All-Optical TDM Data Demultiplexing at 80 Gb/s With Significant Timing Jitter Tolerance Using a Fiber Bragg Grating Based Rectangular Pulse Switching Technology

Ju Han Lee, *Member, OSA*, Leif Katsuo Oxenløwe, Morten Ibsen, *Member, OSA*, Kim Skaalum Berg, Anders T. Clausen, David J. Richardson, and Palle Jeppesen

***Abstract*—We demonstrate the use of fiber Bragg grating based pulse-shaping technology to provide timing jitter tolerant data demultiplexing in an 80 Gb/s all-optical time division multiplexing (OTDM) system. Error-free demultiplexing operation is achieved with $\sim$ 6 ps timing jitter tolerance using superstructured fiber Bragg grating based 1.7 ps soliton to 10 ps rectangular pulse conversion at the switching pulse input to a nonlinear optical loop mirror (NOLM) demultiplexer comprising highly nonlinear dispersion shifted fiber (HNLF). A 2-dB power-penalty improvement is obtained compared to demultiplexing without the pulse-shaping grating.**

***Index Terms*—Demultiplexing, fiber gratings, optical fiber communication, optical fiber devices, optical pulse shaping, optical switches, optical time-division multiplexing.**

I. Introduction

All-optical time-division multiplexing (OTDM) system technology has developed significantly in recent years and has resulted in the demonstration of terabit-per-second single channel data rates [1]. As the data rates increase, and the return-to-zero (RZ) pulses used get correspondingly shorter, OTDM systems suffer increased sensitivity to source noise, and the effects of nonlinearity, group velocity dispersion (GVD), polarization mode dispersion (PMD) and environmental sensitivity associated with the transmission line. These effects generally manifest themselves in terms of increased amplitude jitter, timing jitter and absolute timing drift at the receiver [2]. The synchronization requirements placed on the locally generated pulses required to control an optical demultiplexer at the receiver end can thus become a significant practical limiting issue. The key to obtaining sufficient timing jitter tolerance in such devices is to establish a rectangular switching window [3]–[5]. This reduces the absolute accuracy required for temporal bit alignment and allows for optimal resilience to timing jitter-induced errors. Fig. 1 shows a comparison of the operation of an optical switch with a conventional switching window (assumed to approximate to a Gaussian) and a switch with a rectangular shape switching window. Conventional optical switches are seen to generate a large intensity variation of the output signals as the relative timing drifts between the input and clock signals due to the window shape, which then result in a significant system power penalty. However, flat-top rectangular switching window enables us to operate the switching system with considerable tolerance to relative timing difference over relatively wide timing drift ranges. This provides increased resilience to timing jitter.

To this end a fiber based nonlinear optical loop mirror (NOLM) demultiplexing scheme that provides good ultrafast performance and tolerance to timing-jitter of either, or both, of the control and data signals has been demonstrated previously [4], [5]. These schemes use the difference in group velocity and the resultant walk-off between the control and data signals within the nonlinear medium to define the rectangular switching window. This consequently requires tight specification and control of both the data and signal wavelengths, and the dispersion characteristics of the fiber despite relatively ease of implementation. Whilst this approach is applicable to fiber based switches it cannot be applied to switches based on highly nonlinear semiconductors and within which there are no appreciable dispersive propagation effects over the length scales of relevance. We have demonstrated a simple and robust method to generate a rectangular switching window within nonlinear optical devices based on pulse-shaping superstructured fiber Bragg gratings (SSFBG) [6]. In our first demonstration of this approach, 2.5 ps soliton control pulses were converted into 20 ps wide rectangular pulses through fiber Bragg gratings and then applied to optical switches based on either optical fiber or a semiconductor optical amplifier (SOA). Rectangular switching windows with $+/-7$ ps error-free jitter tolerance were readily achieved. Recently, Schubert *et al.* demonstrated a pulse shaper based on both a HiBi fiber and a polarization beam splitter which can be used to obtain a rectangular switching window [7]. However, the polarization sensitivity of this approach could be a practical limiting issue for its application within real systems.

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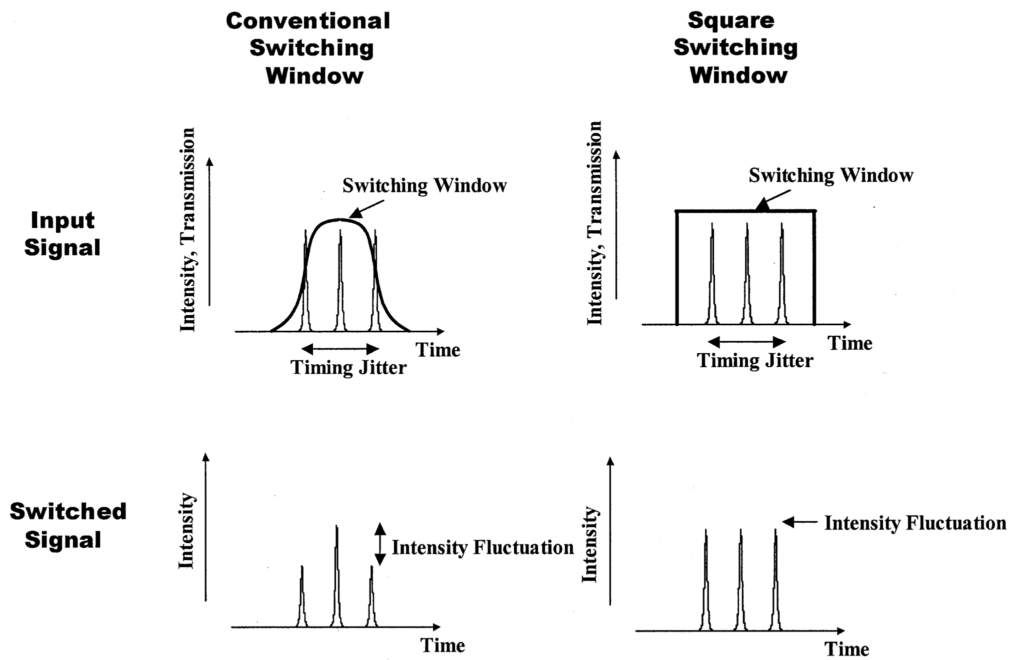


Fig. 1. Comparison of functionality between conventional switching window and rectangular shape switching window.

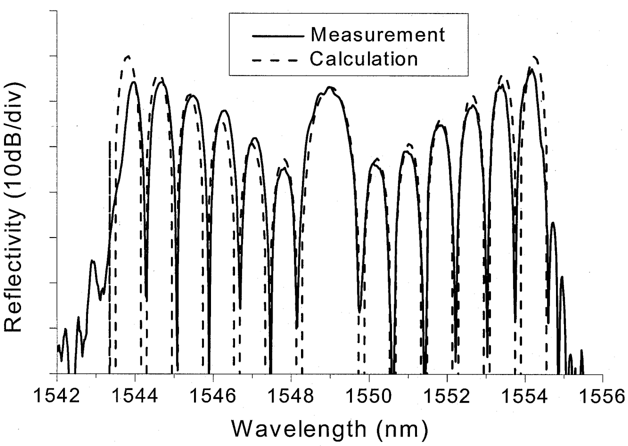
In this paper, we go on to demonstrate the use of SSFBG based rectangular pulse switching technology for data demultiplexing at a data rate of 80 Gb/s in a high-speed OTDM system. We convert 1.7 ps transform-limited soliton pulses from a harmonically mode-locked erbium fiber ring laser into 10 ps rectangular pulses using a polarization-insensitive pulse-shaping SSFBG. These pulses are then used to control a high-speed optical demultiplexer based on a NOLM. High-performance error-free demultiplexing operation with $+/-3$ ps timing jitter tolerance was achieved with 1 dB power penalty relative to the 10 Gb/s base rate back-to-back measurement. A 2-dB power-penalty improvement was also achieved with respect to data demultiplexing without the SSFBG.

II. Pulse-Shaping Superstructured Fiber Bragg Gratings

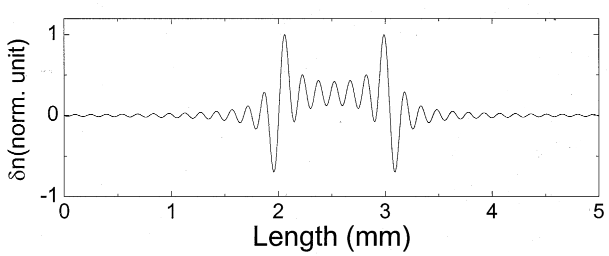
Since our SSFBG based pulse-shaping technique is a purely passive-filtering process, we require a well-defined input pulse form to filter and thereby reshape. For this experiment we used soliton pulses generated from a harmonically mode-locked erbium-doped fiber ring laser. The grating was designed and fabricated with the correct phase and amplitude reflectivity profile to convert the input 1.7 ps transform-limited soliton pulses into 10-ps rectangular pulses [8]. The refractive index modulation profile and the corresponding spectral response of the SSFBG are shown in Fig. 2. We accommodated 13 spectral lobes within the available 12 nm spectral bandwidth and apodized the output spectrum using a Gaussian profile to reduce temporal shape distortion (Gibbs phenomenon) due to the spectral truncation. The length of the grating was 5.1 mm, corresponding to $\mathrm{t} = 50$ ps in the time domain. Note the high ($< 10\ \mu$m) spatial superstructure resolution required of the grating writing process as shown in Fig. 2(b). The fiber Bragg grating based pulse-shaping technology generally requires a well-defined input pulse with an appropriate spectral shape. Although highly accurate alignment of the center wavelengths between the grating and the input pulse is essential to generate the desired rectangular pulses in our experiment, the unique characteristics of our pulse-shaping grating such as wavelength stability and polarization insensitivity allow us to reliably generate high-quality rectangular pulses. The measured optical spectrum of the pulses from the SSFBG is shown Fig. 3(a) together with that of the theoretically calculated single rectangular pulse. Excellent agreement between theory and experiment is obtained highlighting the quality of our grating writing process. We next characterized the rectangular pulses using a SHG autocorrelator (resolution < 100 fs). The measured and theoretically calculated triangular autocorrelation traces are shown in Fig. 3(b) and high-quality rectangular pulses with a 10-ps temporal width are clearly evident (see the inset of Fig. 3(b), where we show the calculated temporal shape of the rectangular pulses).

III. Experimental Setup for 80-Gb/s OTDM Data Demultiplexing

Our experimental setup for 80-Gb/s OTDM data demultiplexing is shown in Fig. 4. 1.7 ps soliton pulses were first generated from a 10-GHz harmonically mode-locked erbium-fiber ring laser (EFRL) with two output channels. The first channel was fed onto a pulse-shaping SSFBG described in Section II. The generated 10-ps-wide 10-Gb/s rectangular pulses were then amplified and used as a control signal for the 80-Gb/s demultiplexer based on NOLM. The other channel of the 10-GHz 1.7 ps pulse stream was first amplified and then fed into the control port of a dual-wavelength NOLM that we employed as a wavelength converter with which to generate a synchronized data stream [9]. The NOLM incorporated a



(a)

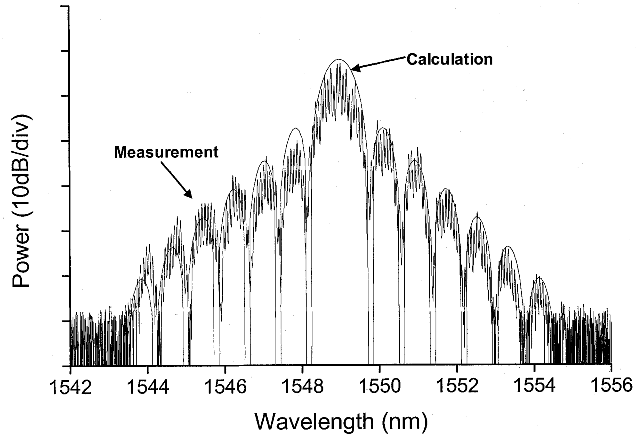


(b)

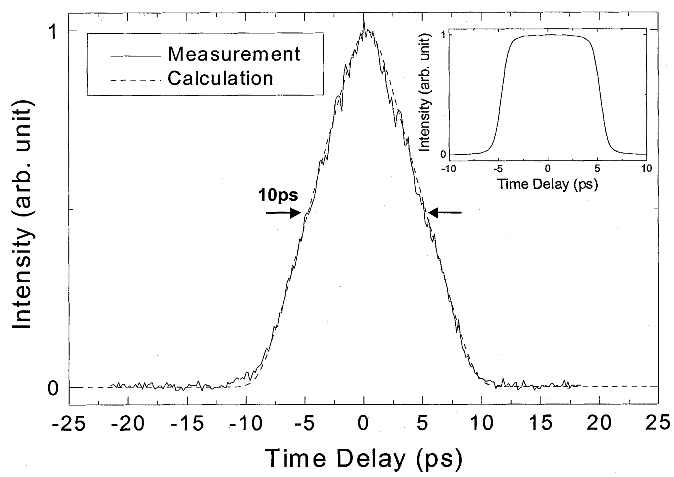
Fig. 2. (a) The spectral reflectivity profile of the pulse-shaping SSFBG converting 1.7 ps soliton pulses into 10 ps rectangular pulses. (b) The corresponding refractive index modulation profile of the SSFBG.

500-m long highly nonlinear fiber (HNLF) with a nonlinearity coefficient $\gamma = 10.9\ \mathrm{W}^{-1}\cdot\mathrm{km}^{-1}$ and a zero-dispersion wavelength $\lambda_0 = 1552$ nm. The output from a continuous wave (CW) external cavity feedback laser at an operating wavelength of 1558 nm was used as a probe signal for the wavelength converter. By appropriately setting the polarization of the light within the NOLM and filtering out the 1549 nm control pulses at the output port, we were able to generate a 10 GHz train of high-quality 3.3 ps pulses at 1558 nm. The measured autocorrelation traces of the wavelength-converted pulses and the original soliton pulses are shown in Fig. 5. Stable and synchronized data pulses were readily achieved using the HNLF-based NOLM. These wavelength converted pulses were modulated to provide a $2^{31}-1$ pseudorandom data sequence at 10 Gb/s using a high-speed $LiNBO_3$ modulator. The 10-Gb/s pseudorandom data stream was multiplexed upto an aggregate bit rate of 80 Gb/s using a two-stage passive multiplexer (MUX) and subsequently sent into the data port of the 80-Gb/s demultiplexer.

The high-speed data demultiplexer we used in this experiment was also based on NOLM using a 1-km length of the HNLF [10]. In order to properly demultiplex 3.3 ps data pulses without any additional power penalty, the NOLM was designed to generate a minimum ~ 3 ps FWHM switching window for the 1.7 ps soliton control pulse. This was achieved by careful selection of clock and data wavelength relative to zero-dispersion wavelength of the fiber in order to use the walk-off effect between the control and data pulses inside the NOLM. The 1558-nm 80 Gb/s data stream incident to the demultiplexer was passed through a



(a)



(b)

Fig. 3. (a) Optical spectrum of the rectangular pulses from the SSFBG described in Fig. 1. (b) SHG autocorrelation traces of the rectangular pulse; Inset: Theoretically calculated temporal shape of the rectangular pulse.

tuneable optical delay line to allow us to adjust the arrival time of the data pulses relative to the 1549-nm rectangular control pulses.

We performed switching window measurements by launching a CW probe signal into the data port of the demultiplexer and measuring the temporal width of autocorrelation traces. As shown in Fig. 6 a good switching window characteristic with a ~ 10 ps FWHM triangular trace was obtained using the rectangular control pulses, in contrast to a value of ~ 4 ps when driving the demultiplexer directly with pulses from the EFRL. These results show that we can expect a maximum10 ps timing jitter tolerance by using the rectangular control pulses.

In order to confirm the benefits of using rectangular control pulses in practical high-speed OTDM demultiplexing systems, we performed bit-error rate (BER) measurements on the 80-Gb/s demultiplexer. At first, we measured the BER under optimal time synchronization between control and data pulses for both cases, i.e., with and without the pulse shaping SSFBG. The results are summarized in Fig. 7(a). Error-free demultiplexing operation for all eight channels was achieved using the 10-ps-wide rectangular shape control pulses with 1-dB power penalty relative to the 10-Gb/s base rate back-to-back.

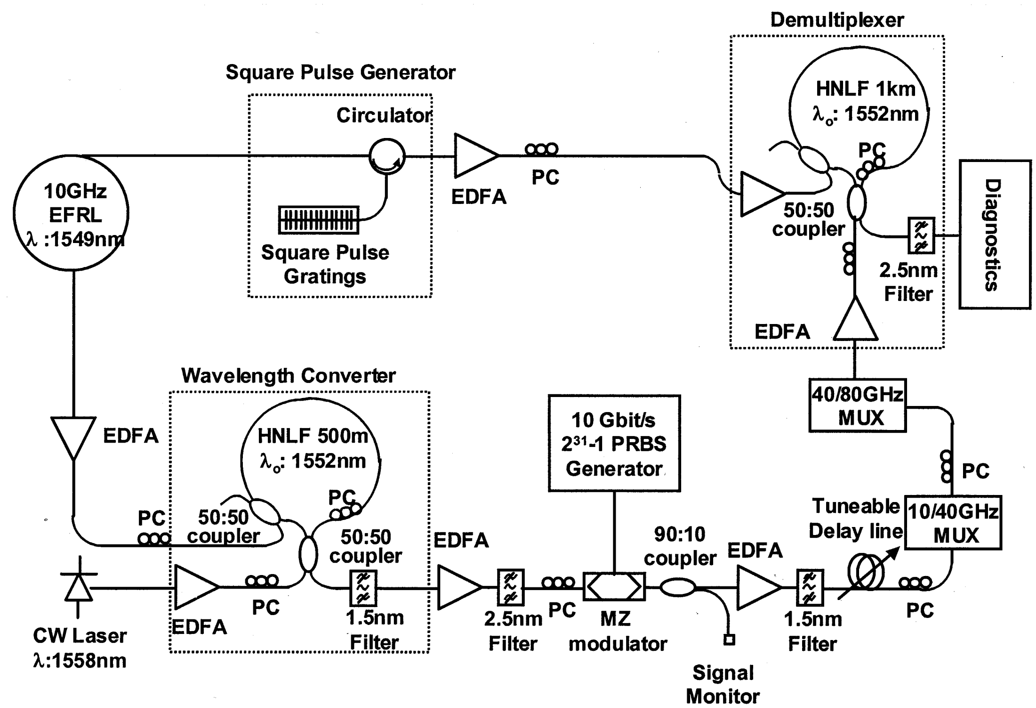


Fig. 4. Experimental setup for 80 Gb/s OTDM data demultiplexing.

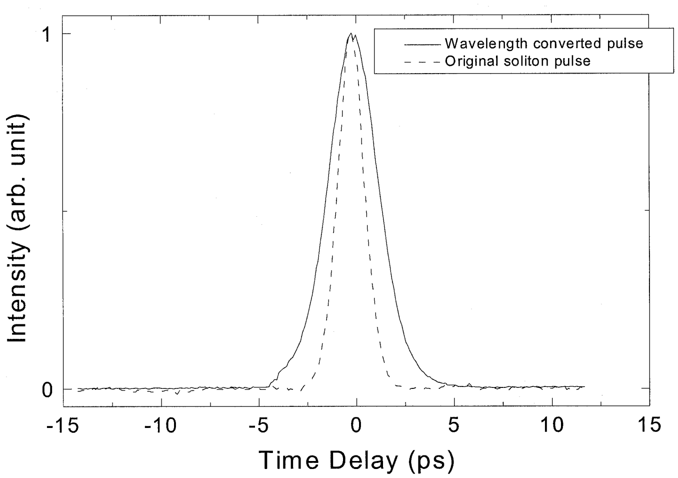


Fig. 5. The measured autocorrelation traces of the wavelength-converted pulses and the original soliton pulses.

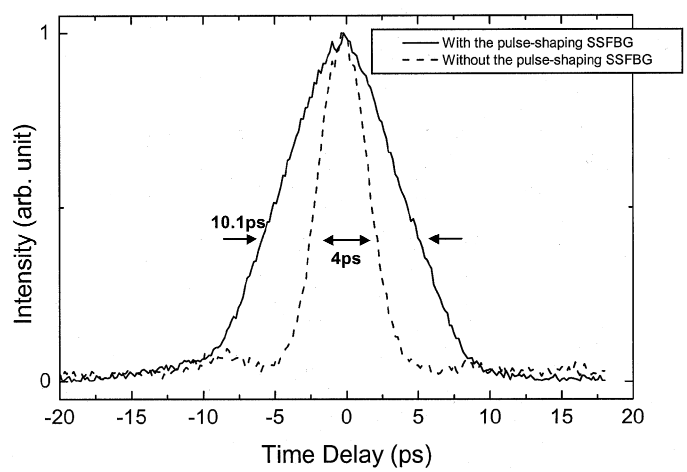


Fig. 6. The autocorrelation traces of the switching windows measured by launching a CW probe signal into the data port of the demultiplexer.

A 2-dB power-penalty improvement was also achieved with respect to data demultiplexing without the SSFBG. We attribute this penalty improvement to the enhanced tolerance to $\sim$ sub-picosecond timing drift inherent to our experimental setup caused by environmental temperature/air flow variations during this particular experiment. The corresponding eye diagrams are shown in Fig. 7(b). Both intensity noise and timing jitter are clearly evident in the eyes of channel number 1 using soliton control pulses without the pulse-shaping SSFBG compared to those of all eight channles under rectangular control pulses. Next, we measured the BER at a fixed received optical power of -31 dBm as a function of relative timing mismatches between control and data pulses and the results are shown in Fig. 8. Error-free performance was readily achieved over a $+/-3$ ps timing mismatch range for the rectangular pulse driven demultiplexer versus a $+/-0.5$ ps range for the demultiplexer driven directly with the soliton pulses.

IV. Conclusion

We have experimentally demonstrated that the SSFBG based rectangular pulse switching technology can be used to provide improved timing jitter tolerance in a high-speed 80 Gb/s OTDM demultiplexing system. Error-free demultiplexing operation with $\sim$ 6 ps timing jitter tolerance was achieved using a $\sim$ 10 ps rectangular control pulses generated through an SSFBG. The 2-dB power-penalty improvement compared to the demultiplexing without the SSFBG highlights that we

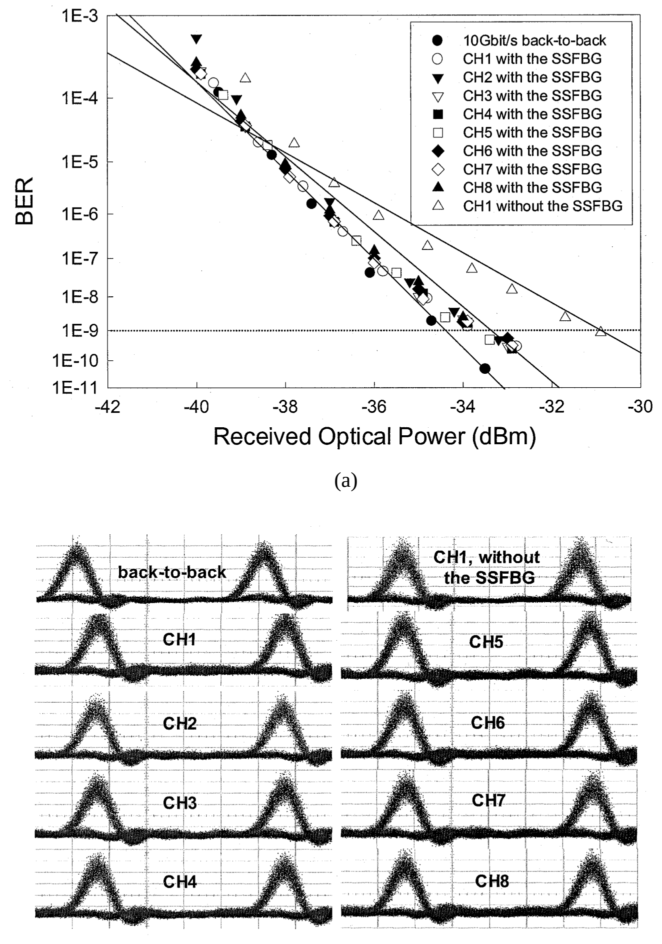


Fig. 7. (a) BER and (b) eye diagrams at -32 dBm, on the 80 to 10 Gb/s demultiplexed signals as a function of received optical power under optimal time synchronization between control and data pulses.

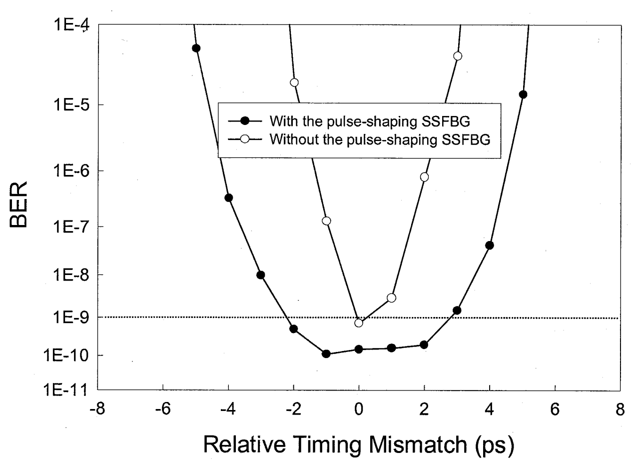


Fig. 8. The BER measured at a fixed received optical power of -31 dBm as a function of relative timing mismatch between control and data pulses.

can obtain significant OTDM demultiplexer performance enhancements simply by adding a SSBFG to the system. This approach could be applied to 160 Gb/s OTDM systems since state-of-the art SSFBG technology should be capable of producing high-quality gratings capable of generating rectangular pulses with rise/fall time less than 1 ps.

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REFERENCES

[1] M. Nakazawa, "Tb/s OTDM technology," in *Proc. 27th Europ. Conf. Opt. Commun. (ECOC'2001)*, 2001, Tu.L.2.3, pp. 184–187.

[2] M. C. Gross, M. Hanna, K. M. Patel, and S. E. Ralph, "Reduction of power fluctuations in ultrafast optically time-division-multiplexed pulse trains by use of a nonlinear amplifying loop mirror," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 690–692, 2002.

[3] K. Uchiyama and T. Morioka, "All-optical signal processing for 160 Gbit/s channel OTDM/WDM systems," in *Proc. Opt. Fiber Commun. Conf.* (OFC'2001), 2001, ThH2.

[4] M. Jinno, "Effects of crosstalk and timing jitter on all-optical time-division demultiplexing using a nonlinear fiber Sagnac interferometer switch," *IEEE J. Quantum Electron.*, vol. 30, pp. 194–202, 1994.

[5] N. A. Whitaker Jr., H. Avramopoulos, P. M. W. French, M. C. Gabriel, R. E. LaMarche, D. J. Di Giovanni, and H. M. Presby, "All-optical arbitrary demultiplexing at 2.5 Gbit/s with tolerance to timing jitter," *Opt. Lett.*, vol. 16, pp. 1838–1840, 1991.

[6] J. H. Lee, P. C. Teh, P. Petropoulos, M. Ibsen, and D. J. Richardson, "All-optical modulation and demultiplexing systems with significant timing jitter tolerance through incorporation of pulse-shaping fiber Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 203–205, 2002.

[7] C. Schubert, R. Ludwig, S. Watanabe, F. Futami, S. Ferber, J. Berger, C. Schmidt, and H. G. Weber, "Improved performance of a 160 Gbit/s fiber based all-optical switch using rectangular gating pulses," in Proc. Europ. Conf. Opt. Commun. (ECOC'2002), 2002, P.8.3.7.

[8] P. Petropoulos, M. Ibsen, A. D. Ellis, and D. J. Richardson, "Rectangular pulse generation based on pulse reshaping using a superstructured fiber Bragg grating," *J. Lightwave Technol.*, vol. 19, pp. 746–752, 2001.

[9] J. Yu, Y. Qian, P. Jeppesen, and S. N. Knudsen, "Broad-band and pulsewidth-maintained wavelength conversion based on a high-nonlinearity DSF nonlinear optical loop mirror," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 344–346, 2001.

[10] K. J. Blow, N. J. Doran, and B. P. Nelson, "Demonstration of the nonlinear fiber loop mirror as a ultrafast all-optical demultiplexer," *Electron. Lett.*, vol. 26, pp. 962–964, 1990.

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