High-speed polarization mode dispersion compensation in a 43-Gb/s RZ-DQPSK transmission system over 1200 km of standard single-mode fibre*

Tian Feng(田 凤)[a)†], Zhang Xiao-Guang(张晓光)[a)], Weng Xuan(翁 轩)[a)], Xi Li-Xia(席丽霞)[a)], Zhang Yang-An(张阳安)[a)], and Zhang Wen-Bo(张文博)[b)]

[a)] *Key Laboratory of Information Photonics and Optical Communications of Ministry of Education, Beijing University of Posts and Telecommunications, P. O. Box 72, Beijing* 100876, *China*

[b)] *School of Science, Beijing University of Posts and Telecommunications, Beijing* 100876, *China*

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This paper reports that the designed optical polarization mode dispersion compensator shows a good performance under the real-time variation of differential group delay, state of polarization and principal state of polarization in a (40×43)-Gb/s dense-wavelength-multiplexing, 1200-km enhanced return-to-zero differential-quadrature-phase-shift-keying (RZ-DQPSK) system. The polarization mode dispersion tolerance of the system is improved by 26 ps using the optical polarization mode dispersion compensator. The short and long time stabilities are tested with the bit error ratio recorded.

Keywords: optical polarization mode dispersion compensator, polarization mode dispersion tolerance, bit error ratio, forward error correction

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1. Introduction

In high-speed long-haul optical transmission systems with channel data rates at 40 Gb/s and beyond, polarization mode dispersion (PMD) is one of the major obstacles which limits system performance.[1−3] It is desired, or in most cases required, to increase the system tolerance through polarization mode dispersion compensation and mitigation.[4−7]

In previous literatures, the real-time endless control of polarization mode dispersion compensation has been realized either in a back-to-back case (just using polarization mode dispersion emulator)[8−11] or in the real fibre link as long as 320 km.[12] In Ref. [10], an experiment of polarization mode dispersion compensation was reported for phase-shaped binary transmission modulation formats, in which only first-order polarization mode dispersion and state of polarization (SOP) variations were emulated, and 10-hour stabilities were tested with the bit error ratio (BER) recorded without transmission in a real fibre link (without high-order polarization mode dispersion effects).

In this paper, real-time polarization mode dispersion compensation is successfully demonstrated in a 43-Gb/s, 1200-km enhanced RZ-DQPSK system. The performances of particle swarm optimization (PSO) and cross-tracing as the tracking algorithms in optical polarization mode dispersion compensator (OPMDC) are compared. The effectiveness of the optical polarization mode dispersion compensator is verified in different conditions,[13] including a fast changing of state of polarization, abrupt variation of differential group delay (DGD), principal state of polarization (PSP) quickly rotating and sharply disturbing on the test system, in which first-order and higher-order polarization mode dispersions all exist. For a 43-Gb/s RZ-DQPSK system, the polarization mode dispersion tolerance can be tripled after the optical polarization mode dispersion compensator within a 1-dB optical signal noise ratio (OSNR) penalty.

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†Corresponding author. E-mail: tian_feng_8888@163.com

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2. The optical polarization mode dispersion compensator configuration and tracking algorithm

2.1. The configuration of the optical polarization mode dispersion compensator

The configuration of the optical polarization mode dispersion compensator used in the experiment is shown in Fig. 1. It consists of a high-speed polarization controller (PC),[14] a piece of polarization maintaining fibre (PMF), an in-line polarimeter and a logic control unit based on digital signal processor (DSP). The differential group delay of the polarization maintaining fibre is set as 30 ps. A polarimeter is used to instantaneously measure the Stokes parameters and the degree of polarization (DOP) in the fibre link.[15−19] A modified particle swarm optimization algorithm combined with a cross-tracing algorithm is used as the entire algorithm for endless feedback control for the entire polarization mode dispersion compensation procedure. A high-speed hardware device and a superior algorithm are two important factors for an optical polarization mode dispersion compensator.[20] In the tracking process, the response time for one loop is dozens of microseconds.

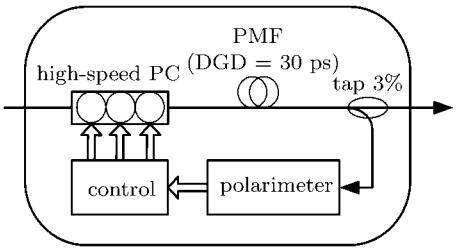


Fig. 1. Configuration of the optical polarization mode dispersion compensator.

In the experiment, we adopted the modified particle swarm optimization as the searching algorithm and the cross-tracing algorithm as the tracking algorithm. Compared with the previous particle swarm optimization algorithm,[9] the modified particle swarm optimization has the advantages of: (i) rapid convergence to the global optimum rather than being trapped in local sub-optima; (ii) robustness to noise. The cross-tracing algorithm is a newly invented endless tracking algorithm, which has strong ability of locking the searched global optimum and takes less time for each feedback.

2.2. The tracking algorithm

In the experiment, we compared the effectiveness of the particle swarm optimization algorithm and cross-tracing as tracking algorithms by recording the average iteration number and each feedback time-consuming in 50 tracing processes. We set the threshold of searching function value (DOP) to 0.98 and let the algorithm run 50 times, each time the maximum number of iteration is 50. If the threshold of the searching function value is larger than the threshold value, the tracking algorithm breaks up and the number of iteration is recorded. The results are shown in Fig. 2 and Table 1. We can see that for the case of using particle swarm optimization algorithm, the average number iteration of searching is about 3.54, the time-consuming for each feedback is 39.64 μs,

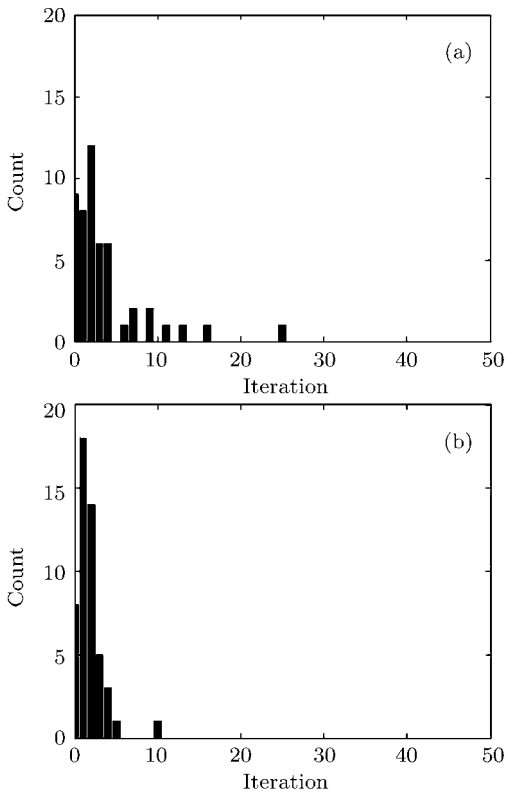


Fig. 2. The feedback number in 50 times tracing processes: (a) particle swarm optimization algorithm; (b) cross-tracing algorithm.

Table 1. Comparison of particle swarm optimization algorithm and cross-tracing algorithm.

Tracking algorithm	Average iteration number	Each feedback time-consuming/μs
Cross-tracing	1.76	25.8
PSO	3.54	39.46

while for the case of using cross-tracing algorithm, the average number iteration of searching is about 1.76, the time-consuming for each feedback is 25.8 μs. It is concluded that the cross-tracing algorithm is a better tracking algorithm for polarization mode dispersion compensation.

3. Experimental setup and experimental results

3.1. Experimental setup

In Fig. 3(a) 43-Gb/s RZ-DQPSK signals with central frequency at 193.1 THz, which is one of the channels of dense-wavelength-multiplexing (DWM) with 50-GHz spacing, is fed into a polarization mode dispersion emulation unit. The polarization mode dispersion emulation unit consists of two polarization scramblers (PSs) and a first-order polarization mode dispersion emulator (PMDE) in the middle. The polarization scrambles before and after the polarization mode dispersion emulator are used to simulate the state of polarization changes and the principal state of polarization changes, repectively. Then the amplified spontaneous emission (ASE) noise is coupled into the link to evaluate the optical signal-to-noise ratio penalties.

Figure 3(b) shows a schematic diagram of the transmission experimental setup. In a (40×43) Gb/s, 50-GHz spacing, 1200-km, DWM RZ-DQPSK system, one channel of 193.1 THz is used. One polarization scrambler (PS) and one polarization mode dispersion emulator are placed before the 1200-km fibre link. The polarization scrambler in front of the polarization mode dispersion emulator acts as a time-varying state of polarization generator. The 1200-km transmission link is comprises 16 spans of 75-km standard single-mode fibre (SSMF) with dispersion compensation (DCM). The fibre span loss is compensated by an erbium-doped fibre amplifier (EDFA) with a gain of 23 dB. An attenuator and an erbium-doped fibre amplifier (EDFA) are used to adjust the optical signal noise ratio, which is monitored by an optical spectrum analyser (OSA).

The one-stage optical polarization mode dispersion compensator is placed in front of the receiver and dynamically adjusted with a feedback signal to track the polarization mode dispersion, state of polarization and principal state of polarization variation. The improved particle swarm optimization algorithm is adopted as the control algorithm; it works in a tracking mode to follow the polarization mode dispersion variation in the link by optimizing the feedback signal.

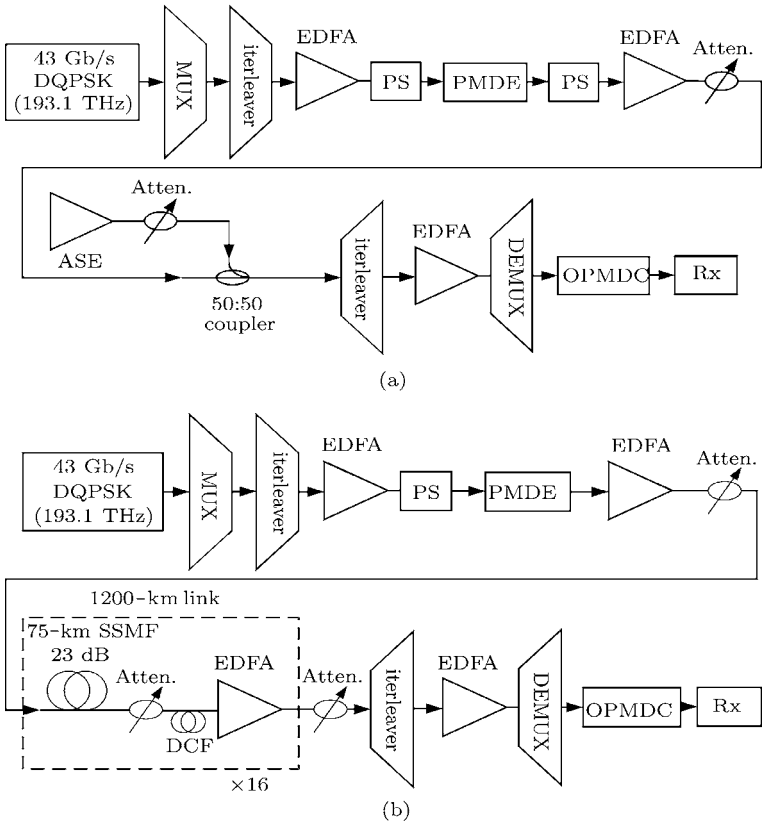


Fig. 3. The emulation experimental setup of the polarization mode dispersion compensation (a) and the transmission experimental setup of the polarization mode dispersion compensation (b).

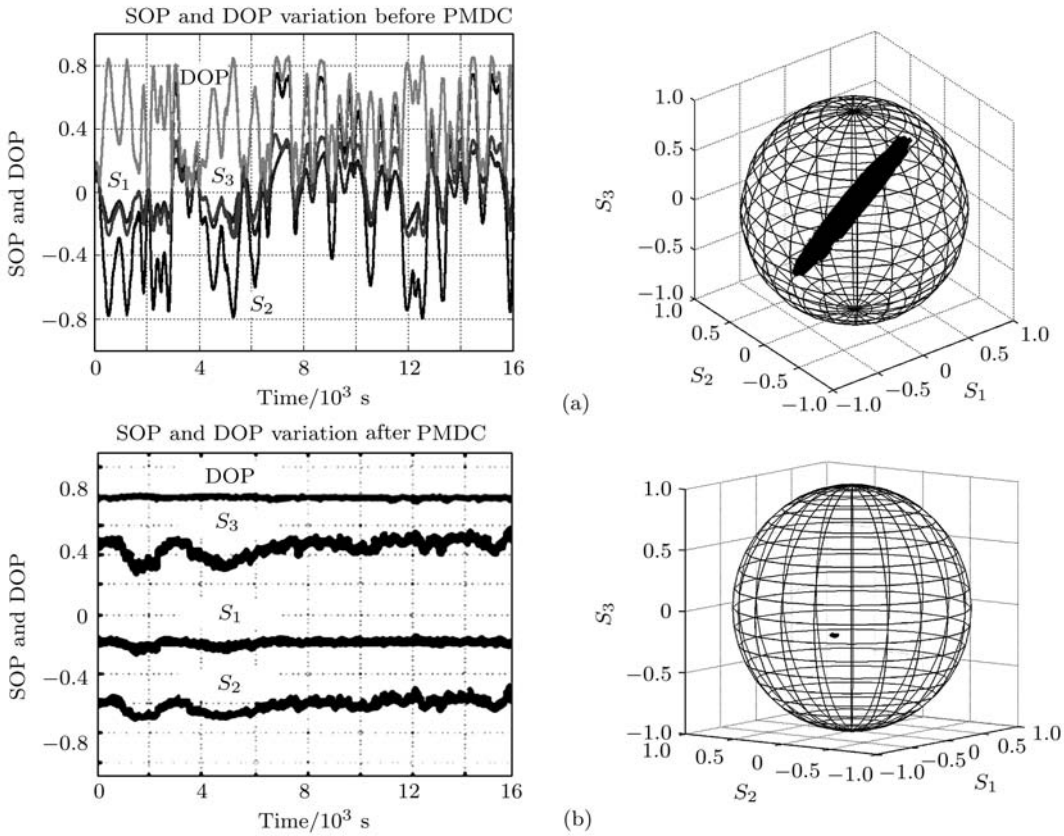


Fig. 4. The state of polarization and degree of polarization variation and corresponding state of polarization track on the Poincaré sphere: (a) before polarization mode dispersion compensation; (b) after polarization mode dispersion compensation.

3.2. Emulation experimental results

3.2.1. The change of SOP

In the emulation experiment, the differential group delay of the polarization mode dispersion emulator in the link is 45 ps and that of the polarization mode dispersion compensator is set to 30 ps. The PS before polarization mode dispersion emulator is set to scan rate 8 of HP11896A which means the average state of polarization variation is about 85 rad/s. The OSNR is set to 13.8 dB. The variation of the state of polarization and the degree of polarization and the corresponding state of polarization track on the Poincaré sphere are recorded before and after polarization mode dispersion compensation. The results are shown in Fig. 4. It can be seen that the variation of the state of polarization and the degree of polarization are very large, the state of polarization track on the Poincaré sphere is a needle-like spheroid before polarization mode dispersion compensation, as shown in Fig. 4(a). After polarization mode dispersion compensation, the state of polarization and the degree of polarization variations are very small, which tend to be a constant value and the state of polarization track on the Poincaré sphere is a point. The results are presented in Fig. 4(b). The degree of polarization takes the maximum value of 0.8 after polarization mode dispersion compensator for considering amplified spontaneous emission noise. So it indicates that the optical polarization mode dispersion compensator works well and can track the fast change of state of polarization.

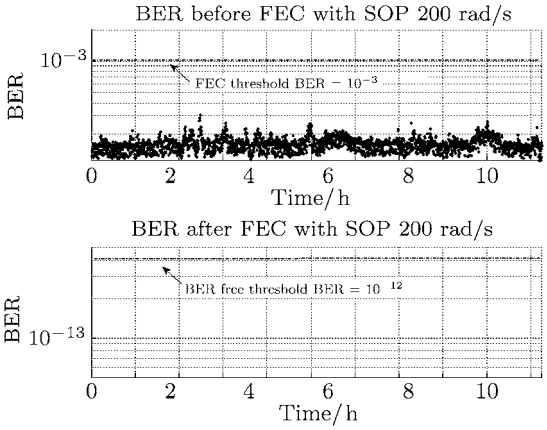


Fig. 5. The bit error ratio recorded with a polarization mode dispersion compensator for 10 hours before and after FEC.

The polarization scrambler before polarization mode dispersion emulator (N7788 Polarization Controller) is set to scan rate 34 and the speed of change

of state of polarization is 200 rad/s. The BER is measured with a polarization mode dispersion compensator. Figure 5 shows that the bit error ratio before forward error correction (FEC) is always below 10^{-3} and bit error ratio after FEC is 0 ($< 10^{-12}$) during the 10-hours test time. So the polarization mode dispersion compensator performance is robust with a fast change of state of polarization.

3.2.2. The change of DGD

Figure 6 gives the measured optical signal-to-noise ratio penalty at a 10^{-3} bit error ratio versus differential group delay for the 43-Gb/s RZ-DQPSK signals with and without the polarization mode dispersion compensator. The polarization mode dispersion tolerance of the 43-G/s RZ-DQPSK system can be increased from 17 ps to 43 ps by using the optical polarization mode dispersion compensation with 1-dB optical signal noise ratio penalty. It means that with the optical polarization mode dispersion compensation prototype, most of the existing optical transmission systems will have the capability of polarization mode dispersion tolerance up to 43 ps. The problem of polarization mode dispersion which occurs in updating the 10-Gb/s optical communication systems to 40-Gb/s can be solved by using a RZ-DQPSK combined with optical polarization mode dispersion compensation.[21]

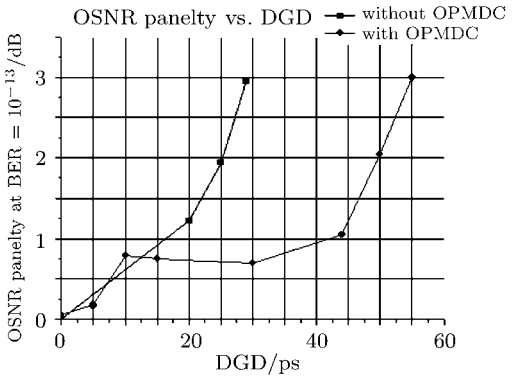


Fig. 6. The OSNR penalty at BER = 10^{-3} versus differential group delay for 43-Gb/s RZ-DQPSK.

Figure 7 shows bit error ratio variation in the case of changing differential group delay from 0 ps to 45 ps (manually jumping 5 ps every 2 seconds) using a polarization mode dispersion emulator (PE4200, fibrepro Co.) with a 1-dB optical signal-to-noise ratio margin. It shows that bit error ratio before FEC is always below the FEC threshold of 10^{-3} bit error ratio and the bit error ratio measured in the whole process after FEC is 0 ($< 10^{-12}$). In optical transmission systems, the change of differential group delay is not very fast, usually several pico-seconds per hour. The optical polarization mode dispersion compensation prototype with FEC is able to perform bit free in that kind of situation.

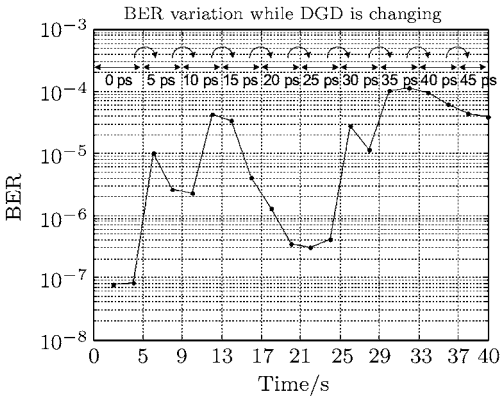


Fig. 7. The bit error ratio variation while the differential group delay is changing.

3.2.3. The change of principal state of polarization

The scrambler (HP11896A Polarization Controller) after the polarization mode dispersion emulator is at scan rate 8 and the speed of the principal state of polarization variation is 85 rad/s. The average differential group delay of the system is 30 ps, according to Ref. [21], the second-order polarization mode dispersion can be calculated about 1530 ps^2. The performance of the polarization mode dispersion compensator is measured with a bit error ratio. Figure 8 shows that the bit error ratio before FEC is always below 10^{-3} and the bit error ratio after FEC is 0 ($< 10^{-12}$) during the 10-hours test time. So the polarization mode dispersion compensator performance is robust with fast change of principal state of polarization (including second-order polarization mode dispersion effects).

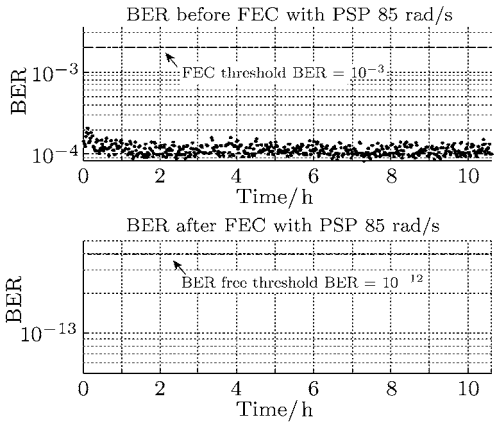


Fig. 8. The bit error ratio recorded with polarization mode dispersion compensator for 10 hours.

3.3. Transmission experimental results

Figure 9 shows the setup of the testbed and figure 10 depicts the bit error ratio variation during 12-hours. The polarization mode dispersion emulator in Fig. 3(b) is set to 30 ps and the polarization scrambler in front of it is set to scan rate 8. The polarization mode dispersion parameter of the fibre we used is about 0.4 ps/km$^{1/2}$. For 1200-km long fibre link, the total differential group delay is about 13 ps. Considering the differential group delay of polarization mode dispersion emulator, we find that the average differential group delay of the transmission link is around 48 ps. The state of polarization changed at an average rate of 85 rad/s. As shown in Fig. 9, the 16 standard single-mode fibre spans are set on the shelf at the right side of the EDFAs and DCMs. We occasionally knocked the shelf and kicked the DCM with moderate strength during the test (with first-order and higher-order polarization mode dispersion), which means that the optical polarization mode dispersion compensation can endure sharp disturbances in the process of polarization mode dispersion compensation. The optical signal noise ratio measured at the point before the signals entering the interleaver is about 15 dB, which is about a 2-dB optical signal-to-noise ratio margin. It shows that the bit error tatio before FEC is always below 10^{-3} and the bit error ratio after FEC is 0 ($< 10^{-12}$) during the 12-hours test time (Fig. 10).

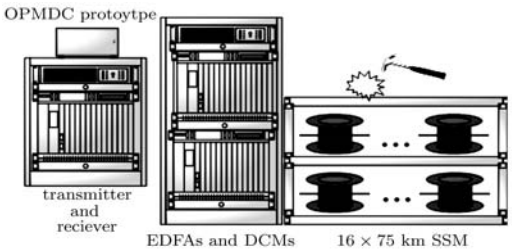


Fig. 9. The setup of the testbed.

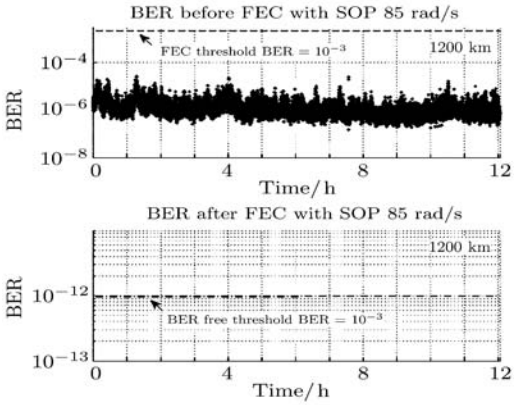


Fig. 10. The bit error ratio recorded with polarization mode dispersion compensator for 12 hours.

In the testbed we also performed the experiment when the polarization scrambler is set to scan rate 34 (N7788 Polarization Controller), whose state of polarization variation rate is about 200 rad/s. The bit error ratio free result is obtained during 1-hour, as shown in Fig. 11.

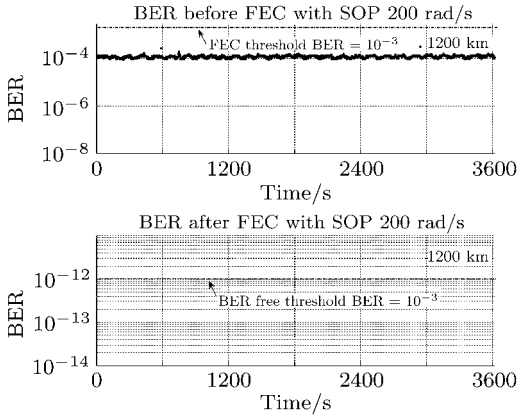


Fig. 11. The bit error ratio recorded with polarization mode dispersion compensator for 1 hour.

4. Conclusion

In this paper, we have reported an automatic optical polarization mode dispersion compensator prototype we made working in a testbed with 43-Gb/s RZ-DQPSK, 1200-km long fibre link under the condition of fast changes of state of polarization and principal state of polarization (including second-order polarization mode dispersion effects), jump variation of differential group delay and moderate knocks on the testbed. Effective polarization mode dispersion mitigation for 43-Gb/s RZ-DQPSK signals was confirmed with long term bit error ratio measurements. The experimental results showed that the tolerance of polarization mode dispersion in the 43-Gb/s RZ-DQPSK system is increased by up to 43 ps with a 1-dB optical signal-to-noise ratio margin and by 50 ps with a 2-dB optical signal-to-noise ratio margin with optical polarization mode dispersion compensation. The prototype can compensate first-order and higher-order polarization mode dispersion and can also endure the sharp disturbances such as knocking on the fibre shelf or kicking the DCMs.

References

[1] Noé R, Koch B, Mirvoda V and Sandel D 2010 *Conference on Optical Fibre Communications* (OFC) paper OThJ1, San Diego, USA

[2] Schmidt B, Lowery A J and Armstrong J 2009 *J. Lightw. Technol. Lett.* **27** 2792

[3] Xie C J, Liu X and Bulow H 2008 *IEEE Photon. Technol. Lett.* **20** 440

[4] Tang X F, Zhang X G , Xi L X, Zhang G Y, Xiong Q J and Li X X 2010 *IEEE/OSA Conference on Optical Fibre Communications* (OFC) paper JWA25, San Diego, USA

[5] Safari M and Shishegar A A 2008 *J. Lightw. Technol. Lett.* **26** 2865

[6] Xie C, Werner D, Haunstein H and Chandrasekhar S 2008 *IEEE/OSA Conference on Optical Fibre Communications* (OFC) paper OThU3, San Diego, USA

[7] Xie C, Chandrasekhar S, Liu X, Werner D and Haunstein H 2008 *European Conference on Optical Communication* (ECOC) paper We.3.E.5, Brussels, Belgium

[8] Zhang X G, Yu L, Zheng Y, Shen Y, Zhou G T, Chen L, Xi L X, Yuan T C, Zhang J Z and Yang B J 2004 *Opt. Commun.* **231** 233

[9] Zhang X G, Zheng Y, Shen Y and Yang B J 2005 *IEEE Photon. Technol. Lett.* **17** 85

[10] Tian F, Xi L X, Zhang X G, Weng X, Zhang G Y and Xiong Q J 2010 *Chin. Opt. Lett.* **8** 815

[11] Zheng Y, Yu L, Yang B J and Zhang X G 2002 *Acta Phys. Sin.* **51** 2745 (in Chinese)

[12] Lanne S and Corbel E 2004 *J. Lightw. Technol. Lett.* **22** 1033

[13] Cai J X, Nissov M, Pilipetskii A N and Bergano N S 2008 *IEEE/OSA Conference on Optical Fibre Communications* (OFC), paper OThU4, San Diego, USA

[14] Zhang X G and Zheng Y 2008 *Chin. Phys.* B **17** 2509

[15] Zhang X G, Fang G Q, Zhao X Y, Zhang W B, Xi L X, Xiong Q J, Li X X and Zhang G Y 2010 *Chin. Phys.* B **19** 044211

[16] Zhang X G, Yu L, Zheng Y, Shen Y, Zhou G T and Yang B J 2004 *IEEE/OSA Conference on Optical Fibre Communications* (OFC), paper ThF1, Los Angeles, USA

[17] Xi L X, Zhang X G, Yu L, Zhou G T, Zhang N, Zhang J Z, Wu B, Yuan T C and Yang B J 2004 *Chin. Opt. Lett.* **2** 262

[18] Sun Y Z, Chun M, Du J and Zhao B C 2010 *Acta Phys. Sin.* **59** 3863 (in Chinese)

[19] Zhang X G, Yu L, Zhou G T, Zhang N, Shen Y, Zheng Y, Li C Y, Liu Y M, Chen L and Yang B J 2003 *Chin. Opt. Lett.* **1** 447

[20] Tanizawa K and Hirose A 2009 *IEEE Photon. Technol. Lett.* **21** 140

[21] Kaminow I and Li T Y 2001 *Optical Fibre Telecommunications* (IVB) (San Diego: Elsevier Science) p. 759