All-Optical 80-Gb/s Time-Division Demultiplexing Using Polarization-Insensitive Cross-Phase Modulation in Photonic Crystal Fiber

A. S. Lenihan, *Member, IEEE*, R. Salem, *Student Member, IEEE*, T. E. Murphy, *Member, IEEE*, and G. M. Carter, *Senior Member, IEEE*

***Abstract*—We describe an all-optical 80-Gb/s time-division demultiplexer, which utilizes cross-phase modulation in a commercial photonic crystal fiber. Compared to back-to-back 10-Gb/s measurements, the demultiplexer achieves better than a 2.5-dB power penalty for all eight channels. More importantly, we demonstrate a novel scheme for polarization-insensitive operation, which uses only the birefringence of the fiber itself and proper alignment of the clock pulse polarization. Using this technique, the polarization sensitivity of the converted power is found to be less than 0.4 dB, allowing for error-free demultiplexing even while the data polarization state is scrambled.**

***Index Terms*—Demultiplexing, nonlinear optics, optical fiber communications, polarization, time-division multiplexing.**

I. INTRODUCTION

HIGH-SPEED demultiplexing is a necessary component of high-data rate optical time-division multiplexed transmission systems. All-optical devices based on nonlinearities in fiber have the advantage of an ultrafast response, but have traditionally required long lengths of fiber which can lead to increased sensitivity to environmental effects. Recent advances in fiber technology, such as photonic crystal fibers (PCFs), have produced fibers which exhibit a high nonlinear coefficient while still allowing for controlling the dispersion profile [1]. This has enabled shorter fiber lengths to be used in applications such as demultiplexing [2] and wavelength conversion [3], [4]. One problem with fiber-based nonlinear devices is that they typically depend on the input polarization state, which can vary unpredictably in installed fiber systems. In response to this, a number of schemes have been proposed such as polarization diversity [4], twisting of the nonlinear fiber [5], [6], and depolarization of the clock pulses [7]. Any of these can eliminate the polarization dependence, but generally require added complexity in the device.

In this letter, we discuss a polarization-insensitive all-optical time-division demultiplexer, which utilizes the cross-phase modulation (XPM) effect in a single pass through 30 m of nonlinear PCF. We show that the polarization dependence of the nonlinear effect can be mitigated by the residual birefringence in the commercially available fiber, requiring only that the polarization state of the local clock pulse be kept fixed relative to the fiber axes. Using this technique, we are able to achieve error-free 80–10-Gb/s demultiplexing, with low power penalty compared to the original 10-Gb/s data, even when the data signal polarization state is being scrambled.

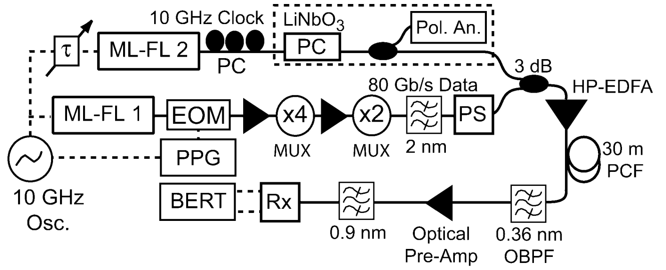

Fig. 1. Experimental setup used for demonstrating polarization-insensitive 80-Gb/s demultiplexing. The dashed box indicates components used only for the results shown in Fig. 4. PC: polarization controller. Pol. An.: polarization analyzer.

II. EXPERIMENTAL SETUP

Our experimental schematic is shown in Fig. 1. The clock and data pulse trains were produced using two 10-GHz actively mode-locked fiber lasers, with pulsewidths of 3.6 and 3.2 ps, respectively. A variable electrical delay (τ) was used to vary the time delay between the clock and data pulses to select the individual channels during demultiplexing. The data pulses were amplitude modulated with a 10-Gb/s $2^7 - 1$ pseudorandom sequence using an electrooptic modulator, then multiplexed to 80 Gb/s using a three-stage passive optical interleaver (MUX). All three stages of multiplexing were polarization maintaining, so that all of the bits in the 80-Gb/s data stream are copolarized. After filtering by a 2-nm optical bandpass filter (OBPF), the data power level was -4.5 dBm. A high-speed polarization scrambler (PS) was used to vary the polarization state of the signal entering the demultiplexer, in order to emulate real system variations. The data and clock signals were combined in a 3-dB coupler, then amplified by a high-power erbium-doped fiber amplifier (EDFA). After the amplifier, the average power levels were $+25.1$ and $+9.7$ dBm for the clock and data, respectively.

Manuscript received January 30, 2006; revised March 17, 2006. This work was supported by the Laboratory for Physical Sciences.

A. S. Lenihan and G. M. Carter are with the Department of Computer Science and Electrical Engineering, University of Maryland Baltimore County, Baltimore, MD 21250 USA, and also with the Laboratory for Physical Sciences, College Park, MD 20740 USA.

R. Salem and T. E. Murphy are with the Department of Electrical and Computer Engineering, University of Maryland, College Park, MD 20742 USA.

Digital Object Identifier 10.1109/LPT.2006.876745

1041-1135/$20.00 © 2006 IEEE

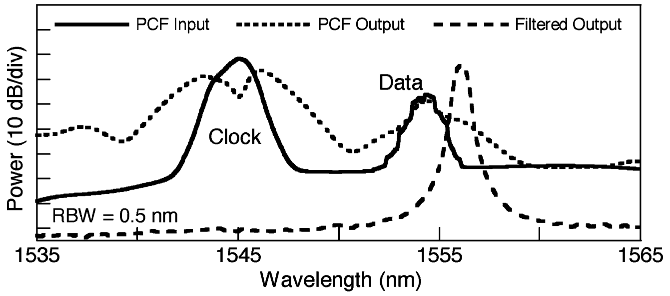

Fig. 2. Optical spectra measured before the PCF (solid trace), after the PCF (dotted trace), and after subsequent filtering and amplification (dashed trace).

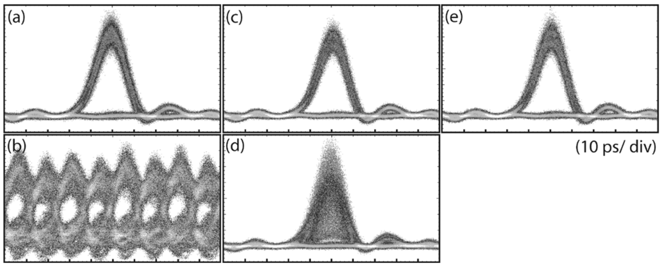

Fig. 3. Eye diagrams: (a) original 10-Gb/s signal; (b) 80-Gb/s signal; (c) demultiplexed 10-Gb/s channel, no polarization scrambling; (d) demultiplexed channel with polarization scrambled data and the clock polarization aligned along one of the fiber birefringent axes; (e) demultiplexed channel with polarization scrambled data and the clock polarization aligned so that the clock power is equally split between the two birefringent axes.

The amplifier was followed by 30 m of commercially available dispersion-flattened nonlinear PCF from Crystal Fibre A/S (NL-1550-NEG-1). The PCF was spliced to standard single-mode fiber at each end, with a total net loss of ~2.5 dB from connector to connector. The PCF has a nonlinear parameter of $\sim 11\ (\mathrm{W} \cdot \mathrm{km})^{-1}$, and a dispersion between -0.75 and 0 ps/nm/km for 1540–1580 nm. The differential group delay (DGD) of the fiber was measured to be 1.25 ps using the method of [8], corresponding to a birefringence of $\Delta n = 1.25 \times 10^{-5}$. These measurements also indicated that the birefringent axes of the PCF do not vary over its length.

The receiver contained a 0.36-nm OBPF, followed by the optical preamplifier consisting of a two-stage low-noise EDFA with a 0.5-nm OBPF placed between stages. This EDFA was followed by an additional 0.9-nm OBPF to reduce the amplified spontaneous emission. The signal was then split and separately detected for data and clock recovery at 10 Gb/s and input to a bit-error-rate (BER) tester. For the eye diagrams, a 40-GHz bandwidth photodiode was used in conjunction with a digital sampling oscilloscope with a 50-GHz electrical sampling module.

III. RESULTS AND DISCUSSION

The optical spectrum measured at the input to the PCF is shown as the solid line in Fig. 2, showing the clock and data signals at 1545.1 and 1554.3 nm. In the PCF, the data signal experiences spectral broadening as a result of the XPM induced by the strong clock pulse, as shown in the dotted curve in Fig. 2. Demultiplexing was then achieved by selectively filtering a portion of the spectrally shifted component on the red side of the data signal [9], with the OBPF following the PCF tuned 2 nm above the data wavelength. After subsequent preamplification and filtering, the spectrum at the receiver is indicated by the dashed curve in Fig. 2. The recorded eye diagrams are shown in Fig. 3. The original 10-Gb/s data and the multiplexed 80-Gb/s data are shown in Fig. 3(a) and (b) for reference. Without polarization scrambling, we can obtain stable and error-free demultiplexing for any of the eight channels, as demonstrated in Fig. 3(c).

In a nonbirefringent fiber, the phase shift resulting from XPM depends on the states of polarization (SOPs) of the two signals being mixed [10]. The resulting spectral broadening depends nonlinearly on this phase shift, potentially resulting in a large polarization dependence in the power measured at the shifted wavelengths. For this PCF, we observe that the polarization dependence is most severe when the clock signal is linearly polarized along one of the fiber birefringent axes, in which case the nonlinear signal power for a copolarized data signal is almost 10 dB higher than for a cross-polarized data signal under the same conditions. As shown in Fig. 3(d), this can lead to a complete eye closure if XPM is used for demultiplexing a data signal with varying polarization. In theory, the polarization dependence could be eliminated if the clock is circularly polarized, but in practice, it is impossible to maintain a circular polarization state unless the fiber is twisted either during drawing or after fabrication [5], [6]. Maintaining a circular polarization in a linearly birefringent fiber is impossible, and most novel highly nonlinear PCFs exhibit significant linear birefringence. For longer fibers, in which the birefringent axes vary over the length, it has been shown that the PMD of the fiber can lead to polarization insensitivity [11]. Unfortunately, this scheme is not applicable in short nonlinear fibers like the one used here, where the birefringent axes do not vary significantly over the length.

In these fibers, if the clock is polarized so that its energy is equally divided between the fiber principle axes, then its polarization state will evolve periodically between linear and circular states as it propagates. The data polarization will evolve in a similar way, but with a different period because of its different optical frequency. If this difference in beat length is sufficiently high, then the integrated XPM signal averages to a result that is independent of the data polarization. We have confirmed this behavior both in theoretical calculations and direct numerical simulations, to be described in a future publication. By correctly aligning the clock SOP in our experiment, we succeeded in reducing the observed polarization-dependent power variation to <0.4 dB, resulting in an open eye even when the data polarization state is scrambled, as shown in Fig. 3(e).

This method imposes two requirements on the demultiplexer design. First, the fiber DGD $(\Delta\tau)$ and the separation between clock and data must satisfy the requirement $(\omega_{\mathrm{clock}} - \omega_{\mathrm{data}}) \cdot \Delta\tau > 2\pi$. For the parameters used here, this quantity is ~10. Second, the clock polarization alignment with respect to the fiber must be maintained. This is a common requirement for polarization diversity schemes, and should not present significant practical difficulties given that the clock would be locally generated at the demultiplexer. Unlike those schemes which twist the fiber to produce circular birefringence, and require a circularly polarized clock, for this method the clock SOP need only be adjusted so that the clock power is evenly split between

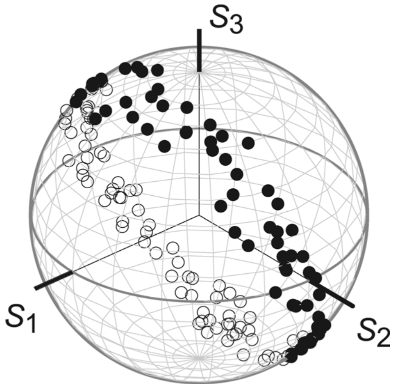

Fig. 4. Clock polarization states which correspond to a demultiplexed BER below 10^{-9}. Open circles indicate points on the opposite side of the sphere.

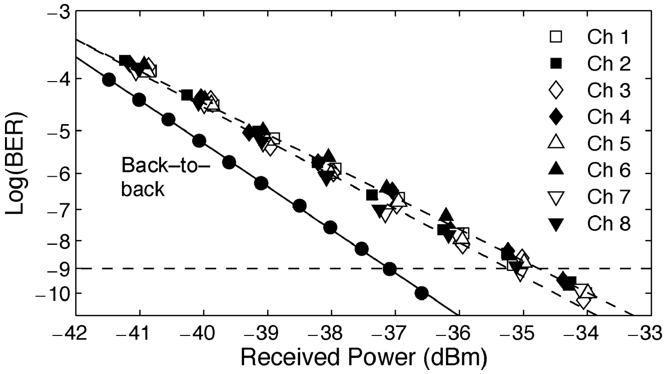

Fig. 5. Receiver sensitivity curves for the eight demultiplexed channels and the back-to-back 10-Gb/s data. The data polarization is scrambled for all cases.

the two birefringent axes, allowing for a wider range of clock SOPs to be used. To confirm this, we added a programmable lithium niobate ($\mathrm{LiNbO_3}$) polarization controller to the clock path, as indicated by the dashed box in Fig. 1. A power tap was added before the 3-dB coupler to allow us to monitor the clock SOP on a polarization analyzer. The BER of one of the demultiplexed polarization-scrambled data channels was measured for 1000 clock SOPs, which were chosen to be uniformly distributed over the Poincaré sphere. For each SOP, the power to the optical preamplifier was adjusted to maintain a fixed level. In Fig. 4, we plot those clock SOPs for which the BER was below 10^{-9}. Because of the intervening single-mode fiber, it is not possible for us to reference the orientation of the sphere to the PCF axes; however, it is clear from the results that there is a circle of clock SOPs which yield error-free demultiplexing, consistent with expectations.

Fig. 5 shows the measured receiver sensitivity for all eight of the 10-Gb/s demultiplexed signals, and the back-to-back 10-Gb/s signal obtained by bypassing the multiplexers and connecting the output of the PS to the 0.36-nm OBPF. The data is polarization scrambled, and the clock is polarized in one of the states shown in Fig. 4. Even with a polarization-scrambled signal, we are able to achieve error-free demultiplexing for all eight of the channels. All channels have similar sensitivity curves, with the best and worst channels showing power penalties of 2.0 and 2.5 dB for a 10^{-9} BER. The measured power penalty when the scrambler was turned OFF differed from the scrambled case by <0.4 dB, indicating that the penalty does not arise from residual polarization dependence.

In order to scale to higher data rates, the birefringence needed for polarization insensitivity must be balanced against the effect of the accumulated DGD on the switching window. For this PCF, the measured switching window was 4.5 ps, which should permit rates up to 160 Gb/s. However, this technique is not specific to PCF, and we expect that by designing nonlinear fibers with optimized birefringence and nonlinear values, this method can be used at data rates above 160 Gb/s.

IV. CONCLUSION

We have demonstrated a polarization-insensitive all-optical time-division demultiplexer, which makes use of the XPM-induced spectral broadening in 30 m of dispersion-flattened nonlinear PCF. The novel scheme for polarization-insensitivity utilizes only the residual birefringence of the fiber and control of the polarization of the locally generated clock pulse. Using this technique, the polarization dependence of the converted signal power is reduced to less than 0.4 dB. This has allowed us to demonstrate error-free demultiplexing of all eight channels, with a maximum power penalty of 2.5 dB relative to the back-to-back 10-Gb/s data, even while the data polarization state is scrambled.

REFERENCES

[1] K. P. Hansen, “Dispersion flattened hybrid-core nonlinear photonic crystal fiber,” *Opt. Express*, vol. 11, pp. 1503–1509, 2003.

[2] A. I. Saihlo, L. K. Oxenlowe, K. S. Berg, A. T. Clausen, P. A. Anderson, C. Peucheret, A. Tersigni, P. Jeppesen, K. P. Hansen, and J. R. Folkenberg, “A high-speed demultiplexer based on a nonlinear optical loop mirror with a photonic crystal fiber,” *IEEE Photon. Technol. Lett.*, vol. 15, no. 8, pp. 1147–1149, Aug. 2003.

[3] J. H. Lee, W. Belardi, K. Furusawa, P. Petropoulos, Z. Yusoff, T. M. Monro, and D. J. Richardson, “Four-wave mixing based 10-Gb/s a tunable wavelength conversion using a holey fiber with a high SBS threshold,” *IEEE Photon. Technol. Lett.*, vol. 15, no. 3, pp. 440–442, Mar. 2003.

[4] K. K. Chow, C. Shu, C. Lin, and A. Bjarklev, “Polarization-insensitive widely tunable wavelength converter based on four-wave mixing in a dispersion-flattened nonlinear photonic crystal fiber,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 3, pp. 624–626, Mar. 2005.

[5] J. W. Lou, K. S. Jepsen, D. A. Nolan, S. H. Tarcza, W. J. Boutona, A. F. Evans, and M. N. Islam, “80 Gb/s to 10 Gb/s polarization-insensitive demultiplexing with circularly polarized spun fiber in a two-wavelength nonlinear optical loop mirror,” *IEEE Photon. Technol. Lett.*, vol. 12, no. 12, pp. 1701–1703, Dec. 2000.

[6] T. Tanemura, J. Suzuki, K. Katoh, and K. Kikuchi, “Polarization-insensitive all-optical wavelength conversion using cross-phase modulation in twisted fiber and optical filtering,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 5, pp. 1052–1054, May 2005.

[7] T. Yang, C. Shu, and C. Lin, “Depolarization technique for wavelength conversion using four-wave mixing in a dispersion-flattened photonic crystal fiber,” *Opt. Express*, vol. 13, pp. 5409–5415, 2005.

[8] C. D. Poole and D. L. Favin, “Polarization-mode dispersion measurements based on transmission spectra through a polarizer,” *J. Lightw. Technol.*, vol. 12, no. 6, pp. 917–929, Jun. 1994.

[9] B.-E. Olsson and D. J. Blumenthal, “All-optical demultiplexing using fiber cross-phase modulation (XPM) and optical filtering,” *IEEE Photon. Technol. Lett.*, vol. 13, no. 8, pp. 875–877, Aug. 2001.

[10] G. P. Agarwal, *Nonlinear Fiber Optics*, 2nd ed. New York: Academic, 1995.

[11] B.-E. Olsson and P. A. Andrekson, “Polarization-independent all-optical AND-gate using randomly birefringent fiber in a nonlinear optical loop mirror,” in *Proc. OFC ’98*, San Jose, CA, Paper FA7.