WDM to OTDM Multiplexing Using an Ultrafast All-Optical Wavelength Converter

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***Abstract*—A robust and scalable all-optical multiplexer combining four 10-Gb/s WDM channels into one 40-Gb/s OTDM channel is presented. The multiplexer generates a coherent output data stream, which does not suffer from channel interference as passively generated OTDM data do.**

***Index Terms*—Fiber optics, optical multiplexing, optical networks.**

I. Introduction

THE RAPID increase in the demand for more optical transmission bandwidth has led to a great interest in increasing the bit rate of individual data channels in wavelength–division-multiplexed (WDM) networks. The highest bit rate of single channel transmitters in deployed networks today is 10 Gb/s, even though 40-Gb/s transmitters are expected in the near future. An alternative way to accomplish higher bit rates is to optically time-division-multiplex (OTDM) multiple 10-Gb/s return-to-zero (RZ) data streams together using passive-time interleaving multiplexers. The traditional method of doing this is by having a 10-GHz clock source, usually a mode-locked or gain-switched laser, generates short pulses and splits the clock signal into the desired number of channels, and subsequently encode data on each of them. All channels are then time interleaved in optical combiners with appropriate time delays between each channel. The main problem with this method is that very high quality clock pulses are necessary to avoid interference problems between adjacent channels [1], leading to a variation in pulse amplitude and, if the pulses are not perfectly coherent, a time varying drift in amplitude. In practice, very short pulses, typically less than one quarter of a bit slot with high extinction ratio ($>$30 dB) are required to achieve a noiseless OTDM data sequence. Here, we demonstrate a multiplexer that takes four channels from a WDM transmitter with nonreturn-to-zero (NRZ) format and convert them to NRZ format, and subsequently wavelength convert all four WDM channels to one wavelength to obtain one OTDM channel. The advantage of this scheme is that existing WDM transmitter technology can be used, while increasing the single channel transmission bit rate, as well as eliminating some problems with passive OTDM multiplexing. For example, the long coherence length of the local laser determines the coherence length of the output optical data. WDM to time-division-multiplexing (TDM) conversion has previously been demonstrated using semiconductor optical amplifier (SOA) technology [2], as well as using the nonlinear optical loop mirror (NOLM) [3]. However, the SOA technology has a limited frequency response and even at 40 Gb/s, it is difficult to obtain short enough pulses at the output to constitute a RZ signal. The NOLM is in general, not suitable for wavelength conversion, since the pulses that induce cross-phase modulation (XPM) have to be very short compared to the bit slot to avoid crosstalk due to unwanted XPM from the high average power [4].

In this experiment, we use an ultrafast wavelength converter based on XPM in an optical fiber [5], which in principle can allow operation at several hundred gigabits [6]. An advantage with this scheme is that the requirements on the RZ pulses are lower due to the nonlinear transfer function of the wavelength converter, which allows pulses with moderate extinction ratio to be used. The output of the wavelength converter is given by the derivative of the input signal, which also allows broader pulses to be used at the input.

II. Experimental Results and Discussion

The basic idea is to demonstrate conversion of 4·10 Gb/s WDM channels to one 40-Gb/s OTDM channel. Fig. 1 shows the experimental setup used for the multiplexer demonstration. Four tunable lasers generated continuous-wave (CW) light at 1544.0, 1545.6, 1547.2, and 1548.8 nm. 10-Gb/s pseudorandom bit stream (PRBS) NRZ data with a word length of $2^{31}-1$ was encoded on all wavelengths, and adjacent wavelength channels were encoded with different data. The four WDM channels were then converted to RZ data by injecting the synchronized WDM channels into an electroabsorption modulator (EAM) followed by a 200-m dispersion compensating fiber (DCF) $(D = -67\ \text{ps/nm}\cdot\text{km})$. With this arrangement, pulses with a pulsewidth between 8–9 ps were obtained for all four WDM channels. Care was taken to equalize the output pulsewidth between the channels by adjusting the dc-bias point of the EAM without leading to a significant crosstalk in the EAM. The total loss in the EAM was 25 dB at the chosen operating point, and it was a tradeoff between maximum allowed input power to avoid crosstalk in the EAM, and signal-to-noise ratio (SNR) at the output of the following erbium-doped fiber amplifier (EDFA). Here the total average power into the EAM was +9 dBm, which

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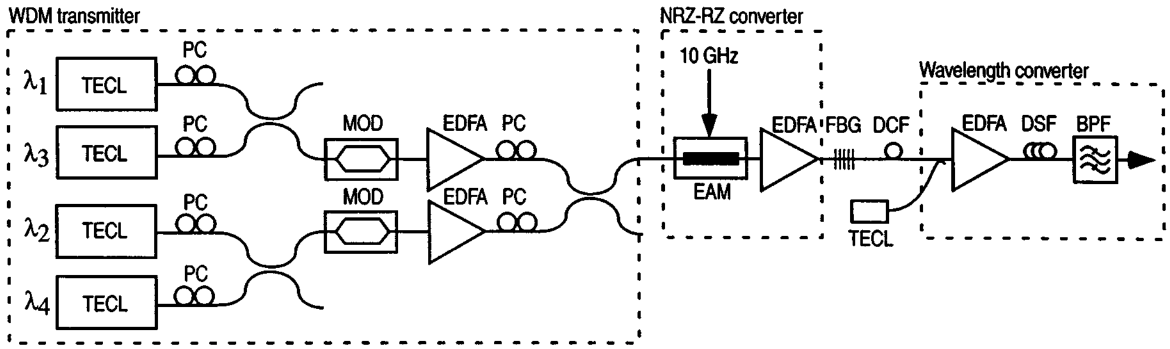

Fig. 1. Experimental setup. TECL: Tunable external cavity laser. PC: Polarization controller; MOD: $LiNbO_3$ external modulator. EDFA; EAM; FBG; DCF; DSF: Dispersion shifted fiber. BPF: 0.4-nm optical bandpass filter.

gave rise to a moderate crosstalk between the WDM channels. The DCF after the EAM served as a pulse compressor, since the pulses from the EAM had some positive chirp, but also to align the four RZ data channels to be delayed 25 ps between each channel. By looking at the four wavelength channels in the time domain, e.g., with a high-speed oscilloscope, the signal looked like a 40-Gb/s OTDM data stream, even though each channel resides on a different wavelength. Since the EDFA after the EAM added noise, a fiber Bragg grating (FBG) was used to remove amplified spontaneous emission (ASE) noise at the wavelength of the output of the wavelength converter. The WDM RZ signals were then combined with CW light at 1554.5 nm and amplified in an EDFA to an average power of 350 mW. An 850-m dispersion shifted fiber (DSF) with a zero dispersion wavelength of 1550 nm was used to impose a phase modulation onto the CW light by XPM in the fiber. This phase modulation was then converted to amplitude modulation by a filter arrangement, which consisted of a FBG to remove the intense original data channels signals, as well as an optical bandpass filter to select one of the generated side bands of the CW light [5]. The output 40-Gb/s OTDM data were investigated using a 40-GHz photo detector on a 50-GHz sampling oscilloscope. An EAM driven at 10 GHz was used to demultiplex the 40-Gb/s data to 10 Gb/s, where bit-error-rate (BER) measurements were performed.

Fig. 2 shows the optical spectrum at various points of the system. The solid line shows the spectrum into the wavelength converter with the four 10-Gb/s RZ signals and the CW light, the dashed line shows the spectrum after the DSF in the wavelength converter, and the dotted line shows the output signal from the wavelength converter. Fig. 3(a) shows the eye pattern of the 4×10 Gb/s WDM channels after the EAM and the DCF. Although each channel is on its own wavelength, they now look like a 40-Gb/s OTDM data stream. Fig. 3(b) shows the output 40-Gb/s OTDM data after the wavelength converter, which is a clearly open 40-Gb/s eye pattern. BER measurements were performed on the output 40-Gb/s data by demultiplexing the data into four 10-Gb/s data channels and the BER of all four channels were measured and are presented in Fig. 4. Fig. 4 also shows the back-to-back measurements for one of the original 10-Gb/s channels after conversion from NRZ to RZ without the presence of the other WDM channels in the EAM. A 3-dB receiver penalty at a BER of 10^{-9} was observed for all channels in the

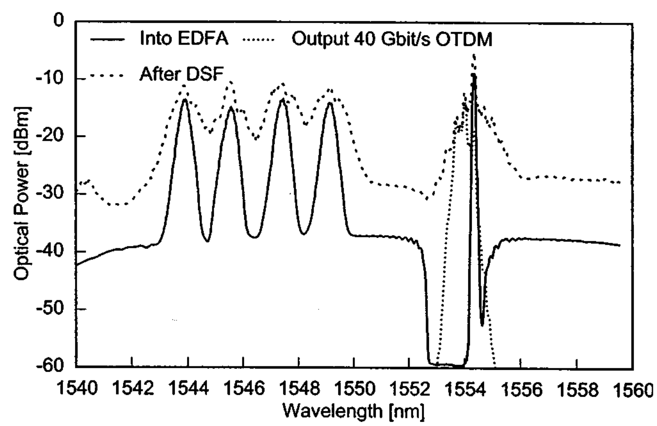

Fig. 2. Spectrum of the input signal to the EDFA in the wavelength converter (solid line), spectrum after the DSF (dashed line), and spectrum of the output 40-Gb/s OTDM data (dotted line). The output extinction ratio is >20 dBm.

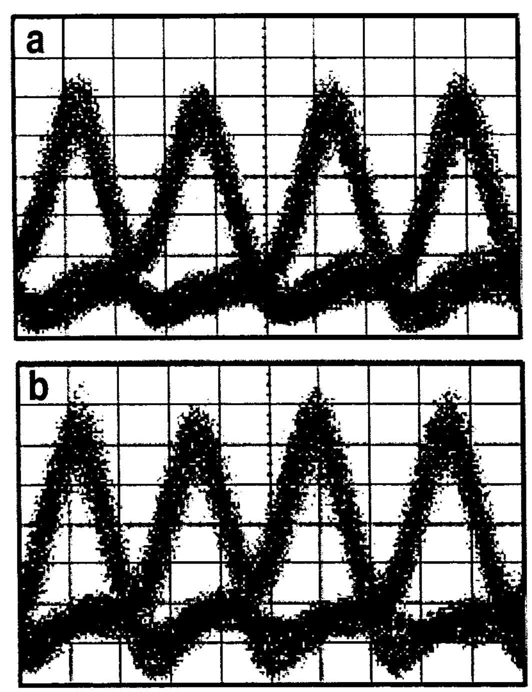

Fig. 3. (a) Eye patterns of the 4·10-Gb/s WDM channels before wavelength conversion. (b) The output 40-Gb/s OTDM data after wavelength conversion.

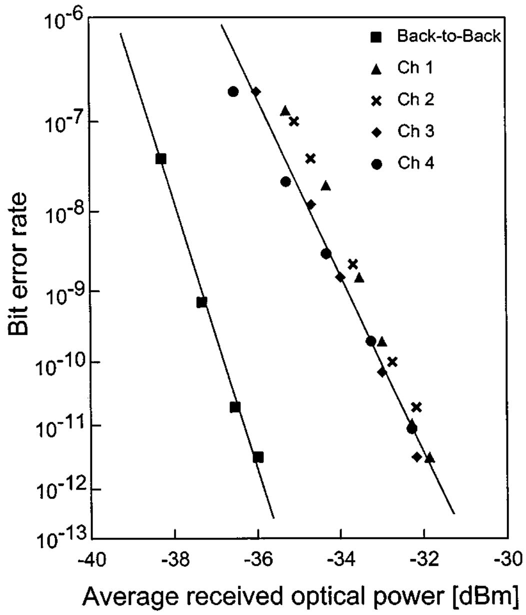

Fig. 4. BER measurements of one input 10-Gb/s channel, back-to-back (■), and the four channels of the output 40-Gb/s OTDM data stream.

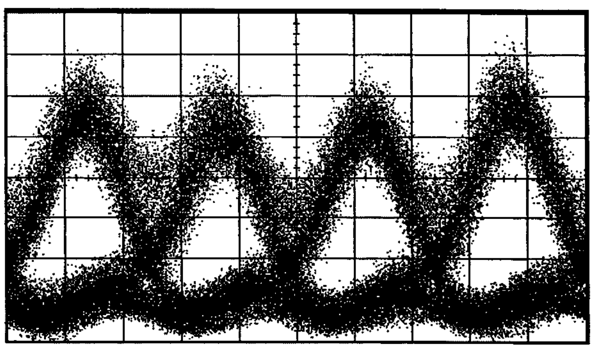

Fig. 5. 10-Gb/s RZ data sent through a passive 10–40-Gb/s OTDM multiplexer. The extinction ratio of the pulses in approximately 20 dB (10 ps/div).

output 40-Gb/s OTDM data. This penalty is primarily due to crosstalk between the WDM channels in the first EAM in the NRZ to RZ conversion process, and also partly due to the high loss in the EAM, which decreases the signal-to-noise ratio (SNR) after the following EDFA. We believe that an EAM with less total insertion loss would eliminate this penalty since a higher SNR would then be maintained and the input power into the EAM can be lower to reduce the crosstalk.

An advantage with this wavelength converter scheme is that only moderate requirements on the input RZ-data channels are required, since the transmission through the wavelength converter is nonlinear and conversion is only intensity dependent. This means that the extinction ratio of the RZ pulses is not critical. The output data is now perfectly coherent and no interference effects occur between adjacent channels in the OTDM pulse train, which can be present in classic passive OTDM multiplexers. To demonstrate the difference between the presented multiplexer and a passive OTDM multiplexer, the 10-Gb/s RZ-data of channel 1 was sent into a passive split-and-interleave 10–40-Gb/s multiplexer. Fig. 5 shows the output 40-Gb/s eye pattern of that OTDM multiplexer and the eyes are heavily distorted and unstable due to interference between adjacent pulses, which occurs due to a limited ER from the pulse source (ER 20 dB).

III. Conclusion

A novel WDM to OTDM multiplexer using an ultrafast wavelength converter is presented. The multiplexer allows high quality conversion from four NRZ WDM channels at 10-Gb/s to one 40-Gb/s OTDM channel. The 3-dB power penalty observed in the output 40-Gb/s data stream can be eliminated if an EAM with lower loss or higher saturation power is obtained. The system is scalable both in terms of the number of input channels, only limited by the bandwidth of the wavelength converter [6], as well as to higher input bit rates in the incoming WDM channels.

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