Simultaneous All-Optical Demultiplexing of a 40-Gb/s Signal to 4 × 10 Gb/s WDM Channels Using an Ultrafast Fiber Wavelength Converter

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***Abstract*—We demonstrate simultaneous demultiplexing of a 40-Gb/s optical time division multiplexed stream to four 10-Gb/s data streams, each on a different wavelength, using a single ultrafast nonlinear fiber wavelength converter. The wavelength converter employs cross-phase modulation in a dispersion-shifted fiber and utilizes control pulses generated at four wavelengths by a single electroabsorption modulator. This technique can be scaled to demultiplex a very high bit-rate signal to multiple wavelength division multiplexed channels simultaneously using just one electroabsorption modulator and one fiber based wavelength converter. Additionally broad control pulses with limited extinction ratio do not adversely affect the performance of the demultiplexer. For a control pulsewidth of 11–12 ps, the measured power penalty is $<$1.5 dB. Increasing the control pulsewidth to 14 ps incurs an additional power penalty of only 0.5 dB.**

***Index Terms*—Demultiplexing, nonlinear optics, optical fiber communication, time-division multiplexing, wavelength conversion, wavelength division multiplexing (WDM).**

I. Introduction

All-optical demultiplexing of high-speed optical time-division multiplexed (OTDM) channels into lower speed wavelength-division-multiplexed (WDM) data streams is an important function for future high-speed DWDM optical networks. This function and its complement (WDM to OTDM multiplexing) form the broader class of all-optical transmultiplexing that interface WDM and OTDM transmission systems and networks [1]. In this letter, we demonstrate a novel scheme of simultaneous demultiplexing a 40-Gb/s OTDM data stream to 4 × 10 Gb/s WDM channels using wavelength conversion through cross-phase modulation (XPM) in 500 m of dispersion-shifted fiber (DSF), which has been described in [2], and using pulses generated from an electroabsorption modulator (EAM). The wavelength conversion technique has the potential to work at ultrahigh bit-rates ($>$100 Gb/s) because its operation is based on fast-fiber nonlinearities. The EAM is operated in travelling wave configuration [3] and has a modulation efficiency of 20 dB/V and total extinction ratio $>$15 dB. Previously demonstrated multichannel demultiplexing approaches include monolithic InP Mach–Zehnder interferometer converters [4], four wave mixing (FWM) in semiconductor optical amplifiers [5] and FWM via supercontinuum light source generation in a highly nonlinear fiber [6]. In this letter, we have demonstrated wavelength conversion over 10 nm. With the appropriate fiber design, this range can be extended to cover the entire *C*-band. A multiwavelength laser can be integrated with a broad band high-speed electroabsorption modulator to obtain an integrated multichannel pulse source. The advantage of this technique is the potential to operate at very high bit rates and over a wide range of wavelengths. Using a highly nonlinear fiber can lower the requirements on the peak power required for conversion.

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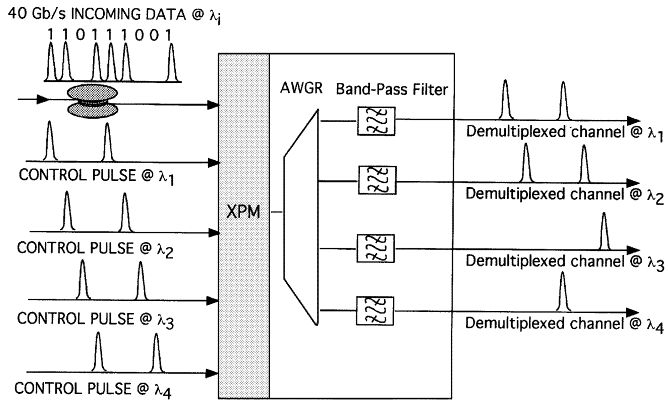
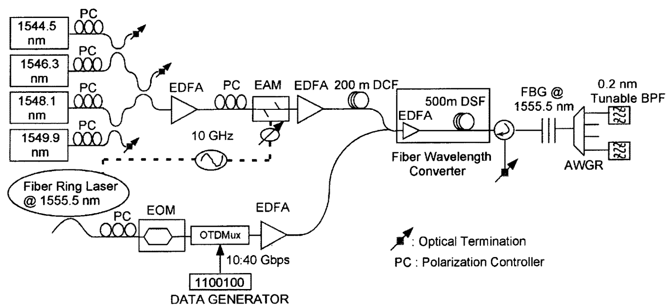
II. Principle of Operation

The demultiplexer operates on the principle of XPM within DSF as explained in Fig. 1(a). Consider an N-channel return-to-zero (RZ) OTDM data stream at an input wavelength λ_i and bit-rate B Gb/s, which is to be demultiplexed into lower bit rate channels, each on a different output wavelength λ_{1-N}. The N WDM local control pulses are generated by a set of continuous-wave (CW) fixed frequency lasers that are combined and then pulse modulated by a single EAM at the repetition rate B/N with a switching window slightly larger than the input OTDM pulses. At the output of the EAM are N temporally overlapping WDM control pulses at frequency B/N. A dispersive delay line (optical fiber) is used to separate these pulses into N temporally discrete clock channels each ($1/B$) ns apart. The EAM switching window is synchronized with the input OTDM data using a clock recovery in order to time align the skewed WDM control pulses with the OTDM input. Both WDM control pulses and OTDM pulses are copropagated in the DSF such that every WDM control pulse overlaps with one of the time channels from the incoming data stream.

The incoming intensity modulated OTDM signal generates double sidebands on each WDM channel (via XPM) corresponding to the data in the synchronized time slot. One of these sidebands is filtered to convert phase modulation to amplitude modulation. A WDM filter, such as an arrayed wave-guide router (AWGR) of appropriate filter bandwidth, can be used to simultaneously filter and separate the sidebands for all WDM channels.



(a)



(b)

Fig. 1. (a) Principle of simultaneous demultiplexing operation. (b) Experimental setup to demonstrate simultaneous demultiplexing.

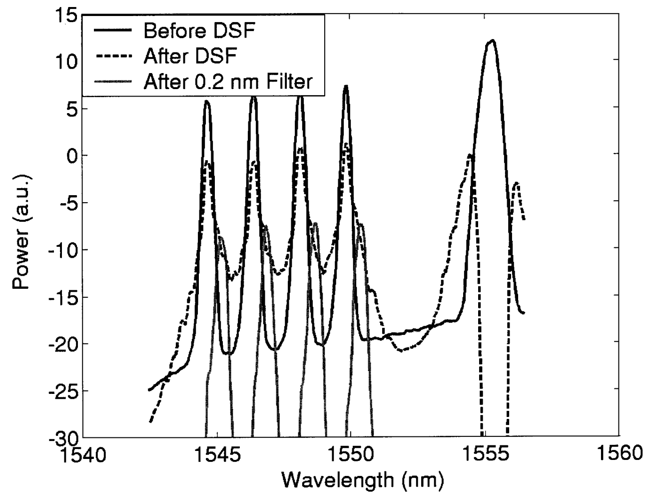


Fig. 2. Optical spectrum at various points in the system.

The efficiency of XPM conversion depends on the differential group delay between the two wavelengths and the peak power of the incoming signal. In 500 m of DSF, the peak power requirement is about 3 W for maximum efficiency and the range of wavelength conversion is nearly 20 nm on either side of the zero-dispersion wavelength. The range of wavelength conversion would be greater in a shorter length of fiber, since the differential group delay between two wavelengths is smaller [7]. Thus, a shorter length of highly nonlinear fiber could be used to scale the system to higher bit-rates and a greater number of WDM channels as well as to reduce the power requirement.

III. Experimental Setup and Results

The experimental setup is shown in Fig. 1(b). A 10-Gb/s optical data stream is generated by encoding $2^{31} - 1$ PRBS data onto a continuous stream of 8-ps pulses generated from an actively mode-locked fiber ring laser (FRL) at 1555.5 nm and a 10-GHz repetition rate. The modulated 10-Gb/s pulsed data stream is multiplexed up to 40 Gb/s using a split, delay, and time interleave multiplexer. The WDM source consists of four CW lasers with output wavelengths separated by 1.8 nm. An EAM is used to generate WDM pulses at 10 GHz at the four wavelengths. The microwave power and the DC bias applied to the EAM are adjusted so that the pulsewidth and the extinction ratio are approximately the same for all of the four wavelength channels. The pulsewidths measured at the EAM output are in the range of 16–17 ps with measured extinction ratios greater than 15 dB. The EAM loss is approximately 20 dB under these operating conditions. The EAM is followed by 200 m of DCF ($D = -67$ ps/nm·km) to delay the four 10-GHz WDM pulse streams by 25 ps with respect to each other, in order to generate a pseudo-40-GHz pulse train. The output pulses are compressed to 11–12 ps after the DCF since the pulses from the EAM are positively chirped. The 40-Gb/s OTDM data and the four WDM 10 Gb/s pulse train are combined using a 50 : 50 coupler and amplified to 600 mW prior to being launched into 500 m of DSF. The ratio between the input data signal and the WDM pulse train is approximately 1 : 1.5, which has been optimized for maximum wavelength conversion efficiency. A circulator and a fiber Bragg grating (FBG) arrangement is used at the output of the DSF to filter out the high-power pump signal. At the output of the FBG, an AWGR is used to separate the different WDM channels. A narrowband 0.2-nm bandpass filter, centered at the sideband associated with each WDM channel was used to convert the phase modulated signals into intensity modulated RZ 10-Gb/s signals. Fig. 2 shows the optical spectrum at the input of the DSF indicated by the solid line, the phase broadened optical spectrum after the DSF indicated by the dashed line and the spectra after the 0.2-nm filter as indicated by the gray line. The four demultiplexed WDM channels are recovered using an optically preamplified receiver, which includes a 0.6-nm optical bandpass filter. The eye diagrams for the incoming OTDM signal and the four demultiplexed channels obtained with a 40-GHz photodetector on a 50-GHz-sampling oscilloscope are shown in Fig. 3(a)–(e). The demultiplexed pulses are broader as compared to the input pulses due to the narrow band optical filter.

Measured bit error rate (BER) curves for the original 10-Gb/s data filtered using a 0.2-nm bandpass filter (back-to-back) and the four demultiplexed 10 Gb/s are shown in Fig. 4. There is a maximum penalty of 1 dB (at BER 10^{-9}) observed between the back-to-back and one of the four demultiplexed channels. The power penalty can be attributed to the channel interference due to passive multiplexing to generate OTDM data, the high loss in the EAM, which decreases the SNR of the generated control pulses after amplification and the process of demultiplexing. Due to the fact that both the EAM and the wavelength converter are polarization sensitive, the polarization dependence of the system is approximately 2–3 dB. Unlike in other schemes, the

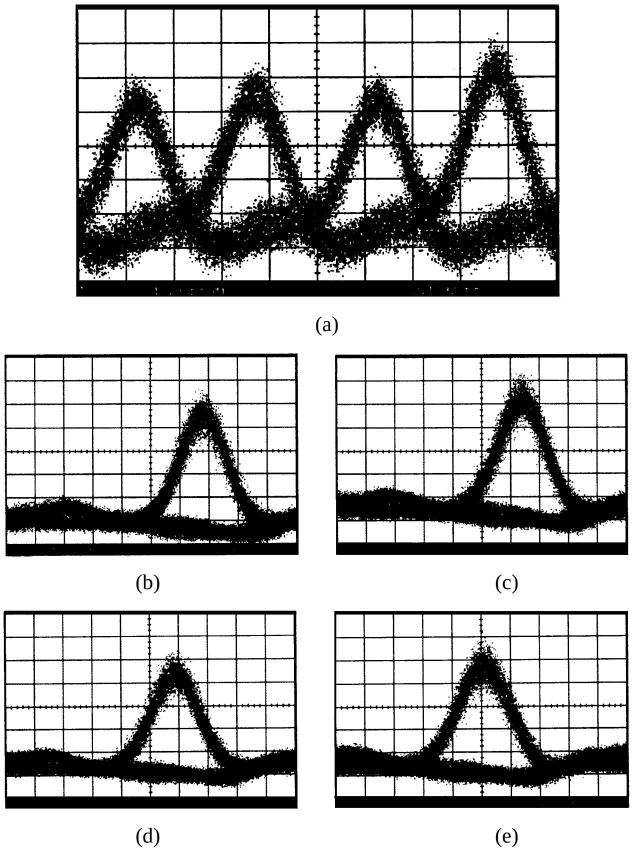


Fig. 3. (a) Input 40-Gb/s OTDM signal. (b) Demultiplexed 10-Gb/s eye at 1544.5 nm. (c) Demultiplexed 10-Gb/s eye at 1546.3 nm. (d) Demultiplexed 10-Gb/s eye at 1548.1 nm. (e) Demultiplexed 10-Gb/s eye at 1549.9 nm.

demultiplexing window in this technique is determined by the pulse-width of the incoming data signal, thus the local clock pulses can be quite broad. An additional power penalty of 0.5 dB was incurred when the control pulsewidth was increased to 14 ps. Thus, the demultiplexer receiver is robust with respect to the control pulsewidths. Recently, we have demonstrated a switching window of 7.0 ps at 10 GHz [8] and with appropriate device engineering, the switching window can be further reduced. Thus, this technique can potentially be scaled to 160 Gb/s.

IV. Conclusion

We have successfully demonstrated a new approach to simultaneously demultiplex 40-Gb/s data onto four different 10-Gb/s data streams using XPM in DSF. The local clock pulsewidths for 40-Gb/s operation range from 11–12 ps and can be as broad as 14 ps. A maximum power penalty of 1 dB is obtained for the worst demultiplexed channel. This technique can be scaled for higher bit rates and a greater number of WDM channels by using a shorter length of highly nonlinear fiber and multiwavelength laser arrays.

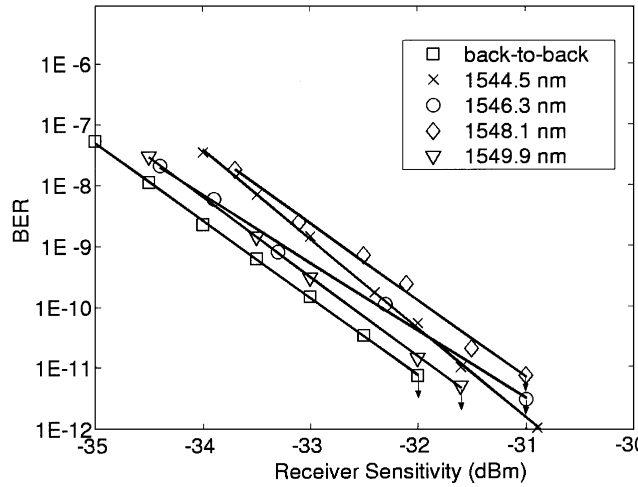


Fig. 4. BER curves for back-to-back and the four simultaneously demultiplexed outputs.

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