The input to the NOLM is the three-channel OTDM signal as shown in Fig. 6. The control signal is amplified and injected into the NOLM using a second 3 dB optical coupler. The peak pulse power of the control injected into the NOLM is 500 mW The basic operating principle of demultiplexing using two wavelength operation of the NOLM is described in [6] and [15]. Optimum operation of our NOLM is found to be at a signal wavelength of 1539 nm. This corresponds to a signal-pulse walk off of 11 ps.

At the loop output, we use a double pass tunable optical filter (to select out the signal wavelength) and an EDFA. The double pass filter (bandwidth of 0.35 nm) is required because at the loop output the power in the control pulse is at a level around 30 dB above the signal power. As the filter only has a return loss of -25 dB, the control pulse is not fully eliminated at the output after passing the optical filter once. By using a double pass of the same filter, we achieve a return loss of -50 dB and the signal wavelength can be selected out with complete rejection of the control pulse. Using the double pass of the optical filter results in a high insertion loss for the switched signal so the EDFA is required to overcome these losses.



(a)

(b)

Fig. 11. Gain-switched pulse from DFB laser (with external injection) compressed using 700 m of highly DSF, and its autocorrelation trace.

Figure 12 shows the OTDM eye diagram at the input to the receiver and the output eye diagrams for the demultiplexed channels. The demultiplexed channel is selected by varying the phase of the recovered electrical clock which is used to generate the control pulses (this allows us to vary the position of the control pulse injected into the NOLM). All the demultiplexed channels have clear eye openings and adjacent multiplexed channels are unaffected, indicating that the control pulse only alters the phase in the bit slot of the selected channel.

To examine the percentage of the selected channel switched from the loop we can adjust the polarization controller in the loop such that the NOLM operates in transmitting mode (i.e., channels not affected by control pulse are transmitted). With the control pulse synchronised with channel 2, the loop output is as shown in Fig 13. From this it can be seen that complete switching of the data channel has not been achieved. This problem of incomplete switching can be explained by examining the control pulse at the output of the NOLM. Fig. 14 shows the autocorrelation trace of the control pulse at the loop output. The control pulse has been compressed down to about 800 fs (assuming a gaussian pulse form) at the loop output due to the soliton effect compression [16]. This compression of the central part of the pulse results in the peak pulse power being increased. Thus, the 4 ps, 500 mW peak power optical pulse at the loop input is compressed and increases in amplitude as it propagates along the loop. The change in control pulse amplitude means that the phase shift induced on the signal pulse due to XPM, and thus the switching window, become asymmetric. For an asymmetric switching window, an equal phase shift cannot be obtained over the entire signal pulse, so complete switching cannot be achieved [17].

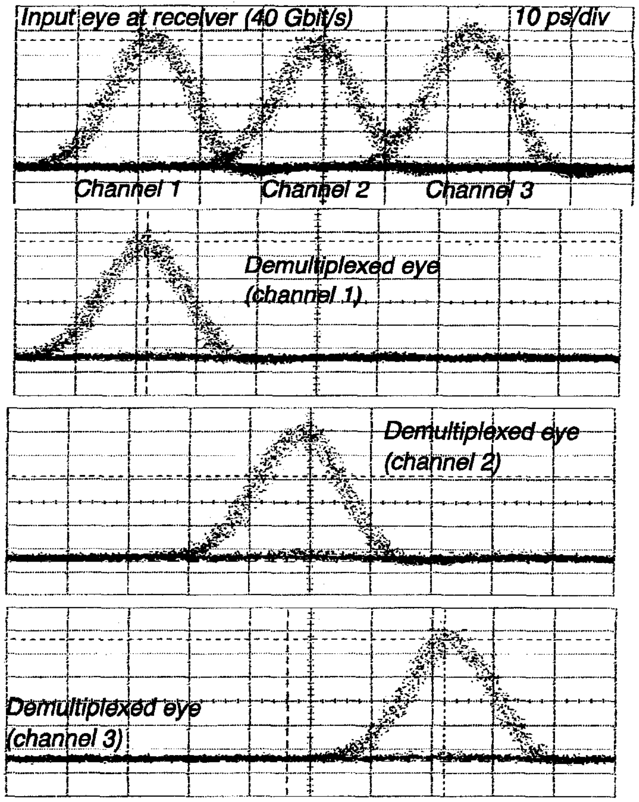


Fig. 12. Input eye diagram to receiver, and eye diagrams of the demultiplexed channels. Channel selection is carried out using phase controller.

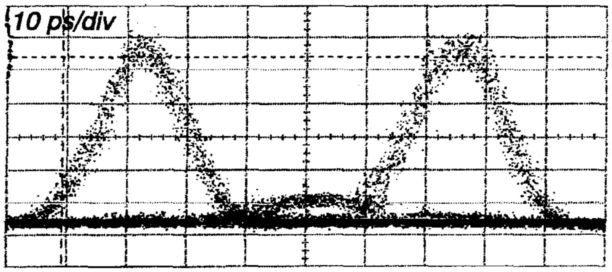


Fig. 13. Complimentary output eye diagram for switching of channel 2. Incomplete switching of data channel can be seen.

IV. NETWORK CONTROL

The channel switched out at a certain station receiver is selected by using the phase controller in the control pulse generation circuitry (as this controls the position of the control pulse arriving at the NOLM). In the experiment, a variable microwave delay line, which is adjusted mechanically, is used as the phase controller. However, a voltage-controlled phase controller may be used. Controlling the phase of the electrical clock signal at the receiver using electronics ensures that the data channel demultiplexed out at a particular station can be

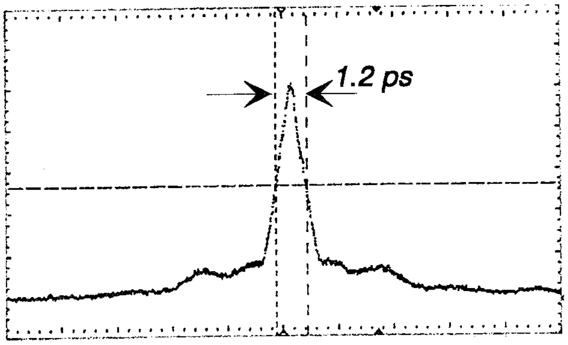


Fig. 14. Autocorrelation trace of control pulse at output of NOLM.

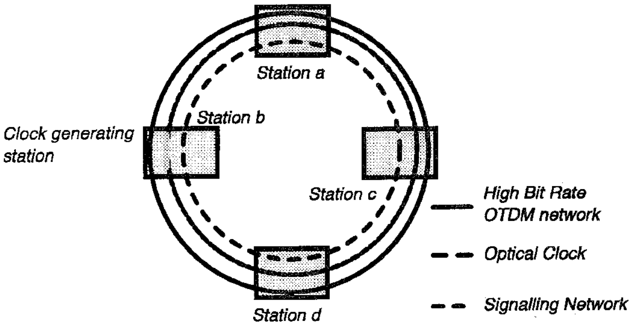


Fig. 15. Configuration for an OTDM ring network.

changed with low delay times. The tuning of the phase of the control pulses to determine which channel is switched out at the station receiver is analogous to the tuning of an optical filter in a WDMA network.

Management of the high bit-rate TDMA network may be achieved by underlaying it with a low bit-rate control network. When station S_i wishes to communicate with station S_j on the high bit-rate network, the two stations must first of all exchange information with each other on the control network. We may consider that S_i sends a connection request to S_j, and provided S_j is not already in communication with another station, S_j tunes its receiver phase controller so that the data from S_i is switched out from the multiplexed signal (using the NOLM). It may also be possible to have the control network distributed optically, by superimposing it on the same optical medium as that used to carry the high bit-rate data, using optical window multiplexing. Such a technique has already been demonstrated for a WDMA network [2].

V. Discussion

The network presented here uses a star architecture in which the central clock is distributed to all the stations. The data from all the stations are then multiplexed together and distributed to each station receiver by using a central $N \times N$ star coupler, where N is the number of network stations. For high capacity networks the data from each station must be inserted into a very narrow bit slot. Environmental variations (e.g., temperature differences), between the different fiber paths from the station transmitters to the central star coupler, will lead to stability problems in placing the data channels into their assigned bit slots. Thus, it would be required to have some form of temperature control for the different fiber paths, to ensure that station data is assigned continually to the correct time slot in the multiplex.

One way to overcome this problem may be to consider the use of a ring configuration OTDM network, as shown in Fig. 15. In this configuration, the high bit-rate optical data is continually circulating on the same fiber, thus eliminating the above problem. This configuration is suitable for networks with a small number of high-speed nodes, e.g., four stations each operating at 10 Gb/s (if there are a large number of network nodes, pulse restoration is necessary to overcome the build-up of noise in optical amplifiers). The optical clock may be generated at one of the network stations, and distributed to all the other stations using an open loop. To realize such an OTDM ring network it is necessary to use OTDM add–drop multiplexers at each station. A possible station configuration is illustrated in Fig. 16. The network station switches out its required data channel from the OTDM signal and then inserts the data which it wishes to transmit into the vacant bit slot. To carry out this function using a NOLM, it is necessary to recover both the demultiplexed channel and the complementary output (OTDM signal less the switched out channel) from the NOLM. This may be achieved by using an optical circulator at the input of the NOLM in order to recover the reflected signal from the loop. For optimum operation it is important that the switching ratio for the demultiplexed channel is close to 100%, as any part of the demultiplexed channel unswitched will lead to interference on the inserted channel.

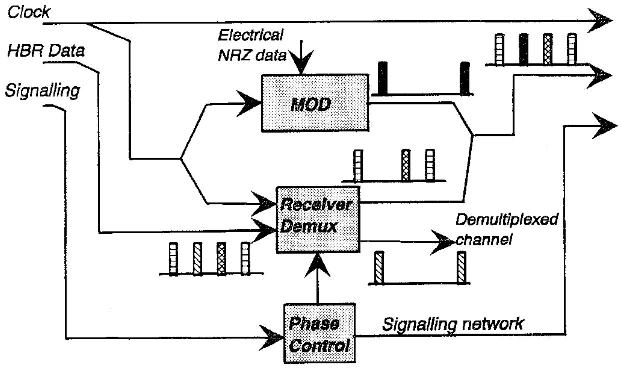


Fig. 16. Possible station configuration for an OTDM ring network. Receiver outputs demultiplexed channel and the TDM signal less the demultiplexed channel.

By using the OTDM with 25 ps bit slots, it would possible to realize a 80 station network with each station transmitting data at 500 Mb/s. To realize a WDMA network which has the same capacity and station number, it would be necessary to use 80 different wavelengths in the 1530–1570 nm range (gain bandwidth of EDFA), i.e., a channel spacing of 0.5 nm. With a TDMA system, it is possible to achieve this capacity by using a single source and a spectral width of only 0.3 nm. Thus, the TDMA system seems to be an efficient way to exploit the available fiber bandwidth. However, OTDM technology is not as mature as WDM technology, so it is necessary to consider ways of using OTDM to complement WDM. For example, as the number of stations and the capacity required in an WDM network increases, OTDM of a number of high capacity channels on one of the wavelengths in the WDM may be used.

VI. CONCLUSION

We have demonstrated the operation of an optical TDMA star network by time multiplexing together three 500 Mb/s optical channels. Each channel is represented using 10 ps optical pulses, and the multiplex is carried out using 25 ps delays between adjacent channels. This allows us to have an overall network capacity of 40 Gb/s. The use of a NOLM at the station receiver allows us to demultiplex this very high capacity signal, and channel selection is achieved by using a variable electrical phase controller at the network receiver. In order to achieve very clear demultiplexed eye diagrams, low jitter optical pulses are used for the signal and control pulses.

The optical nonlinearity used to carry out the all-optical switching has a femtosecond response time; thus, the potential transmission capacity of such a network can be increased to beyond 100 Gb/s by using even narrower optical pulses. Indeed all-optical demultiplexing at 250 Gb/s has already been carried out by using the nonlinearity of a semiconductor optical amplifier in a NOLM configuration [18].

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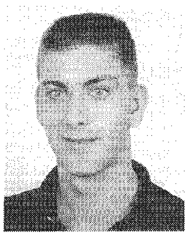

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Philippe Guignard was born in Lorient, France, in 1956. He received the Diplome d'ingénieur from the Ecole Nationale Supérieure des Télécommunications de Bretagne, Brest, France in 1983. In 1988, he received the Doctorate from the Université de Limoges, France.

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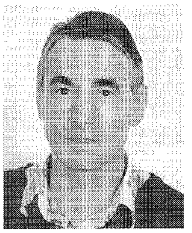

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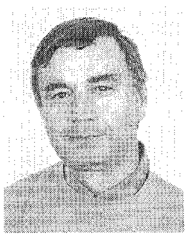

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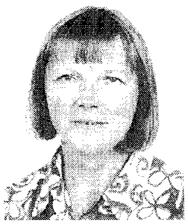

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