Technical University of Denmark

Phase Modulation for postcompensation of dispersion in 160-Gb/s systems

Siahlo, Andrei; Clausen, A. T.; Oxenløwe, Leif Katsuo; Seoane, Jorge; Berg, Kim Skaalum; Xu, Zhenbo; Zeng, Jianming; Jeppesen, Palle

Published in:
I E E E Photonics Technology Letters

Link to article, DOI:
10.1109/LPT.2004.839433

Publication date:
2005

Document Version
Publisher's PDF, also known as Version of record

Phase Modulation for Postcompensation of Dispersion in 160-Gb/s Systems

Andrei I. Siahlo, Anders T. Clausen, Leif K. Oxenløwe, Jorge Seoane, Kim S. Berg, Zhenbo Xu, Jianming Zeng, and Palle Jeppesen

***Abstract*—Tunable postcompensation of second-order dispersion by sinusoidal phase modulation is realized for a 160-Gb/s optical transmission system. Accumulated dispersions with magnitudes up to 4 ps/nm are compensated in the receiver end.**

***Index Terms*—160 Gb/s, chirp modulation, communication systems, dispersion compensation, high-speed optical techniques, optical fiber dispersion, optical transmission lines, phase modulation, time-division multiplexing.**

I. Introduction

HIGH-BIT-RATE optical time-division multiplexing (OTDM) systems are attractive to increase the capacity of optical transmission systems. Transmission of 160-Gb/s OTDM signal over 300 km already has been demonstrated [1]. At increased bit rates, tolerances to dispersion in a transmission span are strongly reduced. For example, in [2], the accumulated dispersion (DL) of a transmission link was carefully designed to a magnitude less than 1.2 ps/nm for 160-Gb/s transmission. Since the thermal coefficient of dispersion of single-mode fiber (SMF) is $-1.5 \cdot 10^{-3}$ ps/nm/km/K [3], the changes of DL over 100-km SMF reach 3 ps/nm for temperature variations of ± 10 K. The dispersion may also be changed at network reconfigurations. Note that according to simulations [4], the accumulated dispersion slope has a tolerance of ± 5 ps/nm^2 for 160-Gb/s transmission; its temperature changes are not essential, though [3]. Chirped fiber gratings can be used for tunable compensation of dispersion at 160 Gb/s [5], but they often have limited optical bandwidths or complex control of optical properties.

Applying a chirp on pulses by phase modulation can compensate both dispersion and dispersion slope [6]–[8]. This simple method requires neither a lot of components nor an advanced technology and it is not wavelength-dependent. However, phase modulation at a frequency lower than the bit-rate of an OTDM signal should be applied before multiplexing (precompensation) to set the proper chirp to pulses of each OTDM channel before transmission, whereas, the dispersion of a transmission system can only be detected in the receiver (Rx) [9]. As the tunable prechirping is situated in the transmitter, dynamic control of it would require a control signal transmitted from the Rx to the transmitter, introducing a substantial complexity to the setup.

Manuscript received March 29, 2004; revised September 23, 2004. This work was supported in part by the European IST project TOPRATE (IST-2000-28657).

The authors are with the COM, Technical University of Denmark, Kgs. Lyngby DK-2800, Denmark (e-mail: ans@com.dtu.dk; atc@com.dtu.dk; lo@com.dtu.dk; paa@com.dtu.dk; j.zeng@tue.nl; pj@com.dtu.dk).

Digital Object Identifier 10.1109/LPT.2004.839433

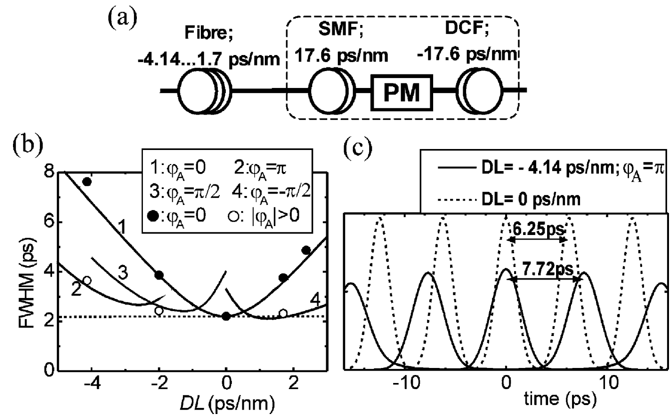

Fig. 1. (a) Dispersion map in which fibers with different accumulated dispersions are placed in the front of the PCU. (b) Pulsewidth as a function of total accumulated dispersion DL of the system shown in (a). (c) Simulated intensity distribution of the pulses of the target channel and neighboring channels of a 160-Gb/s OTDM stream before (dashed) and after (solid) transmission through the system, shown in (a).

In the present letter, we demonstrate that phase modulation can be used for postcompensation of dispersion in 160-Gb/s OTDM transmission systems with a base rate of 10 Gb/s. Successful demultiplexing is obtained in the setup with $-4.14 \leq DL \leq 1.7$ ps/nm using postcompensation by phase modulation in the Rx part.

II. Pre(Post)-Chirping Unit

The pre(post)-chirping unit (PCU) includes SMF with an accumulated dispersion of $DL_{\mathrm{SMF}} = 17.6$ ps/nm, a phase modulator (PM) operating at $f = 10$ GHz, and dispersion-compensating fiber (DCF), compensating the accumulated dispersion of the SMF. First we consider the PCU placed before a transmission span [8]. A pulse with full-width at half-maximum (FWHM) of $T_{\mathrm{FWHM0}} = 2.3$ ps is broadened after the SMF to $T_{\mathrm{FWHM1}} = 26.5$ ps. The phase modulation adds a linear chirp to the pulse of $C = 14.25(f \cdot T_{\mathrm{FWHM1}})^2 \varphi_A$, where φ_A is the amplitude of the sinusoidal phase modulation. The DCF compresses the pulse back, so that after the PCU, the pulse has a width close to T_{FWHM0} and is chirped. The pulsewidth after transmission through a span is changed by changing the chirp, which is controlled by φ_A.

Similarly, adjusting φ_A can change the resulting pulsewidth if the PCU is placed after transmission [Fig. 1(a)]. Fig. 1(b) shows the pulsewidth after transmission through a fiber with nonzero

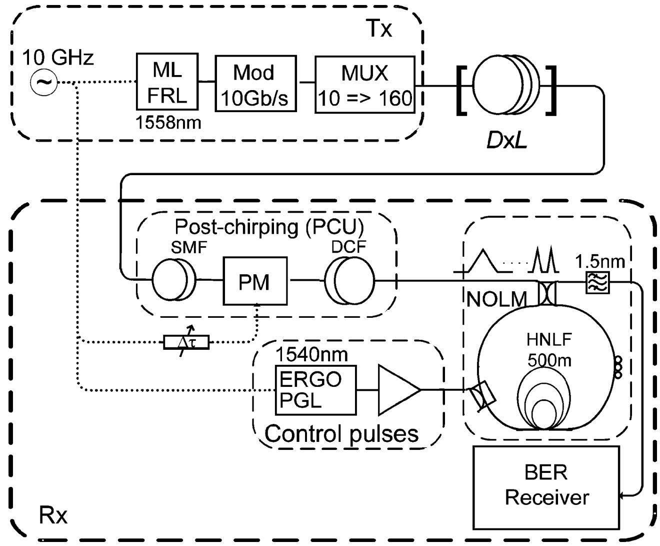

Fig. 2. Experimental setup with the PCU in Rx part.

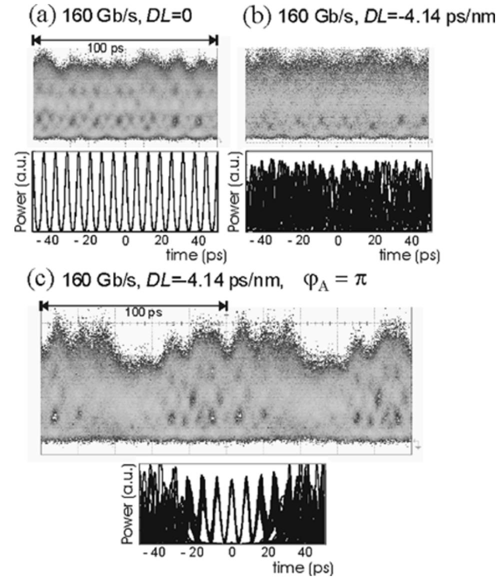

Fig. 3. Eye diagrams of 160-Gb/s signal at the input of the NOLM (a) for $DL = 0$ ps/nm, (b) for $DL = -4.14$ ps/nm with no phase modulation, and (c) for $DL = -4.14$ ps/nm and $|\varphi_A| = \pi$ in the setup with the PCU in the Rx. The calculated eye diagrams are shown below the measured eye diagrams.

dispersion and the PCU as a function of DL and φ_A. Since the bit rate of the OTDM signal (160 Gb/s) exceeds the repetition rate of the control signal applied to the PM (10 GHz), the sinusoidal phase modulation, used to suppress the pulse broadening, is optimized only for one target OTDM channel. However, the difference between the phases of phase modulation for nearest channels is small ($2\pi/16$), so the broadening of the pulses of the nearest channels is also suppressed.

The phase modulation, applied to the neighboring channels to the target channel, becomes nonsymmetrical. Combined with transmission through the DCF of the PCU, this leads to a shifting of pulses in the time domain in opposite directions, away or nearer to the target. An example of this separation of pulses for $DL = -4.14$ ps/nm is shown in Fig. 1(c).

For negative dispersion in the considered link, both suppression of broadening and separation of pulses lead to the elimination of overlap between the pulses of the target channel and its neighboring channels. Thus, the PCU can be used for postcompensation of dispersion.

For positive dispersion, one only avoids pulse broadening, whereas, the pulses of the nearest channels move closer. Therefore, the PCU compensates the negative dispersion better in the considered link.

A single PCU postcompensator compensates for the dispersion only in one OTDM channel. However, all channels may be demultiplexed at the same time if postcompensators are integrated with the demultiplexer.

III. Experimental Setup

The experimental setup using the PCU for postcompensation of dispersion is shown in Fig. 2. The transmitter (Tx) includes a mode-locked fiber ring laser (ML-FRL) generating pulses with FWHM of 2.2 ps at the wavelength $\lambda_D = 1558$ nm at 10 GHz, a Mach–Zehnder modulator modulating the pulse train with a $2^7 - 1$ to $2^{31} - 1$ pseudorandom bit sequence, and a passive fiber-delay multiplexer from 10 to 160 Gb/s.

The Rx includes a nonlinear optical loop mirror (NOLM) as a demultiplexer [8], a 10-GHz erbium glass oscillator pulse-generating laser (ERGO-PGL) as a source of control pulses to the NOLM, and a preamplified 10-Gb/s Rx. The width of the ERGO-PGL pulses is 3.5 ps, and the operating wavelength is 1540 nm. Used as nonlinear element in the NOLM is 500 m of highly nonlinear fiber (HNLF), with zero dispersion at 1559 nm and a low dispersion slope of 0.017 ps/nm^{2}km.

The PCU is set in the Rx just before the NOLM. The 10-GHz clock signal driving the ML-FRL is applied also to the PM in the PCU, to the ERGO-PGL and to the bit-error-rate (BER) Rx. The time delay in the Rx part allows us to synchronize the control signals to the PM and to the NOLM.

In the present setup, fiber segments with different dispersion values are used instead of a transmission span. Formerly, we realized a similar setup with dispersion precompensation with the PCU [8], where a complete transmission span was used. Nonlinearities, noise and timing jitter due to transmission degraded the Rx sensitivity only by 1 dB.

IV. Results and Discussion

Fig. 3 shows the measured and simulated eye diagrams of the 160-Gb/s signal injected into the NOLM. The eye diagrams are measured on a 50-GHz oscilloscope with a 50-GHz photodiode. With no phase modulation, the eye diagram of the OTDM signal is more diffuse at $DL = -4.14$ ps/nm because of pulse broadening [Fig. 3(b)]. At $DL = -4.14$ ps/nm and $\varphi_A = \pi$, both clear and diffuse regions in the eye diagram are seen because some of the 16 channels are not overlapped [Fig. 3(c)].

The BER-curves for the 160 : 10-Gb/s demultiplexing are shown in Fig. 4(a). Successful demultiplexing is obtained with phase modulation at DL from -4.14 to $+1.7$ ps/nm. All 16 OTDM channels are error-free when postcompensation is used.

Fig. 4(b) shows the power penalty defined as the sensitivity of the 160 : 10-Gb/s demultiplexed channel (at BER of 10^{-9}) with respect to the sensitivity at zero dispersion (-29.2 dBm).

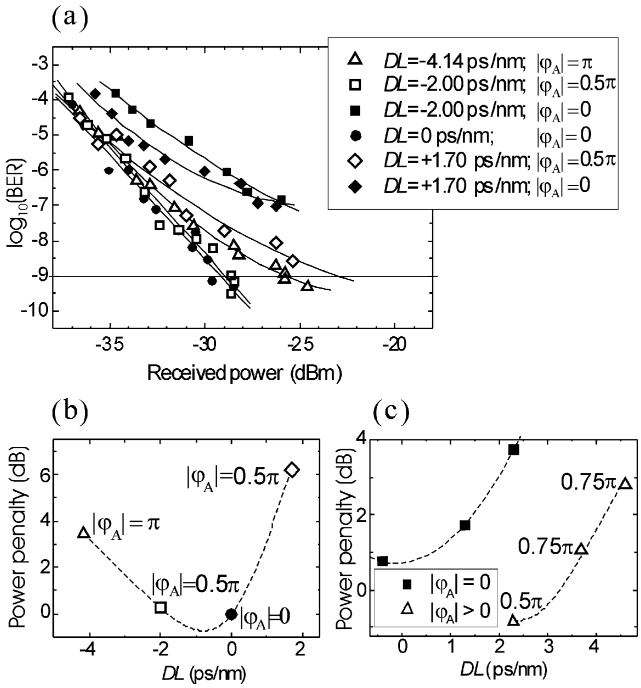

Fig. 4. (a) BER curves for different DL for the present setup. Power penalty as a function of DL (b) for postcompensation and (c) for precompensation [8].

At negative DL, demultiplexing is seen to be more successful, though the pulsewidth for negative dispersion is larger. The reason for this effect is the separation of the pulses of the nearest channels to the demultiplexed one [Fig. 1(c)], whereas, at positive DL, they close in on the target channel.

Fig. 4(c) shows the power penalty curves, according to [8] for the setup with the precompensation by the PCU placed in Rx. The same tuning range for precompensation and postcompensation, as Fig. 4(b) and (c) shows, is obtainable with the additional advantage for postcompensation that dynamic control can be applied in the Rx part.

V. Conclusion

In this letter, postcompensation of dispersion by phase modulation is demonstrated for a 160-Gb/s setup. The error-free demultiplexing at an accumulated dispersion from −4.14 to 1.7 ps/nm is achieved.

Acknowledgment

The authors would like to thank HHI, Berlin, for kindly supplying the multiplexer and OFS Denmark I/S for the fiber span and HNLF.

References

[1] B. Mikkelsen, G. Raybon, R.-J Essiambre, K. Dreyer, Y. Su, J. E. Johnson, G. Shtengel, A. Bond, D. G. Moodie, and A. D. Ellis, "160 Gbit/s single-channel transmission over 300 km nonzerodispersion shifted fiber with semiconductor based transmitter and demultiplexer," in *ECOC 1999*, Nice, France, Postdeadline Paper PD2-3.

[2] R. Ludwig, U. Feiste, C. Schmidt, C. Schubert, I. Berger, E. Hilliger, M. Kroh, T. Yamamoto, C. M. Weinert, and H. G. Weber, "Enabling transmission at 160 Gbit/s," in *OFC 2002*, Anaheim, CA, Paper TuA1.

[3] M. J. Hamp, J. Wright, M. Hubbard, and B. Brimacombe, "Investigation into the temperature dependence of chromatic dispersion in optical fiber," *IEEE Photon. Technol. Lett.*, vol. 14, no. 11, pp. 1524–1526, Nov. 2002.

[4] S. Vorbeck and R. Leppla, "Dispersion and dispersion slope tolerance of 160-Gb/s systems, considering the temperature dependence of chromatic dispersion," *IEEE Photon. Technol. Lett.*, vol. 15, no. 10, pp. 1470–1472, Oct. 2003.

[5] B. J. Eggleton, "Dynamic dispersion compensation devices for high speed transmission systems," in *OFC 2001*, Anaheim, CA, Paper WH1-1.

[6] E. Hellstrom, H. Sunnerud, M. Westlund, and M. Karlsson, "Third-order dispersion compensation using a phase modulator," *J. Lightw. Technol.*, vol. 21, no. 5, pp. 1188–1197, May 2003.

[7] M. Nakazawa, T. Hirooka, F. Futami, and S. Watanabe, "Ideal distortion-free transmission using optical Fourier transformation and transform-limited ultrashort pulses," in *ECOC 2003*, Rimini, Italy, Paper Th4.3.8.

[8] A. I. Siahlo, L. K. Oxenløwe, K. S. Berg, A. T. Clausen, K. Yvind, P. Jeppesen, and K. P. Hansen, "Using a phase modulator for improvement of the tolerance to second-order dispersion in a 160 Gb/s transmission system," in *ECOC 2003*, Rimini, Italy, Paper We 4.P.105.

[9] T. Inui, K. Mori, T. Ohara, H. Takara, T. Komukai, and T. Morioka, "160 Gbit/s adaptive dispersion equalizer using a chirp monitor with a balanced dispersion configuration," in *Proc. ECOC 2003*, Rimini, Italy, Paper Tu3.6.3.