A Fast Channel-Tunable Optical Transmitter for Ultrahigh-Speed All-Optical Time-Division Multiaccess Networks

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***Abstract*—This paper describes the design and the experimental demonstration of a novel fast channel tunable optical transmitter which is suitable for ultrahigh-speed all-optical time-division multiaccess (TDMA) networks. This optical transmitter is capable of performing fast channel tuning and data modulation in a simple and cost-effective way without using the expensive optical modulators and optical switches. By employing this transmitter, together with the proposed destructive writing scheme, ultrahigh-speed channel multiplexing with relaxed synchronization requirements for data access can be achieved. The demonstrated prototype can be arbitrarily tuned to any one of the 16 1-Gb/s channels in a 16-Gb/s all-optical TDMA network with channel switching time less than 5 ns. This is suitable for use in most high-speed optical time-division multiplexed (TDM) systems and tunable-channel multiaccess (TCMA) networks.**

I. Introduction

RECENTLY, a single wavelength 400-Gb/s optical time-division multiplexed (TDM) transmission system has been demonstrated [1]. This shows the potential of realizing an optical network with a capacity of more than a hundred gigabits per second. In this paper, we consider all-optical, ultrahigh-speed TDM networks, where each node is assigned a TDM channel. Each node has a receiver and transmitter, so that its receiver receives data on its assigned channel, while its transmitter may transmit on different channels. Both the transmitter and receiver communicate at the channel rate. Note that it is desirable to have a transmitter that can change channels quickly, to reduce channel access time. It is also desirable that implementation should be simple and cost-effective. We propose a novel optical transmitter with such properties. We also present a high-speed TDM channel multiplexing scheme which can relax the timing requirement. The experimental demonstration shows that the transmitter and the channel multiplexer are very feasible and practical for ultrahigh-speed time-division multiaccess (TDMA) networks. In Section II and III, the design, the implementation issues, and the experimental demonstration of the proposed channel-tunable optical transmitter and channel multiplexer are presented, respectively. In Section IV, an application example of our work is presented.

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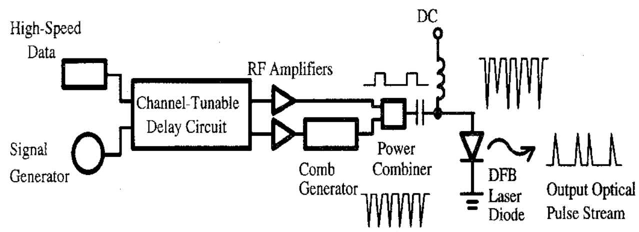

Fig. 1. Schematic of the fast channel-tunable optical transmitter.

II. Transmitter Design and Experimental Demonstration

The schematic of the proposed fast channel-tunable optical transmitter is shown in Fig. 1. It has two major functions, namely fast channel tuning and high-speed data modulation, which are described below.

A. Fast Channel Tuning

For fast channel tuning, a common and straightforward method is to use optical delay lines with expensive optical switches/modulators to route optical pulses through different lengths of fiber delay lines. Tuning with a time slot interval of 156.25 ps has been demonstrated [2], with a tuning speed of about 50 MHz. This type of tunable delay line is usually polarization-dependent and suffers from a high insertion loss and thus has a degraded power budget.

We propose a novel channel-tuning method for high-speed optical TDM systems using only electronic components, instead of optical ones, to generate channel-tunable optical short pulses. The tunable optical pulse source is fairly simple. A sinusoidal signal is first delayed by an electronic channel-tunable delay circuit which has a switching time less than 5 ns. The delayed signal then drives a comb generator which, in turn, drives a laser diode to generate channel-tunable optical pulses by gain-switching.

The delay circuit is designed for a 16-Gb/s and 16-channel optical TDM systems. Each TDM frame has 16 time slots, each slot carries a single bit and has duration $\tau = 62.5$ ps. The electronic channel-tunable delay circuit consists of four stages of 1×2 RF switches. These switches are controlled by a computer to select between the upper (longer) paths or the lower (shorter) paths that have relative time delays of $1\tau, 2\tau, 4\tau$, and 8τ, respectively, in the four stages. Thus, the

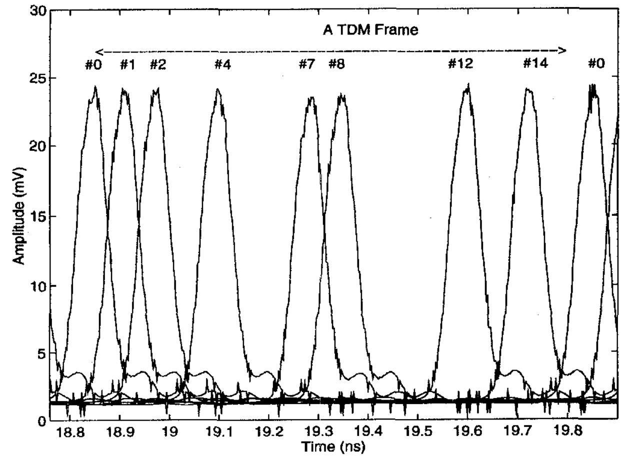

Fig. 2. Optical pulse waveforms after being tuned to different channels.

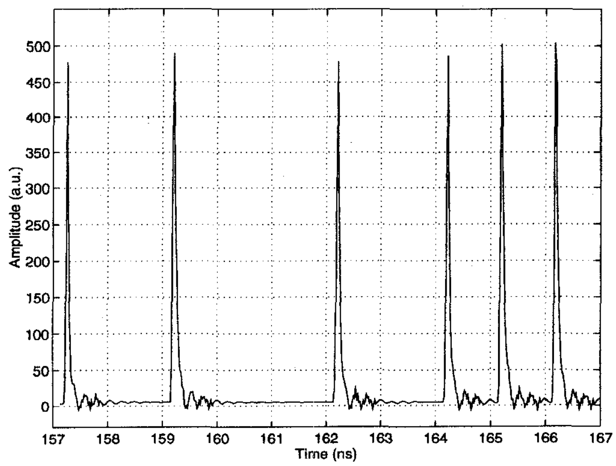

Fig. 3. Detected optical pulse stream (with modulation) by a 40-GHz photodiode, data pattern: <1010010111> at 1 Gb/s.

delayed clock signal gives a delayed electrical pulse train and in turn gives a delayed gain-switched optical pulse train. Fig. 2 shows the waveforms of the gain-switched optical pulses that are tuned to different time slots. The typical channel-tuning or switching time is 3 ns, less than 1% of an asynchronous transfer mode (ATM) packet (53 bytes) transmission time at 1 Gb/s.

B. High-Speed Data Modulation

With this fast channel-tunable delay circuit, a channel-tunable high-speed data modulation scheme can be achieved. As shown in Fig. 1, high-speed data is first delayed in synchronous with the sinusoidal clock signal using the channel-tunable delay circuit. The channel-tuned data is then superimposed on the electronic short pulse from the comb-generator, and the combined signal is used to gain-switch a DFB laser to generate channel-tunable data-modulated optical pulses.

We have experimentally demonstrated such channel-tunable data-modulation scheme. An 1-Gb/s NRZ high-speed data stream ($V_{\text{pk-pk}} = 2$ V with $V_{`0'} = 0$ V and $V_{`1'} = -2$ V) is

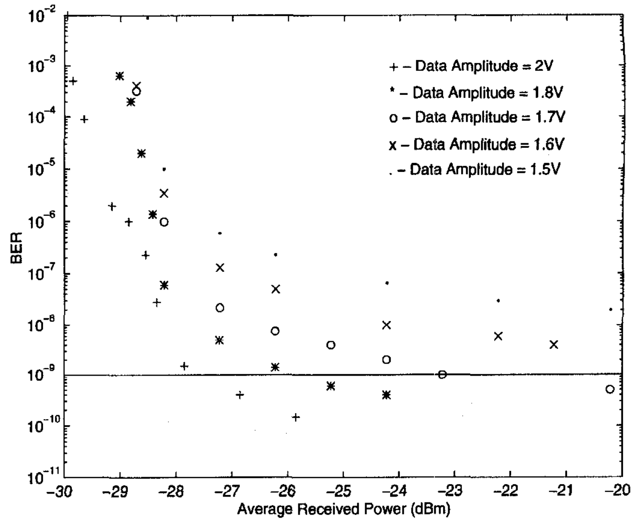

Fig. 4. BER performance of optical pulse stream modulation after preamplification, data pattern: $(2^7 - 1)$ PRBS at 1 Gb/s.

generated from a pattern generator (HP 70941B) and added to the comb generator output ($V_{\text{pk-pk}} = 9$ V with $V_{\text{spike}} = -9$ V), as shown in Fig. 1, before driving the 1.55-μm DFB laser diode [3]. The output waveform of the modulated gain-switched pulse stream (data pattern: <1010010111>) after being preamplified and detected by a 40-GHz photodiode is shown in Fig. 3. As seen from Fig. 3, the extinction ratio of output '1' and '0' is quite good and it is found to have great dependence on the input data amplitude. We have measured the bit-error rate (BER) performance of this data-modulation scheme using $(2^7 - 1)$ pseudorandom (PRBS) data with different data amplitudes, and the results are shown in Fig. 4. The results show that our fast channel-tunable optical transmitter is a feasible way of performing data modulation without the need of optical modulators. Also, the higher the input data amplitude used, the higher the output extinction ratio and thus the better the receiver sensitivity. The maximum 2-V amplitude is limited by our equipment's output voltage.

C. Advantages

Since only the electrical clock and data (1 GHz) are delayed, not the comb generator output (18 GHz) or the optical pulses (>40 GHz), the bandwidth requirement of the tunable delay circuit is much reduced and so is the cost. The simplicity of this channel-tuning scheme also makes the scheme practical. The generated optical pulse stream is modulated according to the data. This provides a simple alternative for high-speed optical modulation other than using an optical modulator which is polarization-dependent, much more expensive and has high insertion loss. Furthermore, using this transmitter, we can convert a long pulse width electrical data stream to a short pulse width optical pulse stream. Effectively, we eliminate the bandwidth bottleneck of the electrical signal, and we will be able to use the ultrahigh-speed all-optical signal processing schemes like nonlinear optical loop mirrors (NOLM) [4] or four-wave mixing (FWM) [1] for data modulation and

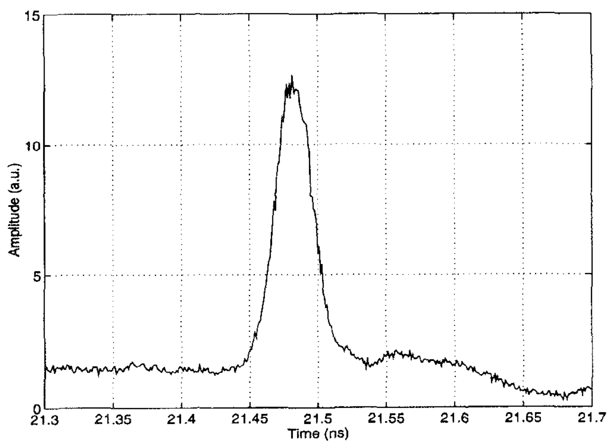

Fig. 5. Waveform of gain-switched optical pulse at 1 Gb/s, pulse width = 27 ps.

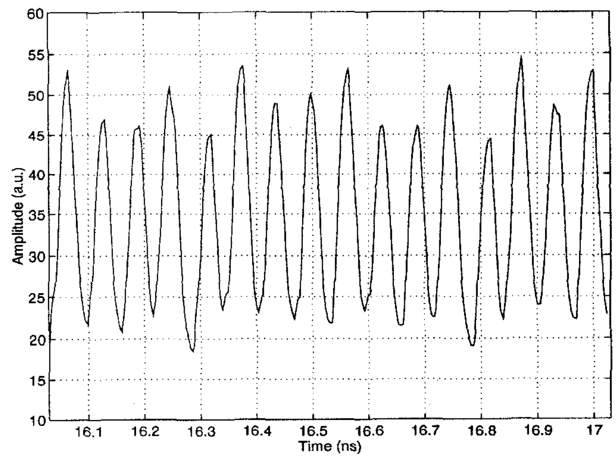

Fig. 6. Waveform of a 16-Gb/s optical pulse stream.

demultiplexing. In short, this fast channel-tunable optical transmitter is simple, practical and cost-effective to be used in high-speed TDM systems and networks. One of the important applications is that it can be used to achieve an ultrahigh-speed TDM channel multiplexer which will be described in the next section.

III. Ultrahigh-Speed Channel Multiplexer

In optical TDM systems, transmitting high speed data and multiplexing the data to a specific channel with channel-tunability and a high timing accuracy is a great challenge. The traditional method is to multiplex the optical data pulses directly to the system optical data stream. However, this method requires very stringent time accuracy. Otherwise, part of the data pulse's power may fall into its adjacent channels (time slots) and cause adjacent channel interference. Moreover, different transmitters in the network may transmit at different power levels and also may suffer different transmission losses. This will result in power fluctuations in all time slots in the multiplexed data stream and thus degrade the receiver sensitivity.

We propose a novel ultrahigh-speed channel multiplexing scheme that uses a centralized pulse source, our fast channel-tunable transmitter and an ultrafast optical switching device to alleviate the above problems.

A. Centralized Pulse Source

In our scheme, a single-wavelength centralized pulse source is employed to generate an optical pulse stream at the system multiplexed bit rate. Along the transmission link, any network node can transmit data to it by switching "on" or "off" the optical pulse in the designated time-slot (channel) of this centralized pulse stream. Moreover, any node can get its own data sent from other nodes by demultiplexing at its own designated time-slot. Such an approach can solve the "near–far problem" caused by the different transmission losses from remote nodes. Also, the centralized pulse stream can provide the clock information for every network node to achieve synchronization.

The optical pulse generation technique we employed is gain-switching. It is simple and relatively inexpensive as compared to other techniques such as mode-locking. A 1-GHz comb generator is used to generate short electrical pulses to drive the DFB laser diodes. The pulse width of the 1-Gb/s gain-switched optical pulses obtained is about 27 ps as shown in Fig. 5. The pulses are then multiplexed to 16 Gb/s by a 1-to-16 multiplexer using a four-stage optical fiber delay lines with couplers. The multiplexed optical pulse stream in one 16-Gb/s TDM frame with 16 channels is shown in Fig. 6. The amplitude variation among different pulses is due to splitting ratio deviation of the 3 dB couplers. This variation can be easily eliminated by adding variable attenuators in various paths. The pulse width can be further compressed by compression fibers to less than 10 ps [5] in order to achieve higher system bit-rate.

B. Destructive Writing Scheme for Ultrahigh-Speed Channel Multiplexing

With the proposed centralized pulse source, ultrahigh-speed channel multiplexing can be realized by employing our proposed multiplexing scheme called *destructive writing*. This scheme requires a nonlinear optical loop mirror (NOLM) [6] together with a fast channel-tunable transmitter as the channel multiplexer. The NOLM functions as an ultrafast optical gating device. A nonlinear amplifying loop mirror (NALM) [7], which is similar to NOLM but having an erbium-doped fiber amplifier (EDFA) inside the loop, may be used alternatively for its lower switching power needed. Both NOLM and NALM have the merits that they provide amplified spontaneous emission (ASE) reduction [8], pulse shaping, compression, and pedestal suppression [9]. Besides, they have switching response time on the order of sub-picoseconds. Thus they are very suitable to be used as multi/demultiplexers in ultrahigh-speed all-optical systems and networks [4].

In this scheme, as shown in Fig. 7, an optical pulse stream at the system multiplexed bit rate is generated from the centralized pulse source. The data to be transmitted is first channel-tuned and converted to an optical pulse stream by our fast channel-tunable optical transmitter. This optical pulse

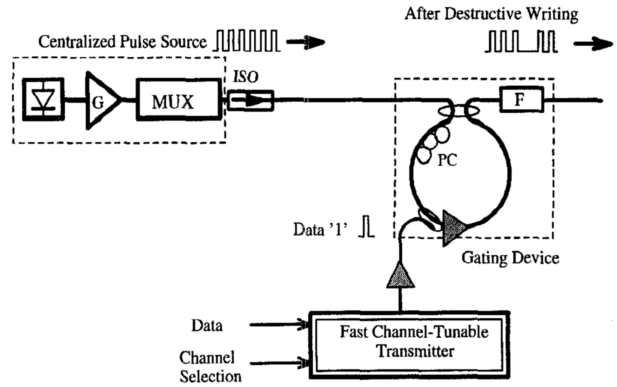

Fig. 7. Ultrahigh-speed channel multiplexer with destructive writing scheme. G denotes the optical amplifier, MUX denotes the fiber multiplexer, ISO denotes the optical isolator, F denotes the optical filter, and PC denotes the polarization controller.

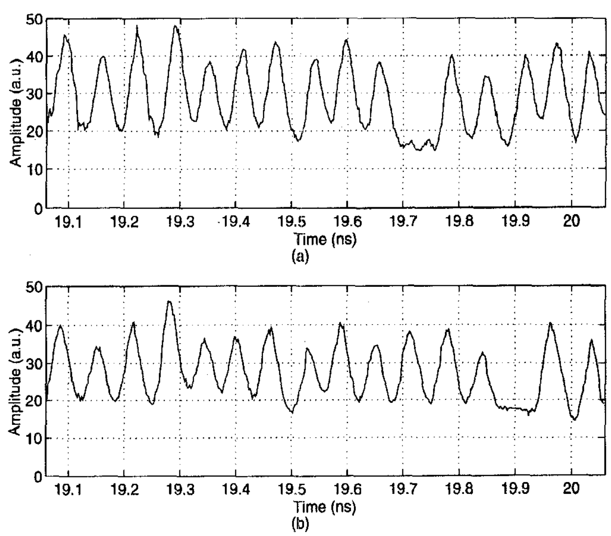

Fig. 8. Detected optical pulse stream by a 40-GHz photodiode after destructive writing at (a) channel 11 and (b) channel 14.

stream is then injected into an NOLM as the control pulse stream. When the transmitter transmits a "0" bit, the NOLM will switch to "forward" state and the corresponding optical pulse in the centralized pulse stream will be forwarded. Conversely, when a "1" bit is transmitted, the NOLM will switch to "reflect" state. The corresponding optical pulse in the centralized pulse stream will be reflected and thus no pulse is forwarded to the subsequent network nodes. Thus, the central pulse stream carries the transmitted data in complementary format. The transmitter can be interpreted as destroying rather than adding an optical pulse when transmitting a "1" bit. This is why the scheme is called "destructive writing."

By using the NOLM/NALM as the ultrafast all-optical gating device, the timing requirement can be relaxed since individual nodes can perform the gating function (similar to a logical AND) within a relaxed time interval (gating window) wider than the optical pulse. Such a gating window is due

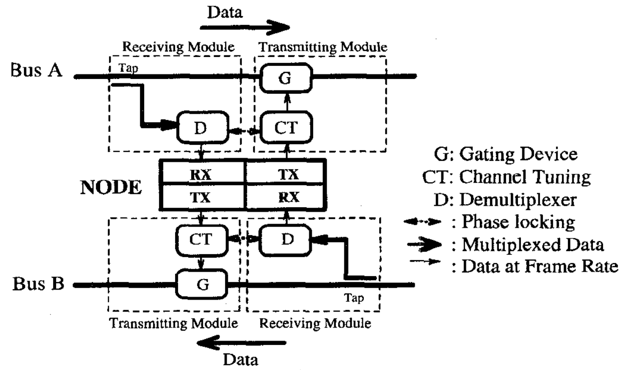

Fig. 9. An TCMA node employing TDM.

to the walkoff characteristics [10] in the NOLM/NALM. This provides better timing jitter tolerance. An additional advantage is that a high extinction ratio can be achieved [9]. Therefore by employing the destructive writing scheme, together with the NOLM and the fast channel-tunable transmitter, an ultrahigh-speed channel-tunable channel multiplexer with relaxed timing requirement can be realized.

Figure 8 shows the waveforms of a 16-Gb/s 16-channel TDM optical stream after having been destructive-written on two different channels (channel 11 and channel 14). An NALM with 6.6 km dispersion-shifted fiber loop is used. The peak power of the control pulses before entering the loop is about 20 mW, which is easily achieved by a high-power gain-switched DFB laser. The result demonstrates the feasibility of fast channel-tuning and multiplexing for ultrahigh-speed TDMA networks.

IV. Applications

Our fast channel-tunable optical transmitter and the ultrahigh-speed channel multiplexing scheme can be applied to most all-optical time-division multiaccess networks. One example is the time-division tunable-channel multiaccess (TD-TCMA) networks [11], which is a class of multichannel optical bus networks that use local channel tuning to reduce the complexity of the network nodes. In such networks, a centralized pulse source is used at the head node of the optical bus to generate optical pulses at the system bit-rate. Each TDM channel occupies a single bit in every frame. Thus each TDM frame contains a total of M bits when there are M channels in the system. Fig. 9 shows the structure of a TD-TCMA node in a dual-bus topology. Each node consists of two receiving modules and two transmitting modules, one for each bus. The receiving module is permanently connected to a designated channel whereas the transmitting module can be tuned to any output channel. In Fig. 9, the channel-tuning (CT) module can be achieved by using our fast channel-tunable optical transmitter while the gating device (G) can be realized by using an NOLM with our proposed channel multiplexing scheme. So, our work forms the major part of the transmitting module with channel-tunability and ultrahigh-speed channel multiplexing in an ultrahigh-speed all-optical TD-TCMA network.

V. Conclusion

In conclusion, we have proposed and experimentally demonstrated a fast channel-tunable optical transmitter and an ultrahigh-speed channel multiplexing scheme. The channel-tunable optical transmitter is simple and cost-effective while the channel multiplexing scheme can relax the timing requirement. They can be applied to most all-optical TDM systems such as TD-TCMA networks. Therefore these schemes are quite useful in realizing a practical ultrahigh-speed all-optical time-division multiaccess network.

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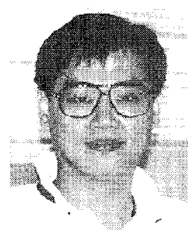

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