All-Optical Demultiplexing Using Fiber Cross-Phase Modulation (XPM) and Optical Filtering

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***Abstract*—All-optical demultiplexing of 80-Gb/s data to 10 Gb/s is demonstrated using spectral broadening-induced by cross-phase modulation (XPM) with subsequent optical band-pass filtering. Due to the time derivative effect of XPM, the control pulsewidth can be larger than the bit-slot of the incoming data, and still give a switch window suitable for demultiplexing. Operation at 10^{-12} bit-error rate is demonstrated. In principle, this approach will scale to extremely high bit rates due to the ultrafast fiber nonlinearities.**

***Index Terms*—Cross-phase modulation, fiber nonlinearities, optical demultiplexing, optical filtering, optical networks, optical time-division multiplexing, optical-wavelength conversion.**

I. INTRODUCTION

FUTURE ultrahigh bit-rate optical time division multiplexed (OTDM) systems may require all-optical demultiplexing to down convert the high bit-rate data to, e.g., 10 or 40 Gb/s where electronic circuits can be used. Many examples of such demultiplexers have been proposed over the years. The most common device is the nonlinear optical loop mirror (NOLM) that allows switching due to cross-phase modulation (XPM), in either a fiber [1] or a semiconductor optical amplifier (SOA) [2]. Another approach is to use four-wave-mixing (FWM) in either an SOA or a fiber [3]. In all these schemes, the switch window for the demultiplexed OTDM channel can usually not be shorter than the pulsewidth of the control pulse that initiates the XPM or FWM, and thus, a very short high-quality optical pulse is required [4].

In this letter, we demonstrate a new 1550-nm waveband demultiplexer based on XPM in a fiber that utilizes the time derivative effect of XPM-induced spectral broadening. Low bit-error-rate (BER) operation ($<10^{-12}$) is demonstrated with 80-Gb/s data optically demultiplexed to 10 Gb/s. In principle, this approach will scale to extremely high bit rates, in excess of 160 Gb/s, due to the ultrafast fiber nonlinearities. This approach is based on optically induced frequency shifting of the modulated input signal with a control pulse. The leading edge of the control pulse, generates a red shift of the spectrum of the XPM modulated input signal, and the trailing edge generates a blue shift. Optically-induced frequency shifting has previously been demonstrated for pulses at an 980-nm 82-MHz repetition rate using a resonantly-excited semiconductor nonlinear waveguide combined with an optical filter [5], however, demonstration at communications bit rates (10 Gb/s) and wavelength with real data, was not investigated and only single-pulse operation shown.

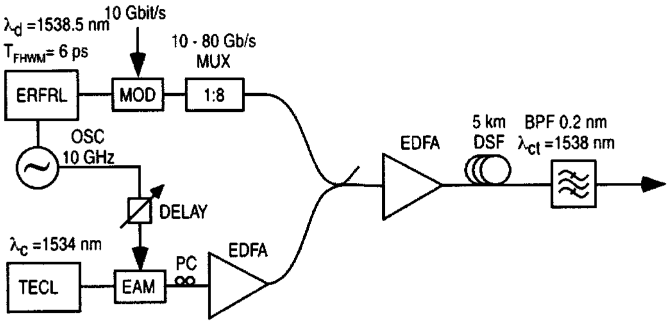

Fig. 1. Experimental setup. ERFRL: Erbium-doped fiber ring laser. MOD: LiNbO3 modulator. MUX: Passive 10–80 Gb/s multiplexer. TECL: Tunable external cavity laser. EAM: Electroabsorption modulator. PC: Polarization controller. EDFA. OSC: 10-GHz microwave oscillator. DELAY: Variable electrical delay. DSF: Dispersion-shifted fiber. BPF: Bandpass filter.

Previously, we have reported wavelength conversion using this technique, where the incoming data modulates the phase of a continuous wave (CW) signal with subsequent conversion to amplitude modulation [6]. In this letter, only one of the OTDM data channels in the high bit-rate data is spectrally broadened, and that channel is extracted using a narrow-band optical band-pass filter (BPF) at either side of the original spectrum. Thus, if dispersive walkoff is neglected, only one edge of the control pulse governs the width of the demultiplexing switch window. Therefore, a control pulse broader than the actual bit slot can be used for demultiplexing. Another important feature of this demultiplexer compared to the interferometric techniques like the NOLM, is its insensitivity to environmental disturbances.

II. EXPERIMENTS

The experimental setup is shown in Fig. 1. An actively mode-locked fiber ring laser generated 6-ps pulses at a 1538.5-nm wavelength with a 10-GHz repetition rate. 10-Gb/s PRBS $2^{31}-1$ data was encoded onto the fiber ring laser output using an external modulator. A passive optical interleaver multiplexer was used to generate an 80-Gb/s data stream. The control pulses were generated using an electroabsorption modulator that output 14-ps pulses at a wavelength of 1534

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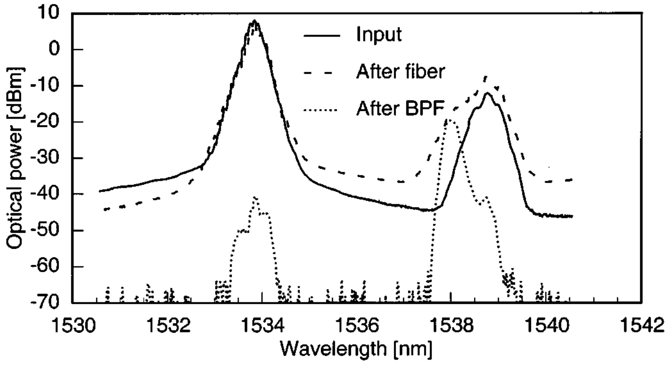

Fig. 2. Optical spectrum at the input of the DSF, after the DSF, and after the 0.2-nm BPF.

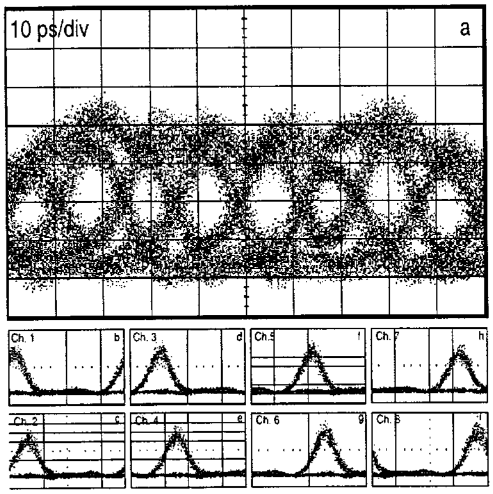

Fig. 3. 80-Gb/s eye pattern. (a) Demultiplexed 10-Gb/s channels (b)–(i). The extinction ratios of the output pulses were estimated to be better than 15 dB.

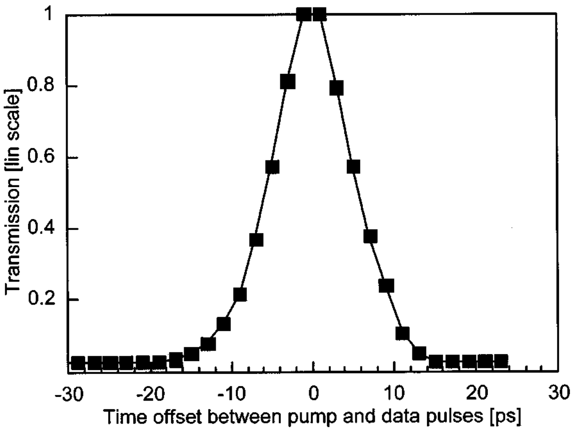

Fig. 4. Measured switch window of the demultiplexer.

nm. The 80-Gb/s data and the control pulses were combined in a 50 : 50 coupler and amplified in an erbium-doped fiber amplifier (EDFA) to +18 dBm average output power. A 5-km dispersion shifted fiber (DSF) with a zero dispersion wavelength of 1543 nm, was used to induce XPM from the control pulses on to one of the 10-Gb/s data channels in the 80-Gb/s data stream.

The optical spectrum was broadened only during the time slot of one 10-Gb/s channel, and that channel was extracted by using a narrow 0.2-nm optical BPF positioned at a center wavelength of 1538 nm. The output from the BPF was then sent to an optically preamplified receiver for inspection on a sampling oscilloscope, as well as for BER measurements. Fig. 2 shows the optical spectra in various points of the system. The solid trace shows the spectrum after the 50 : 50 combiner. The power ratio between the control pulse and the 80-Gb/s data was about 20 dB, to avoid saturation of the EDFA in front of the DSF from the incoming data. The dashed trace shows the spectrum after the DSF, where the spectrum of the 80-Gb/s data is broadened due to XPM from the control pulse. The dotted trace in Fig. 2 shows the filtered XPM broadened spectrum, i.e., the demultiplexed channel at the output. Since the BPF is only 0.2 nm, the output pulsewidth of the demultiplexed data is 17 ps. Fig. 3(a) shows the input 80-Gb/s data eye pattern as measured with a 40-GHz detector on a 50-GHz sampling oscilloscope. Fig. 3(b)–(i) shows the eight demultiplexed 10-Gb/s channels. No crosstalk was present even though the control pulsewidth was 14 ps and the bit-slot at 80-Gb/s is 12.5 ps. The extinction ratios of the output pulses were estimated to be better than 15 dB.

To estimate the actual switch window in the device, the cross correlation between a 6-ps data pulse and a 14-ps control pulse was measured. Fig. 4 shows the measured cross correlation between the two pulses in the demultiplexer. The measurement was made by sliding the 14-ps control pulses across the 6-ps data pulses, while recording the demultiplexer output power with a power meter. The width of the switch window was 11 ps, even though a 14-ps control pulse was used, which is suitable to demultiplex 80 Gb/s. We also noticed a somewhat rectangular shape of the switch window, which is due to dispersive walkoff between control and data pulse, and this effect is useful to absorb timing jitter in the incoming data. The net polarization dependence of the demultiplexer was about 3 dB, even though the polarization dependence of XPM in standard DSF is 5 dB. The reason for this, is that for orthogonal relative polarization of data and control pulses, the spectral broadening is at its minimum, and for decreased orthogonality, the spectrum gets broader, but still leaving energy within the filter band width. However, the polarization dependence depends heavily on the available pump power, as well as the position of the BPF.

BER measurements of the demultiplexed data are shown in Fig. 5. The back-to-back receiver sensitivity was measured from 10 Gb/s to −36.8 dBm, after the data modulator. Full BER plots are shown for channel one to four, and BER measurements around 10^{-9} are shown for channel five to eight. All channels performed almost the same, giving a penalty of about 2 dB. This penalty is believed to arise primarily due to nonoptimal filtering of the narrow bandwidth demultiplexed 10-Gb/s data in the receiver. The optically preamplified receiver included a 0.6-nm optical BPF that is close to optimum for 6-ps pulses, and thus gives a low receiver sensitivity for the original 10-Gb/s data. After demultiplexing, the pulsewidth is 17 ps with a spectral width of 0.2 nm, which is far from optimum for this particular receiver. In fact, sending the original 10-Gb/s data with 6-ps pulses through the 0.2-nm filter, before entering the receiver gave also about 2-dB penalty, but with a slightly better slope of the BER.

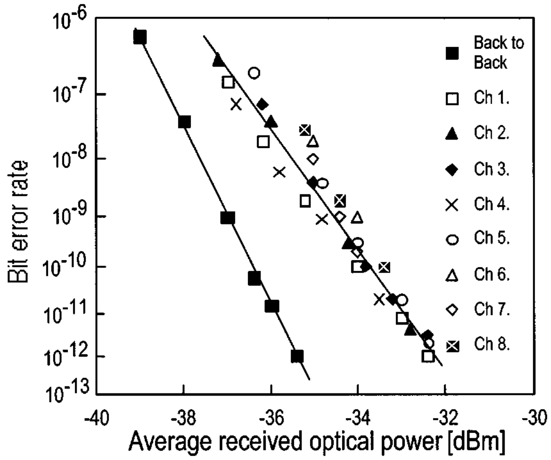

Fig. 5. BER measurements for 80–10-Gb/s demultiplexing.

III. CONCLUSION

A new all-optical demultiplexer based on XPM in a fiber followed by a narrow optical BPF is described and demonstrated. An 80-Gb/s data channel was successfully demultiplexed to 10 Gb/s with <2 dB receiver penalty using a control pulse of 14 ps. Due to the derivative effect of XPM, a control pulse that is wider than the bit-slot of the high bit-rate data can be utilized. The demultiplexer is insensitive to environmental disturbances, and can be made polarization independent by using a diversity scheme [7], circular birefringent fiber [8], or possibly by managing the input power condition. The demultiplexer scheme, is also well suited for simultaneous demultiplexing by using both slopes of the control pulse, and control pulses at multiple wavelengths, which is subject to further investigation.

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