Front. Optoelectron. 2014, 7(3): 399–405
DOI 10.1007/s12200-013-0376-0

RESEARCH ARTICLE

Chromatic dispersion monitoring using semiconductor optical amplifier

Zhao WU, Yu YU, Xinliang ZHANG (✉)

Wuhan National Laboratory for Optoelectronics, School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China

Abstract An all-optical real-time chromatic dispersion (CD) monitoring technique is proposed and demonstrated for 40 Gbit/s differential phase-shifts keying (DPSK) signal, utilizing the cross modulation effects of semiconductor optical amplifier (SOA). The optical power of the output spectral components, which is from the probe's frequency up to the signal bandwidth, is used for CD monitoring. This technique provides a wide monitoring range with large variation scale. The impacts of the polarization mode dispersion (PMD) and the optical signal-to-noise ratio (OSNR) on the CD monitoring results are theoretically analyzed and then experimentally investigated, showing that they have slight influence on the monitoring results within a certain range. Furthermore, simulated results for quadrature phase shift keying (QPSK) signal at 80 Gbit/s are also demonstrated, indicating that this technique is suitable for advanced modulated format as well.

Keywords optical performance monitoring, chromatic dispersion (CD), semiconductor optical amplifier (SOA), cross modulation

1 Introduction

In recent years, as the bit rate increases in demand for capacity, the chromatic dispersion (CD) effect on the optical system cannot be ignored and has been a crucial factor that limits transmission capacity and distance in high-speed optical fiber communication system. Thus, the CD monitoring is essential for long-haul optical fiber transmission network in order to achieve adaptive and exact dispersion compensation [1,2]. Several approaches of CD monitoring have been reported in recent years, for instance, using asynchronous amplitude histogram evaluation (AAHE) method [3–5], employing asynchronous delay-tap sampling (DST) technique [6,7], utilizing nonlinear effects [8–10], using radio frequency (RF) spectral analysis [11–14], and exploiting digital signal processing [15–17]. It is crucial for a simple CD monitoring to be less affected by other coexisting impairments, including polarization mode dispersion (PMD) and amplified spontaneous emission (ASE) noise. In addition, real-time CD monitoring is especially important, since the degradation varies with time in the dynamic optical networks. Moreover, it is better for a CD monitoring to be deployed in all-optical domain. This avoids optical-to-electrical conversion and accommodates the high-speed systems, and has the potential to be integrated into a single chip inside the optical nodes.

A CD monitoring technique using a semiconductor optical amplifier (SOA) has been reported [10]. However, this approach is only suitable for return-to-zero (RZ) signal, and cannot provide independent CD measurement from other impairments. In this paper, we propose a CD monitoring technique using the cross modulation effect of SOA for 40 Gbit/s differential phase shift keying (DPSK) system. The spectral component, which is from the probe's frequency up to the signal bandwidth, is extracted out for CD monitoring. The CD up to 1000 and 700 ps/nm are experimentally measured for non-return-to-zero (NRZ) DPSK signal and return-to-zero (RZ) DPSK signal, respectively. The impact of PMD and optical signal-to-noise ratio (OSNR) is also investigated, indicating that they have slight influence on the monitoring results within a certain range. This method transfers the RF-based monitoring technique [12] into all-optical domain for higher speed signal and maintains the characters of small PMD sensitivity, owing to the less polarization dependence of the cross modulation effect in the SOA. It provides a wide monitoring range with large variation scale, and it is

Received August 8, 2013; accepted September 23, 2013

E-mail: xlzhang@mail.hust.edu.cn

feasible integrated into a single chip. Furthermore, this technique can well accommodate the quadrature phase shift keying (QPSK) signal. The CD monitoring result for 80 Gbit/s QPSK signal is also theoretical simulated and investigated.

2 Operation principle

The idea for the CD monitoring scheme is derived from two validated conclusions. The first one is the total amount of RF power, ranging from the DC up to the signal bandwidth, increases with the accumulated CD and hence can be used to monitor the CD for DPSK signal. This had been reported in Ref. [12]. While the other one is the intensity-to-field conversion can be performed using the cross modulation effect of the SOA. In this sense, the RF characteristics of the pump signal is mapped onto the optical spectrum of the probe via the SOA, which will be theoretically analyzed later. Thus, the power of the probe spectral component, which is from the probe's frequency up to the signal bandwidth, can be used to monitor the CD of the signal.

At the receiver, a strong pump signal and a weak continuous wave (CW) probe are injected into the SOA. Due to cross gain modulation (XGM) and cross phase modulation (XPM) effect, the gain and the phase shift of the output probe are modulated by the intensity of the pump signal through the carrier dynamics of the SOA, while insensitive to the phase information of the pump signal [18,19]. Moreover, the gain and phase shift are approximately linear to the intensity of the pump signal while the SOA locates in saturation state. As a result, through the SOA, the temporal field of the probe is modulated by the temporal intensity of the signal. The optical spectrum around the output probe is related to the RF spectrum of the signal, which is the power spectrum of its temporal intensity. The operation principle is illustrated in Fig. 1. The total spectra of the pump signal and probe before and after SOA are illustrated in Figs. 1(a) and 1(b), and their carrier frequencies are f_s and f_p, respectively. Similar results achieving the RF of high speed signal are demonstrated using the XPM of nonlinear media [20,21].

In our scheme, the spectral components of the output probe, which is from the probe's frequency up to the signal bandwidth, is extracted out by an optical band-pass filter (BPF), and used to measure the CD for the DPSK signal. This method transfers the RF-based monitoring technique into all-optical domain for higher speed signal and maintains the characters of small PMD sensitivity, owing to the less polarization dependence of the cross modulation effect in the SOA. Furthermore, it is feasible integrated into a single chip.

$P(CD)$ is defined as the optical power of the filtered signal along with the accumulated CD of the received signal.

$$P(CD) = \int_{f_p}^{f_p+B} \left|F_{\text{probe}}(f)\right|^2 \mathrm{d}f, \tag{1}$$

where $F_{\text{probe}}(f)$ is the spectrum at the output of SOA, and B is the baud rate of the DPSK signal. In practice, the filtered spectral components are slightly deviated from f_p (i.e., the f_p is exclusive), in order to avoid the strong but slightly-variant carrier of the probe, and thus achieves a high monitoring sensitivity. $P(CD)$ increases monotonously with the increase of accumulated CD on the received signal. Parameter F, which denotes the relative power change, is introduced to monitor the CD of the signal, and defined as

$$F = \frac{P(CD)}{P(0)}. \tag{2}$$

3 Experiment and results

The experimental setup for 40 Gbit/s (N)RZ-DPSK systems is shown in Fig. 2. A distributed feedback laser operating at 1554.72 nm is externally modulated to a (N)RZ-DPSK signal by a $LiNbO_3$ Mach-Zehnder modulator (MZM), which is driven by a $2^{31}-1$ pseudorandom binary sequence signal at 39.81 Gbit/s. A second MZM is used as a pulse carver for RZ-DPSK signal. An erbium-doped fiber amplifier (EDFA1) and a variable optical attenuator (VOA1) are used to adjust the optical power to 0 dBm,

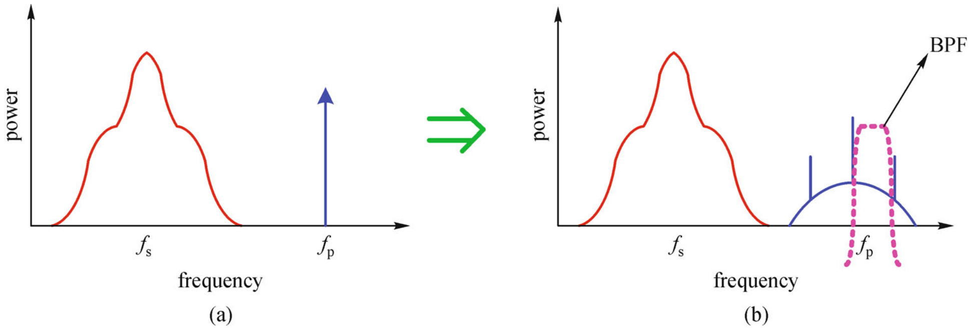


Fig. 1 Optical spectrum (a) before and (b) after SOA

ensuring the negligible nonlinear effect in the subsequent single mode fiber (SMF). Accurate PMD is generated by the General Photonics Corp. PMD-1000 PDM emulator, in which the signal is split equally into two orthogonal polarizations and a relative time delay is introduced between the two polarizations. A preset CD is realized by using a standard SMF with premeasured length. At the end of the fiber, the OSNR of the optical signal is adjusted by tuning the following VOA2 before EDFA2. A fraction of the signal is tapped out by a coupler for OSNR measurement. The OSNR is measured by the Anritsu MS9710C optical spectrum analyzer (OSA) with 0.1 nm resolution. A tunable BPF1 with a 3 dB bandwidth of 0.8 nm is used to eliminate the redundant ASE noise.

At the receiver, a CW probe at wavelength of 1551.88 nm is combined with the distorted signal and then coupled together into an SOA. The SOA is a CIP nonlinear device (CIP SOA-NL-1550), which is operating at bias current of 210 mA. The optical power of probe and distorted signal are −7 and 13 dBm, respectively. At the output of SOA, an optical BPF2, which is centered at 1551.72 nm with a 3 dB bandwidth of 0.3 nm, is used to extract the part of the spectral components from the probe's frequency up to the first sideband of the probe channel. Finally, the filtered signal is measured by an optical power meter to monitor the CD value of the received signal.

Figure 3 shows the combined spectrum before SOA, the output spectra before and after BPF2, respectively. The spectrum of the probe is broadened and the sidebands appear accordingly, due to the cross modulation effect of SOA.

The CD monitoring results for 40 Gbit/s NRZ-DPSK signal are illustrated in Fig. 4. The OSNR of the signal is fixed at 35 dB. F changes by around 11 dB when CD varies from 0 to 1000 ps/nm through different length of SMFs.

The inset in Fig. 4 shows the filtered optical spectra of

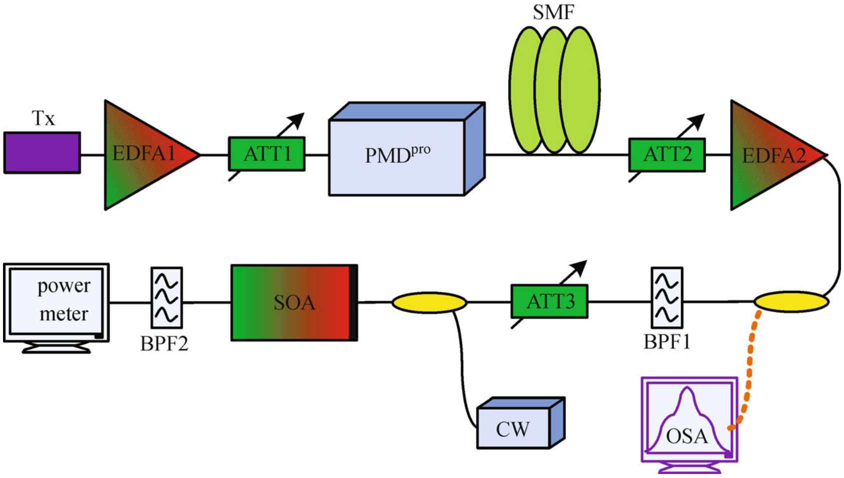


Fig. 2 Experimental setup for CD monitoring

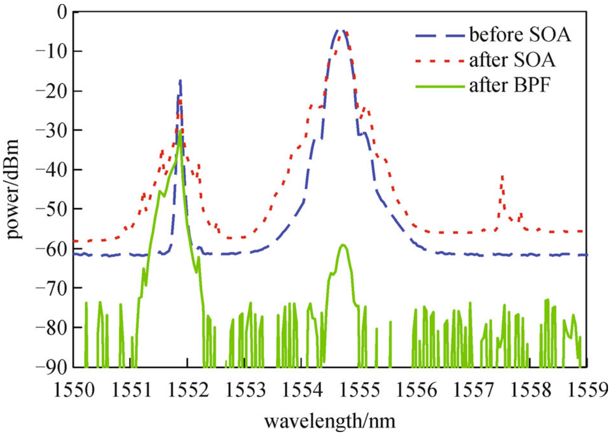


Fig. 3 Optical spectra at the output of SOA

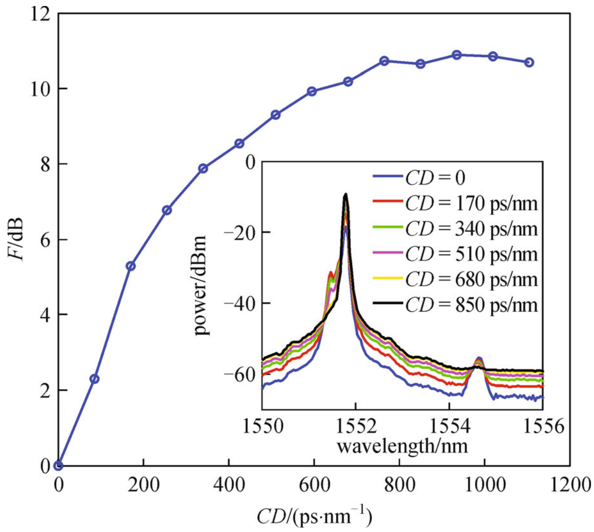


Fig. 4 CD monitoring results for 40 Gbit/s NRZ-DPSK signals

the probe channel under different CDs of the received signal. It can be seen that, the power spectrum value of the filtered probe channel increases monotonically with the increase of CD value on the received signal.

The effects of the first-order PMD and OSNR on the CD monitoring results are also experimentally investigated. Figure 5 shows the CD monitoring results under different differential group delays (DGDs) of 10, 20, and 25 ps, respectively. The optical power of the filtered spectral components decreases slightly with the increase of DGDs. Since the cross modulation effect of SOA is small sensitive to polarization state of the injected signal, the RF of the signal relates to the DGD of the transmission link [22,23].

$$RF(DGD,f) = RF(0,f)\cdot\frac{1+\exp(\mathrm{j}2\pi f\cdot DGD)}{2}, \qquad (3)$$

where DGD is the value of the first-order PMD on the signal. $RF(\bullet,f)$ is the RF spectrum of the signal with DGD of $\bullet$. The second term in Eq. (3) is considered to be an electric filter with a wide baseband. Thus, the DGD induces tiny impact on the RF from 0 to B, and then has little effect on the CD monitoring results.

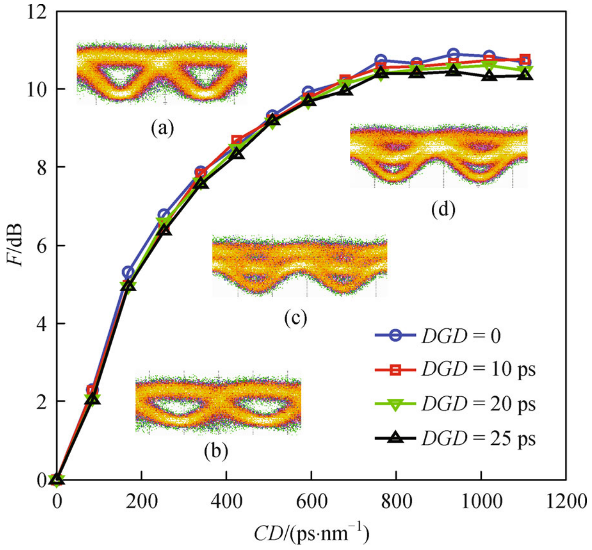


Fig. 5 F versus different cumulated dispersion under different DGDs

The inset (a) in Fig. 5 shows the eyediagram of original NRZ-DPSK signal without PMD, the insets (b), (c) and (d) show the eyediagrams of the signal with DGDs of 10, 20, and 25 ps, respectively.

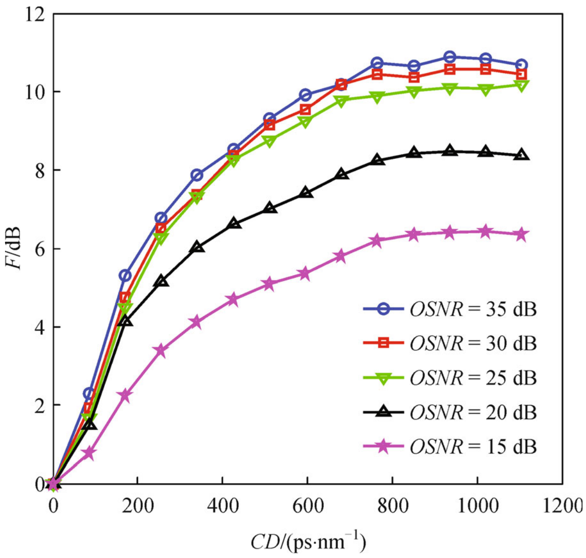


Fig. 6 F versus different cumulated dispersion under different OSNRs for 40 Gbit/s NRZ-DPSK signal

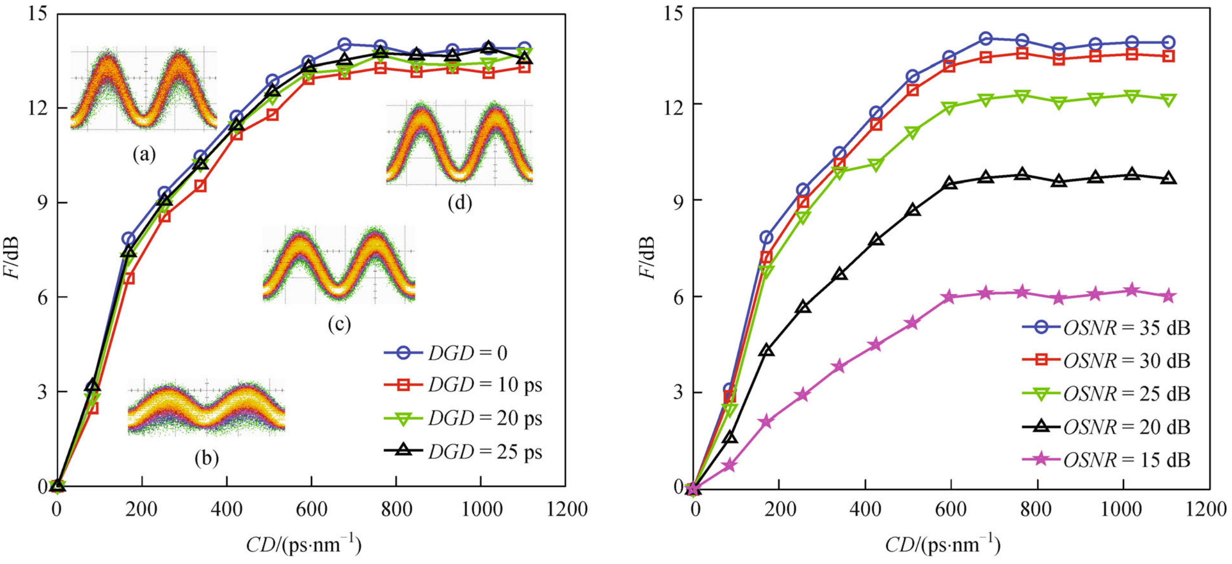
Figure 6 shows the effect of OSNR on the CD monitoring results. The monitoring curves are measured under the OSNR values of 35, 30, 25, 20, and 15 dB, respectively. It can be seen that, the slope of F curves corresponding to the monitoring sensitivity decrease with the decrease of OSNR. The technique works well when the OSNR is higher than 25 dB. However, the monitoring curves decrease dramatically when the OSNR value is less than 25 dB, since the cross modulation effect will be also decreased correspondingly, and the measured optical power increases more slowly along with the CD. Nevertheless, the F still increases with the increasing of the CD on the signal. In practice, the impact of the OSNR on the monitoring scheme can be solved by keeping the OSNR value in the fixed value before deploying the CD measurement. Thus, the scheme works yet but with lower monitoring accuracy.

The scheme is also carried out experimentally for RZ-DPSK signal at 40 Gbit/s. The CD monitoring results under different DGDs and OSNRs are shown in Figs. 7(a) and 7(b), respectively. F changes by around 13 dB when the CD varies from 0 to 700 ps/nm. The CD curves under DGDs of 0, 10, 20, and 25 ps are illustrated in Fig. 7(a). It is shown that the PMD has slight effect on the CD monitoring results. The eyediagrams of the RZ-DPSK signal without PMD and with DGDs of 10, 20 and 25 ps are illustrated in insets (a), (b), (c) and (d), respectively.

The effect of OSNR on the CD monitoring result for RZ-DPSK signal is illustrated in Fig. 7(b). The decreased OSNR value of the signal weakens the cross modulation effect of the SOA, and then affects the monitoring result. The monitoring curves coincide well for OSNR higher than 25 dB, but deviate greatly for OSNR value lower than 25 dB.

4 Discussion

The phase noise on the signal, which is induced by the jitter of the transmitter or the nonlinear effects of fiber link, has no influence on the monitoring results by itself, since



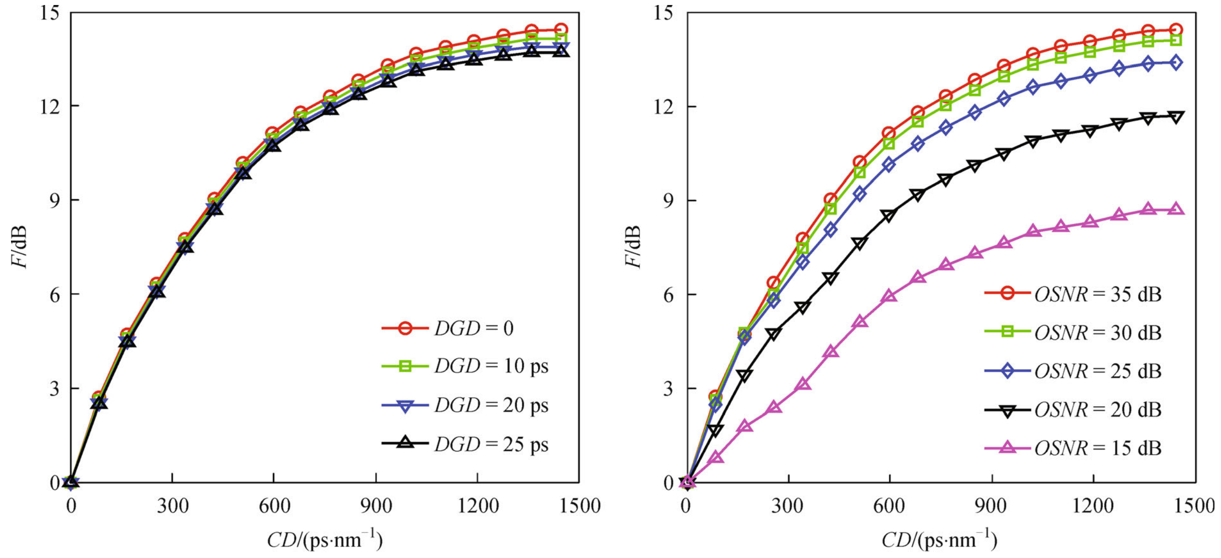
(a) (b)

Fig. 7 *F* versus different cumulated dispersion under different (a) DGDs and (b) OSNRs for 40 Gbit/s RZ-DPSK signal

the RF of the signal is independent of its phase variation. However, the phase noise aggravates the dispersion effect and will convert into the intensity noise on the signal after propagating through a section of dispersive fiber. Nevertheless, the nonlinear effect can be eliminated by decreasing the optical power in the fiber link, and a slight noise on the received signal is tolerable, since the scheme works well under OSNR value within a certain range.

This technique can also be applied to NRZ-QPSK signal. The simulated results for 80 Gbit/s NRZ-QPSK signal, which is generated by employing nest MZMs as they are widely used for QPSK signal generation, are demonstrated in Fig. 8 using the commercial software Virtual Photonics Inc. (VPI). The SOA is operating at bias current of 240 mA. The optical power of the pump signal and the CW signal are 30 and 1 mW, respectively. The relative optical power changes by around 14 dB when CD varies from 0 to 1200 ps/nm. The CD monitoring results under different DGDs and OSNRs are illustrated in Figs. 8 (a) and 8(b), respectively.

It can be seen that, the slope of *F* corresponding to the monitoring sensitivity decreases slightly with the increase of DGD value. Figure 8(a) shows that, the impact of PMD on the CD monitoring results is negligible. Figure 8(b) shows that the monitoring curves coincide well in general for OSNR value higher than 25 dB, but deviates for OSNR



(a) (b)

Fig. 8 *F* versus different cumulated dispersion under different (a) DGDs and (b) OSNRs for 80 Gbit/s NRZ-QPSK signal value lower than 25 dB. However, *F* still increases with the increasing of the dispersion.

5 Conclusions

In this paper, an all-optical CD monitoring scheme is proposed and demonstrated utilizing the cross modulation effects of SOA for 40 Gbit/s (N)RZ-DPSK system. In particular, the optical power of the output spectral components, which is from the probe's frequency up to the signal bandwidth, is used for CD monitoring. The CD value reaching 1000 and 700 ps/nm are monitored for NRZ-DPSK and RZ-DPSK signal in real-time, respectively. In addition, the effects of PMD and OSNR on the monitoring results are also experimentally investigated, indicating that the technique works well with different DGDs and OSNRs within a certain range. Since the monitoring curve increases yet with the CD of the signal under lower OSNR, the scheme still works in practice by keeping the OSNR of the signal in a fixed value before deploying the CD monitoring. Moreover, the CD monitoring results for 80 Gbit/s NRZ-QPSK signal under different PMDs and OSNR are also simulated and demonstrated, showing that this method is applied to advanced modulated formats.

Acknowledgements This work was supported by the National Basic Research Program of China (No. 2011CB301704), the National Science Fund for Distinguished Young Scholars (No. 61125501) and the National Natural Science Foundation of China (NSFC) (Grant No. 61007042).

References

1. Pan Z Q, Yu C Y, Willner A E. Optical performance monitoring for the next generation optical communication networks. Optical Fiber Technology, 2010, 16(1): 20–45
2. Chan C C, ed. Optical Performance Monitoring: Advanced Techniques for Next-Generation Photonic Networks. Burlington, MA: Academic Press, 2010
3. Li Z, Li G. Chromatic dispersion and polarization-mode dispersion monitoring for RZ-DPSK signals based on asynchronous amplitude-histogram evaluation. Journal of Lightwave Technology, 2006, 24 (7): 2859–2866
4. Wu Z, Yu Y, Zhang X. Chromatic dispersion monitoring for NRZ-DPSK system using asynchronous amplitude histogram evaluation. Photonics Journal, IEEE, 2012, 4(4): 1212–1219
5. Kozicki B, Takuya O, Hidehiko T. Optical performance monitoring of phase-modulated signals using asynchronous amplitude histogram analysis. Journal of Lightwave Technology, 2008, 26(10): 1353–1361
6. Zhao J, Li Z, Liu D, Cheng L, Lu C, Tam H Y. NRZ-DPSK and RZ-DPSK signals signed chromatic dispersion monitoring using asynchronous delay-tap sampling. Journal of Lightwave Technology, 2009, 27(23): 5295–5301
7. Kozicki B, Maruta A, Kitayama K I. Experimental demonstration of optical performance monitoring for RZ-DPSK signals using delay-tap sampling method. Optics Express, 2008, 16(6): 3566–3576
8. Vo T D, Corcoran B, Schröder J, Pelusi M D, Xu D X, Densmore A, Ma R, Janz S, Moss D J, Eggleton B J. Silicon-chip-based real-time dispersion monitoring for 640 Gbit/s DPSK signals. Journal of Lightwave Technology, 2011, 29(12): 1790–1796
9. Yang J Y, Zhang L, Wu X, Yilmaz O F, Zhang B, Willner A E. All-optical chromatic dispersion monitoring for phase-modulated signals utilizing cross-phase modulation in a highly nonlinear fiber. Photonics Technology Letters, IEEE, 2008, 20(19): 1642–1644
10. Vorreau P, Kilper D C, Leuthold J. Optical noise and dispersion monitoring with SOA-based optical 2R regenerator. Photonics Technology Letters, IEEE, 2005, 17(1): 244–246
11. Yang J, Yu C Y, Yang Y F, Cheng L H, Li Z H, Lu C, Lau A P T, Tam H, Wai P K A. PMD-insensitive CD monitoring based on RF clock power ratio measurement with optical notch filter. Photonics Technology Letters, IEEE, 2011, 23(21): 1576–1578
12. Zhao J, Lau A P T, Qureshi K K, Li Z H, Lu C, Tam H Y. Chromatic dispersion monitoring for DPSK systems using RF power spectrum. Journal of Lightwave Technology, 2009, 27(24): 5704–5709
13. Lize Y K, Christen L, Yang J Y, Saghari P, Nuccio S, Willner A E, Kashyap R. Independent and simultaneous monitoring of chromatic and polarization-mode dispersion in OOK and DPSK transmission. Photonics Technology Letters, IEEE, 2007, 19(1): 3–5
14. Tsai K T, Way W I. Chromatic-dispersion monitoring using an optical delay-and-add filter. Journal of Lightwave Technology, 2005, 23(11): 3737–3747
15. Shen T S R, Lau A P T, Yu C Y. Simultaneous and independent multi-parameter monitoring with fault localization for DSP-based coherent communication systems. Optical Express, 2010, 18(23): 23608–23619
16. Faruk M S, Mori Y, Zhang C, Igarashi K, Kikuchi K. Multi-impairment monitoring from adaptive finite-impulse-response filters in a digital coherent receiver. Optics Express, 2010, 18(26): 26929–26936
17. Qi S, Lau A P T, Lu C. Fast and robust chromatic dispersion estimation using auto-correlation of signal power waveform for DSP based-coherent systems. In: Proceedings of Optical Fiber Communication Conference. Los Angeles: Optical Society of America, 2012
18. Joergensen C, Danielsen S L, Stubkjaer K E, Schilling M, Daub K, Doussiere P, Pommerau F, Hansen P B, Poulsen H N, Kloch A, Vaa M, Mikkelsen B, Lach E, Laube G, Idler W, Wunstel K. All-optical wavelength conversion at bit rates above 10 Gb/s using semiconductor optical amplifiers. IEEE Journal on Selected Topics in Quantum Electronics, 1997, 3(5): 1168–1180
19. Durhuus T, Mikkelsen B, Joergensen C, Lykke Danielsen S, Stubkjaer K E. All-optical wavelength conversion by semiconductor optical amplifiers. Journal of Lightwave Technology, 1996, 14(6): 942–954
20. Dorrer C, Maywar D N. RF spectrum analysis of optical signals using nonlinear optics. Journal of Lightwave Technology, 2004, 22 (1): 266–274

21. Pelusi M, Luan F, Vo T D, Lamont M R E, Madden S J, Bulla D A, Choi D Y, Luther-Davies B, Eggleton B J. Photonic-chip-based radio-frequency spectrum analyser with terahertz bandwidth. Nature Photonics, 2009, 3(3): 139–143
22. Nezam S M R M, Song Y W, Yu C, McGeehan J E, Sahin A B, Willner A E. First-order PMD monitoring for NRZ data using RF clock regeneration techniques. Journal of Lightwave Technology, 2004, 22(4): 1086–1093
23. Park K J, Lee J H, Youn C J, Chung Y C. A simultaneous monitoring technique for polarization-mode dispersion and group-velocity dispersion. In: Proceedings of Optical Fiber Communication Conference. Anaheim, CA: IEEE, 2002, 199–200