Demultiplexing of 80-Gb/s Pulse-Position Modulated Data With an Ultrafast Nonlinear Interferometer

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***Abstract*—Pulse-position modulation may be used to reduce patterning effects arising from gain saturation in all-optical switches employing semiconductor optical amplifiers. We present a novel technique for return-to-zero pulse-position modulation of data suitable for use in optical time-division–multiplexed (OTDM) networks. We demonstrate two methods for all-optical demultiplexing of a pulse-position modulated data stream using an ultrafast nonlinear interferometer. Errorfree operation is obtained for demultiplexing from OTDM data rates as high as 80 Gb/s with control pulse energies of 25 fJ.**

***Index Terms*—Demultiplexing, gain saturation, optical switches, pulse position modulation, semiconductor optical amplifiers, time-division multiplexing.**

I. Introduction

As THE CHANNELIZED data rates in optical networks continue to increase, all-optical logic is expected to play an important role in the development of future networks. All-optical logic has been demonstrated for network tasks such as synchronization, header processing, and demultiplexing. Inteferometric logic gates based on gain and index nonlinearities in semiconductor optical amplifiers (SOAs) are of particular interest due to their compact size, low latency, low required switching pulse energies, and potential for large-scale integration (see, for example [1]–[3]). However, interband carrier dynamics in the semiconductor lead to gain-saturation effects that recover on a time scale of $\sim$100 ps. This recovery time is comparable to or slightly longer than the bit period for channel rates of $\sim$10 Gb/s or higher, and can cause intersymbol interference (ISI) at the output of the switch.

Various balanced interferometer designs have been used to compensate for the long-lived index changes in the semiconductor [4]–[6]. However, gain-saturation remains a problem and leads to pattern-dependent amplitude modulation at the output of the switch. Several methods for reducing the effects of gain-saturation in SOAs used for inline amplification of nonreturn-to-zero (NRZ) systems have been recently proposed [7], [8]. These techniques maintain a constant intensity in the SOA by modulating both the data and the inverse data on orthogonal polarizations or wavelengths. They are not easily extended to return-to-zero (RZ) formats, such as those used in optical time-division-multiplexed (OTDM) networks.

By contrast, pulse-position modulation (PPM) is a modulation format with a constant energy-per-bit that can be easily implemented in existing OTDM architectures. With PPM, a pulse exists in every bit slot, ensuring a constant energy-per-bit. Information is conveyed via the temporal placement of the pulse within the bit slot. In the present work, we use a binary PPM format where a pulse in the first half of the bit slot represents a ZERO, while a pulse in the second half of the bit slot represents a ONE. Thus, at a data rate of 80 Gb/s (12.5 ps/bit), the difference in arrival time between a ONE and a ZERO is only 6.25 ps. Since this is much shorter than the gain recovery time of the SOA, patterning due to gain saturation is greatly reduced as compared to other intensity modulation formats [9]. Recently, an OTDM system demonstration using a PPM data format has been presented [10]. Here we present a method for generating optical binary return-to-zero pulse-position modulated data. We also demonstrate two techniques for demultiplexing OTDM PPM data at rates as high as 80 Gb/s using an SOA-based ultrafast nonlinear interferometer (UNI) [6].

II. Experiment

To generate a pseudorandom stream of binary PPM pulses, we use the setup shown in Fig. 1(a). A mode-locked fiber laser (MLFL) emitting pulses at a repetition rate of 10 GHz is used as the input to a 2×2 $LiNbO_3$ modulator. A 10-Gb/s NRZ pseudorandom binary sequence (PRBS) from a pulse pattern generator (PPG) causes the modulator to switch between cross and bar states. This produces an RZ on–off-keyed (OOK) version of the data in one output arm of the switch, and the inverse of the data in the other output of the switch. A variable optical delay line in one of the arms introduces the temporal PPM offset. The two pulse streams are then recombined in a 50/50 polarization-maintaining coupler to produce the PPM data stream. Fig. 1(b) shows an experimental autocorrelation of a 10-Gb/s PPM PRBS. Here, the PPM offset of 6.25 ps was chosen to allow the modulated pulses to be passively multiplexed to data rates as high 80 Gb/s.

Fig. 2 shows the standard experimental setup for demultiplexing with the UNI [6]. In this setup, the data at the aggregate OTDM rate of $N \cdot 10$ Gb/s is used as the signal input to the UNI. Control pulses at 10-GHz gate the incoming signal data, routing every N-th pulse to the output of the switch. Pulses from a MLFL producing a 10-GHz stream of transform-limited 2-ps pulses at 1550 nm are modulated with a 10-Gb/s PPM data pattern of $2^{31} - 1$ bits. The temporal PPM offset is 6.25 ps. These pulses are then passively multiplexed to rates of 10, 20, 40, or 80 Gb/s using a free-space multiplexer with multiple-bit delays to

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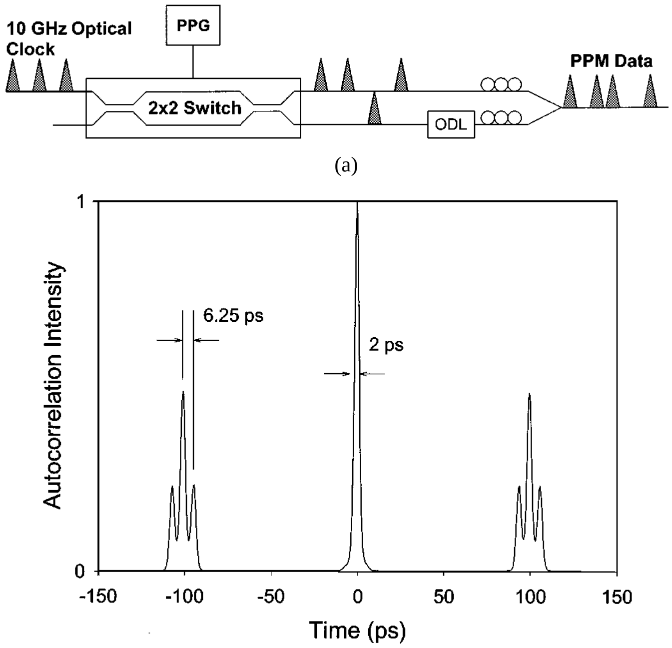

(b)

Fig. 1. Pulse position modulation generation. (a) Modulator schematic. (b) Autocorrelation of 10-Gb/s pulse-position modulated pseudorandom bit sequence of 2-ps pulses. PPG: Pulse pattern generator. ODL: Optical delay line.

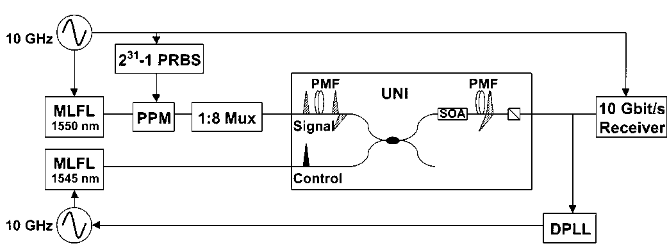

Fig. 2. Experimental setup for demultiplexing of data on signal input of UNI. MLFL: Mode-locked fiber laser. PPM: Pulse-position modulator. PMF: Highly birefringent polarization-maintaining fiber. DPLL: Dithering phase-locked loop.

provide the signal input to the UNI. A second MLFL producing a 10-GHz stream of 2-ps pulses at 1545 nm is used as the control input to the UNI. A dithering phase-locked loop (DPLL) is used to maintain bit-phase alignment between the control and signal pulses. The DPLL applies a 1-kHz phase modulation to the RF synthesizer driving the control MLFL. The temporal shape of the UNI switching window converts the 1-kHz bit-phase modulation to an amplitude modulation at the output of the UNI. The DPLL adjusts the DC signal into the phase modulator to minimize the 1-kHz tone at the output, thereby aligning the signal pulses to the maximum transmission point of the switching window. The commercially available SOA used in the experiment is a 1-mm-long InGaAsP device. The SOA bias current is 150 mA, providing a fiber-to-fiber gain of 28 dB at 1550 nm. The birefringent fiber length in the UNI is chosen to provide a switching window duration of 5 ps. Because the switching window duration is less than the PPM offset, the control pulses may be temporally aligned to gate exclusively the ONE's in the overlapped channel of the aggregate OTDM data, thus providing a format conversion to 10-Gb/s OOK modulation

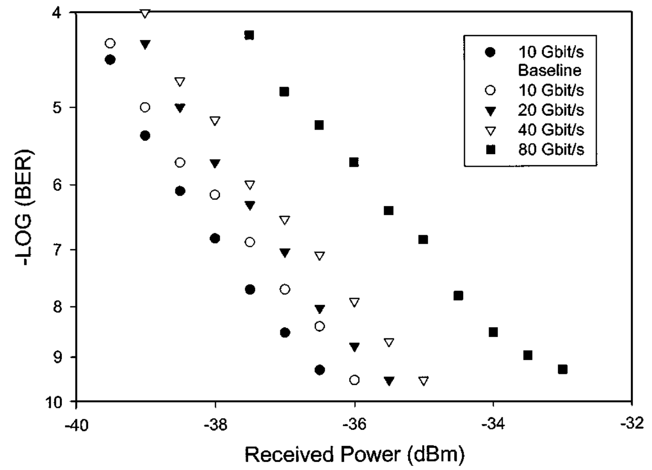

Fig. 3. Bit-error-rate performance for demultiplexing from aggregate PPM data rates of 10, 20, 40, and 80 Gb/s on signal input to UNI.

at the output of the demultiplexer. A longer switching window could be used to maintain the PPM format.

The results of bit-error-rate (BER) tests performed at the attenuated output of the switch using a 10-Gb/s OOK optically preamplified receiver are shown in Fig. 3. The baseline is measured using the OOK data directly from one of the arms in the PPM modulator shown in Fig. 1(a). The control pulse and signal pulse energies in the demultiplexing experiments were maintained at 500 and 12.5 fJ, respectively. For aggregate PPM data rates up to 40 Gb/s, a maximum power penalty of 1.2 dB at a BER of 10^{-9} is observed. This penalty is largely due to the wavelength selectivity of the receiver, imperfect contrast of the demultiplexer, and increased saturation of the SOA as the signal data rate is increased. The larger power penalty of 3 dB observed at 80 Gb/s is due to intersymbol interference (ISI) in the UNI. This arises due to the fact that signal pulses in the UNI are split into orthogonally polarized pairs, temporally separated by 5 ps by the birefringent fiber. Because of the PPM data format, pulses in the data stream may be separated by as little as 6.25 ps. Thus, adjacent pulse overlap may occur in the UNI leading to the observed ISI. This effect may be mitigated by reducing the length of birefringent fiber in the UNI, thereby reducing the temporal separation of the signal pulse pairs in the SOA.

Because the use of PPM data reduces gain-saturation-induced patterning in the UNI, demultiplexing may also be performed with data at the aggregate rate ($N \cdot 10$ Gb/s) used as the control input to the UNI, as shown in Fig. 4. In this configuration, the UNI acts as a wavelength converter, converting every N-th control pulse to the signal wavelength. As in the previous demonstration, signal and control pulses are provided at 10-GHz repetition rates by two MLFLs producing 2-ps pulses at 1550 and 1545 nm. The control pulses are modulated with a PPM data pattern. To demonstrate the pattern independent operation of the switch, a long data pattern of length $2^{31} - 1$ is used. The PPM data is then passively multiplexed to rates of 10, 20, 40, and 80 Gb/s, and input to the control port of the UNI. As in the first demonstration, the UNI switching window duration of 5 ps provides a format conversion from PPM to OOK at the output of the UNI. In this setup, maintaining the PPM data format at the

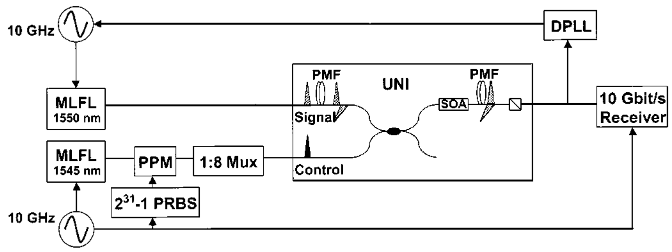

Fig. 4. Experimental setup for demultiplexing of data on control input of UNI. MLFL: Mode-locked fiber laser. PPM: Pulse-position modulator. PMF: Highly birefringent polarization-maintaining fiber. DPLL: Dithering phase-locked loop.

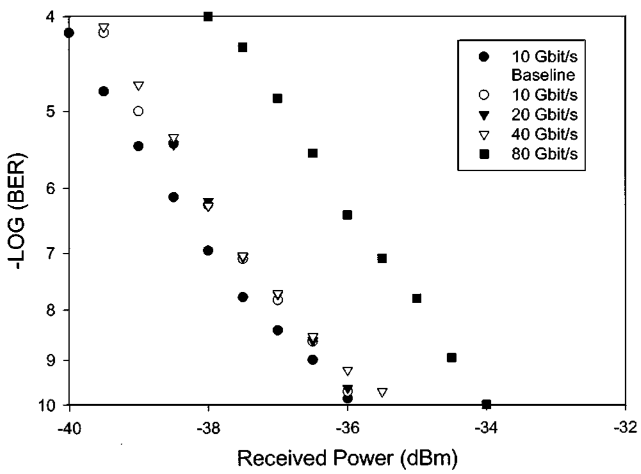

Fig. 5. Bit-error-rate performance for demultiplexing from aggregate PPM data rates of 10, 20, 40, and 80 Gb/s on control input to UNI.

output of the switch would require splitting each signal pulse into two pulses separated by the PPM offset.

The results of BER tests at the output of this demultiplexer are shown in Fig. 5. Errorfree operation $(\mathrm{BER} < 10^{-9})$ is obtained for all aggregate data rates with control and signal pulse energies of 25 and 12.5 fJ, respectively. Because the signal pulses are at the demultiplexed rate, the contrast ratio of the demultiplexer between signal pulses is not as important in this experiment as compared to the first demultiplexing experiment. Thus, good performance is obtained with significantly reduced control pulse energies. For aggregate control pulse data rates of up to 40 Gb/s, a small power penalty of $<$0.5 dB from baseline is observed. Since the data pulses on the control input are not temporally separated in the UNI, the intersymbol interference observed in the first demultiplexing experiment is not present in this experiment. At 80 Gb/s, the power penalty of 2 dB is thought to be a result of the increased saturation of the SOA due to the high average power of the control pulses.

III. Conclusion

Pulse-position modulation provides a means for mitigating the effects of gain-saturation-induced patterning in semiconductor optical amplifiers. A novel technique for generating RZ PPM formatted optical data using a commercially available $LiNbO_3$ modulator has been presented. Errorfree demultiplexing and format conversion of OTDM PPM data at rates as high as 80 Gb/s has been demonstrated. With the 2-ps pulses used in this experiment, we expect that this technique can be scaled to demultiplex PPM data at rates as high as 160 Gb/s. Beyond 160 Gb/s, shorter pulsewidths will be required for optimal performance. The use of the PPM data format reduces the deleterious effects of gain-saturation in the SOA, thus reducing the required switching energies in the UNI and improving receiver sensitivity. Additionally, the PPM data format allows for demultiplexing to be performed with the data at the aggregate rate on the control input to the UNI, providing simultaneous demultiplexing, wavelength conversion, and format conversion. Such a device may be useful in optical networks for a variety of functions such as wavelength conversion, 3R-regeneration, and OTDM-to-WDM conversion.

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