PHOTONIC SENSORS / Vol. 7, No. 1, 2017: 88–96

Performance Analysis of 112 Gb/s × 4-Channel WDM PDM-DQPSK Optical Label Switching System With Spectral Amplitude Code Labels

Isaac Adjaye ABOAGYE*, Fushen CHEN, and Yongsheng CAO

Key Laboratory of Optical Fiber Sensing and Communications, Ministry of Education, School of Communication and Information Engineering, University of Electronic Science and Technology of China, Chengdu, 611731, China

*Corresponding author: Isaac Adjaye ABOAGYE E-mail: ikeaboagye94@gmail.com

Abstract: We present the performance analysis of 112 Gb/s×4 wavelength division multiplexing (WDM) 100 GHz channel spacing polarization division multiplexed-differential quadrature phase shift keying (PDM-DQPSK) optical label switching system with frequency swept coherent detected spectral amplitude code labels. Direct detection is chosen to demodulate the payload by applying a polarization tracker, while 4-bits of 156 Mb/s spectral amplitude code label is coherently detected with a scheme of frequently-swept coherent detection. We optimize the payload laser linewidth as well as the frequency spacing between the payload and label. The label and payload signal performances are assessed by the eye-diagram opening factor (EOF) and bit-error rate (BER) at 10^{-9} as a function of the received optical power (ROP) and the optical signal to noise ratio (OSNR). The payload could well be demodulated after 900 km at a bit error rate of 10^{-3} using forward error correction (FEC).

Keywords: Optical label switching (OLS); polarization division multiplexed (PDM); spectral amplitude code (SAC); wavelength division multiplexing (WDM)

Citation: Isaac Adjaye ABOAGYE, Fushen CHEN, and Yongsheng CAO, "Performance Analysis of 112 Gb/s × 4-Channel WDM PDM-DQPSK Optical Label Switching System With Spectral Amplitude Code Labels," *Photonic Sensors*, 2017, 7(1): 88–96.

1. Introduction

The ever-growing transmission capacity demand in optical transmission systems has brought out the necessity of increasing transmission speed in optical networks. In today's scenario, with the growing demand for a large number of services like video on demand, the use of internet, voice over internet protocol (IP), and live video, has put extreme pressure for the high bandwidth and data rate [1]. Optical transmission networks based on the wavelength division multiplexing (WDM) architecture have bit rates exceeding several terabit per second to serve the ever increasing demand for IP networks. Very high capacity long haul optical transmission systems can be designed using wavelength division multiplexing. The optical label switching (OLS) technology empowers quick optical packet routing and forwarding in IP WDM networks, where the switching of high speed optical payload signals can be controlled by the information provided by low complexity labeling processing schemes [2]. WDM performance is downgraded by dispersion and nonlinearities. With dispersion being

---

Received: 18 May 2016/ Revised: 1 September 2016

DOI: 10.1007/s13320-016-0345-5
Article type: Regular

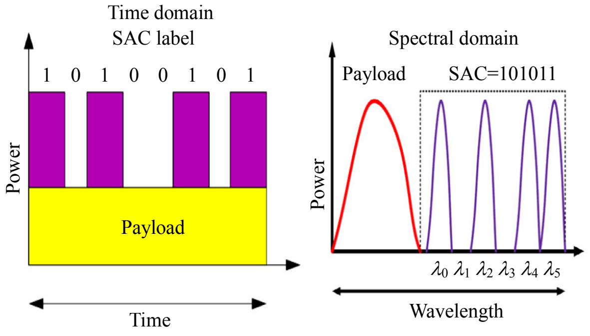
main factor, it must be managed in order to avoid its deleterious effects. In dispersion managed systems, the positive dispersion of single mode fiber (SMF) can be compensated by the large negative dispersion of dispersion compensation fiber (DCF) [3, 4] which must have low insertion loss and low nonlinearity. OLS exploits the enormous bandwidth of optical fibers and the capability of switching data directly in the optical domain. As of late, the spectral amplitude code (SAC) labeled switching system has gained much attention. It is considered as one of the most encouraging labeling scenarios because of its relatively basic structure, high throughput, high speed, and adaptability [5–11]. One technique used to improve the efficiency of the optical communication system is polarization division multiplexing (PDM). Combining PDM signaling and differential quadrature phase shift keying (DQPSK) modulation will realize 4 bits per symbol. PDM permits the multiplication of the transmission capacity as different signals can be transmitted over orthogonal states of polarization of the same light. However, the complexity of label decoder and low speed payload constrains the application of SAC labels. Also a major problem with the practical use of PDM over fiber-optic transmission systems is the drift in the polarization state. This occurs continuously over time due to physical changes in the fiber environment.

In this paper, we build a robust long haul transmission system to evaluate the transmission performance of 112 Gb/s×4-channel PDM-DQPSK SAC label switching system in simulation. Using the polarization tracker, we recover the orthogonal polarization state of the PDM payload signal in order to mitigate the effects of polarization mode dispersion (PMD) and polarization dependent loss (PDL). A novel method of frequency-swept coherent detection is employed to decode SAC label, which reduces the complexity of the label decoder. We analyze the factors that influence the received signal qualities of both the payload and label. The PDM payload is directly detected which allows a significant increase in transmission robustness [12–14] while the parameters are optimized to obtain good transmission performance for the payload and label.

The remaining parts of the paper are organized as follows. Section 2 provides a description of the principles of our proposed frequency-swept coherent detection for SAC labels. The simulation setup of SAC labeling scheme for 112 × 4 Gb/s WDM 100 GHz channel spacing PDM-DQPSK SAC label system with the polarization tracker is presented in Section 3. In Section 4, the simulation result is presented and analyzed. Finally, in Section 5, we conclude the paper.

2. Operation principles of frequency swept coherent detection

Coherent detection allows flexibility in modulation formats as information can be encoded in amplitude and phase, or alternatively in-phase (I) and quadrature (Q) components of a carrier. The receiver exploits knowledge of the carrier's phase to detect the signal. In a SAC label framework, SAC label and payload occupy the same time space however they occupy different wavelengths. Labels are encoded in wavelength domain and recognized by their amplitudes [15]. Figure 1 shows a schematic diagram of SAC label in both the wavelength and time domains.



(a) (b)

Fig. 1 Schematic diagrams of SAC label: (a) time domain and (b) wavelength domain.

The structure of frequency swept coherent detection scheme of SAC label is shown in Fig. 2. Figure 2 (a) is a SAC label which has 4 bits code “1010” in the wavelength domain. Figure 2 (b) is a frequency-swept local oscillator (LO) whose swept frequency covers the entire SAC label’s frequencies. The SAC label and LO are combined by a 3-dB coupler, and the hybrid signal is transferred to the baseband electrical signal in the time domain after photo-detection (PD). Therefore, the label signals can be recovered by low pass filters (LPF) as shown in Fig. 2(c).

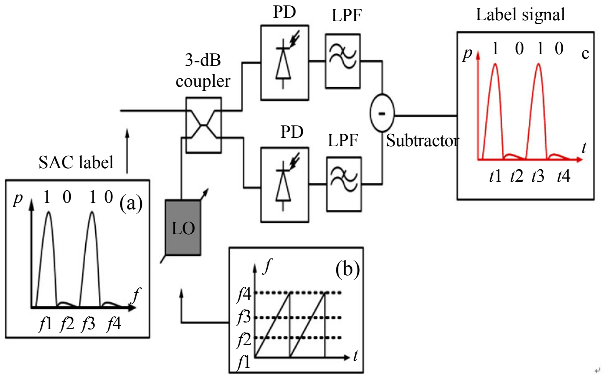


Fig. 2 Principle of frequency-swept coherent detection of SAC label: (a) input SAC label in the wavelength domain, (b) frequency-swept LO, and (c) output SAC label in the time domain.

3. System model setup

The virtual photonic integrated (VPI) transmission maker 8.3 is used to set up the 112 Gb/s × 4-channel WDM PDM-DQPSK transmission system as shown in Fig. 3. Four-channel PDM-DQPSK payload signals with 100-GHz frequency spacing are generated using four distributed feedback (DFB) lasers as the source [16]. For the convenience and simplification of the payload generator, two orthogonal polarization channels are generated for each channel by each distributed feedback (DFB) laser source. A 28 Gbaud DQPSK signal at the transmission wavelengths of 1552.52 nm, 1553.32 nm, 1554.12 nm, and 1554.88 nm respectively for each of the four channels is split by a polarization beam splitter (PBS) into two beams. One beam goes through 0 degree polarization controller (PC), while the other one goes through 90 degree PC after 1-ns delay to make the two signals uncorrelated. A polarization beam combiner (PBC) is employed to combine the two orthogonal polarization signals from each channel into one beam of 112 Gb/s PDM-DQPSK payload for each of the four channels giving a total of 448 Gb/s PDM-DQPSK payload for the four channels which are then multiplexed.

The SAC label is generated using a continuous wave (CW) laser array, an optical switch, and a label encoder used to generate 2^7-1 pseudo random binary sequence (PRBS) label signals. To generate the SAC label signal, a four-DFB laser array and a label encoder are applied at the label rate of 156 Mb/s. The chosen label laser wavelengths are at 1552.92 nm, 1552.96 nm, 1553.00 nm, and 1553.04 nm, respectively. The frequency interval between each label is 5 GHz while the spacing between the payload and label is 40 GHz so as to control the laser pulse signal and encode SAC label. The 156 Mb/s PRBS controls the on-off condition of the optical switch and hence controls the laser pulse signal and encodes the SAC label. By combining the payload and label, we obtain an optical packet of 448 Gb/s PDM-DQPSK payload and 156 Mb/s four-code SAC label. A standard single mode fiber (SSMF) and a dispersion compensation fiber are used as the transmission fiber. An erbium-doped fiber amplifier (EDFA) is installed in the link to compensate for lost power.

A polarization tracker is installed to transform the arbitrary polarization to the settled polarization state. In our simulation, it recovers the orthogonal polarization states of the PDM payload signal with a power loss of greater than 0.1 dB. The polarization tracker recovers 0 degree and 90 degree of two orthogonal polarization states of our PDM payload signal in order to mitigate the PMD impairment. After the polarization tracker, the packet is split into two branches by a 3-dB coupler. The payload signals are demultiplexed and fed into four different payload receivers while the label is fed into a label receiver and demodulated, respectively. In the case of payload, the PBS separates the signals into *X* and *Y* and demultiplexes the PDM signal based on the fact that the polarization states have been set to orthogonal *X* and *Y*. The signal is filtered by an optical band pass filter (OBPF) with a bandwidth of 112 GHz and demodulated by a DQPSK receiver. Each receiver has a pair of MZIs with 0.05-ns delay, Gaussian order of 2, and a bit error rate test (BERT) for each channel to evaluate the DQPSK signal performance.

For the label, a frequency swept laser is simulated by using an optical frequency modulator, driven by a ramp wave generator. The frequency-swept range is from 1552.91 nm to 1553.05 nm, in order to cover all the label available frequencies. The SAC labels are combined with the frequency-swept LO by a 3-dB coupler, and the combined signal is transferred to the electrical domain by a balanced photo detection receiver. The electrical label signal is filtered by a 150-MHz dual-low-pass filter (LPF) and the original SAC label obtained [17, 18].

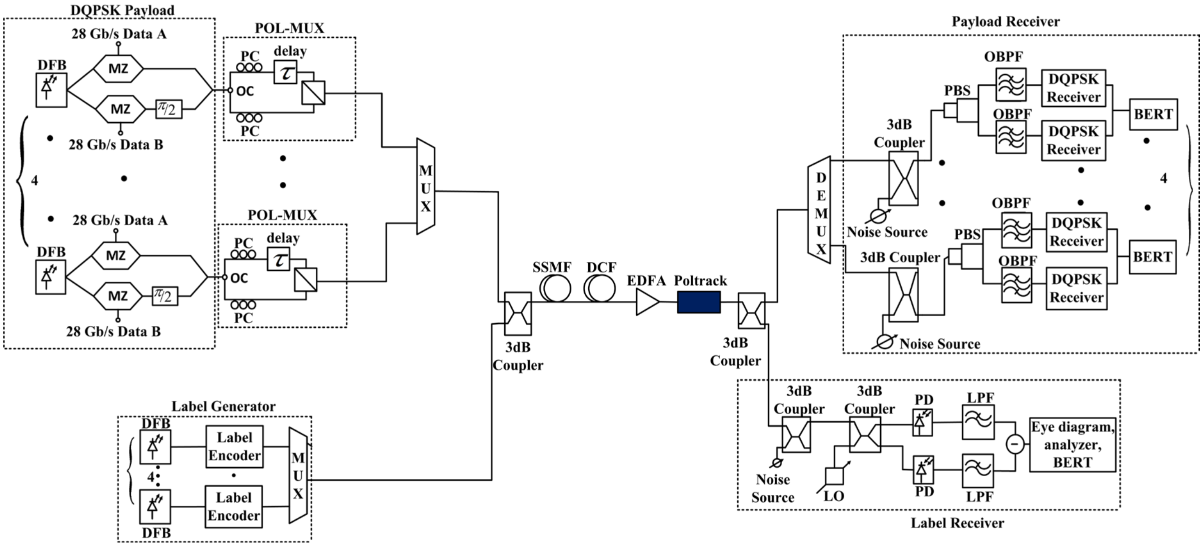


Fig. 3 Simulation setup of 112 Gb/s × 4 WDM 100 Gb/s channel spacing PDM-DQPSK SAC label system.

4. Performance analysis and results of the system

The eye diagram of I and Q components of the received DQPSK signal after 120-km transmission is shown in Fig. 4. The polarization condition of the SAC labels is unusual after transmission. Yet in frequency-swept coherent detection, which is not sensitive to the label's polarization state; the SAC label can in any case be demodulated in our proposed system.

I and Q branches

The reception quality of the payload is affected by the laser linewidth. In Fig. 5, for 1-MHz laser linewidth case, the bit error rate (BER) is smaller than the BER in a 10-MHz laser linewidth in back-to-back (BTB) transmission conditions in all the four channels for the same received optical power (ROP) and optical signal to noise ratio (OSNR). To achieve good transmission performance, the system should operate with current conventional DFB lasers with a typical linewidth value in the order of up to 10 MHz.

Polarization effects due to the interaction between the PMD and PDL can significantly impair optical fiber transmission systems. When PMD and PDL are both present, they interact. The PDM system is very sensitive to both the PMD and PDL effects. A PMD produces a polarization state that varies randomly and a PDL which breaks the orthogonality of the two polarizations. This makes it hard for the signal to be demultiplexed. The polarization tracker is installed to repair the PMD and PDL impairments. This causes a power loss of less than 0.1 dB in our simulation. Figure 6 shows the effects of the polarization tracker and PMD.

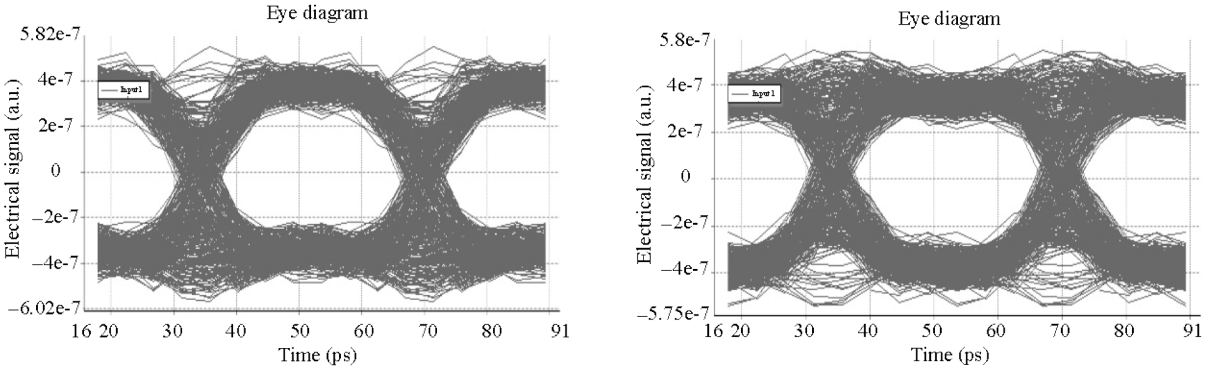
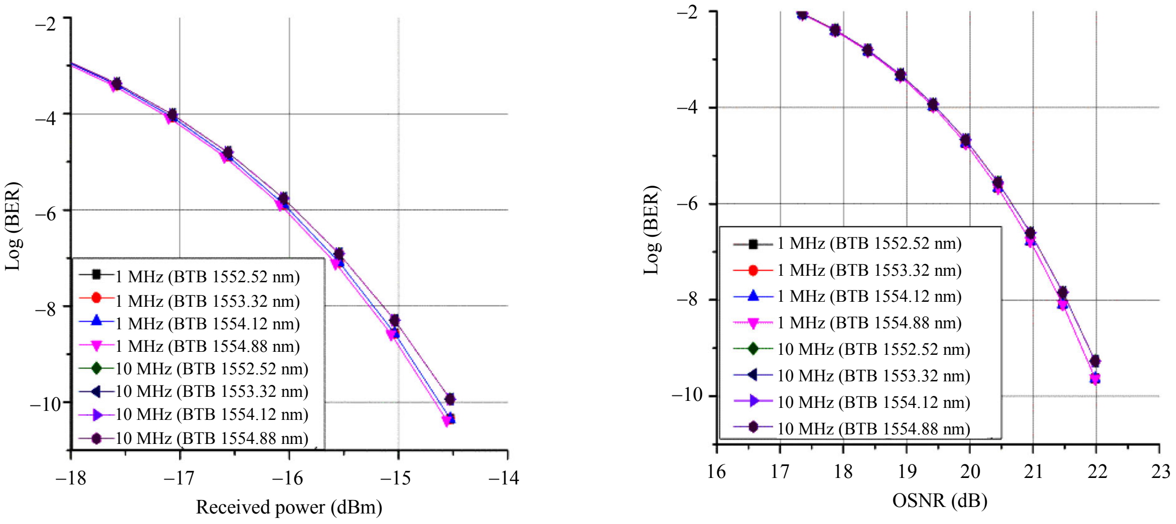
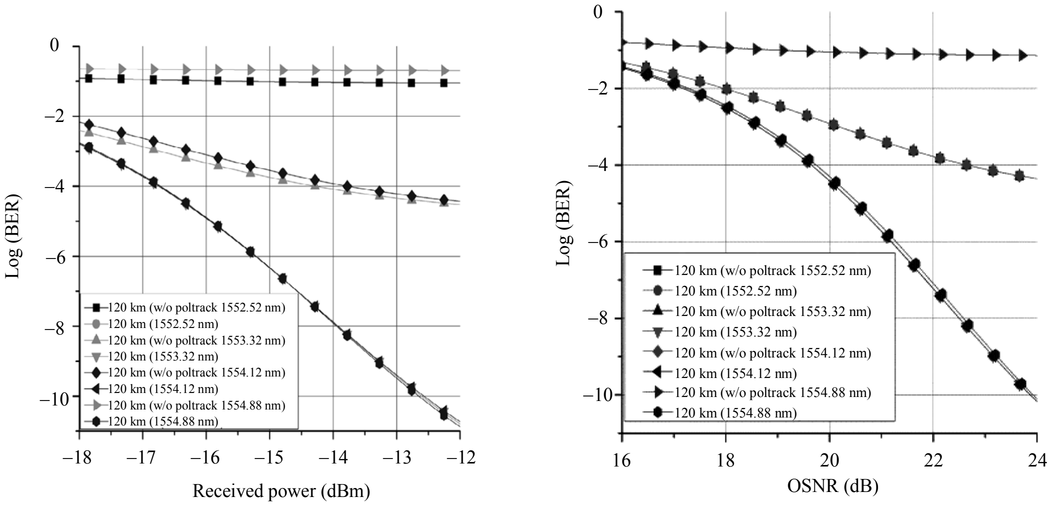


Fig. 4 Eye diagram of the DQPSK payload after 120-km transmission for I and Q branches.



(a) (b)

Fig. 5 Effects of payload’s laser linewidth on WDM channels: (a) BER vs. ROP and (b) BER vs. OSNR.



(a) (b)

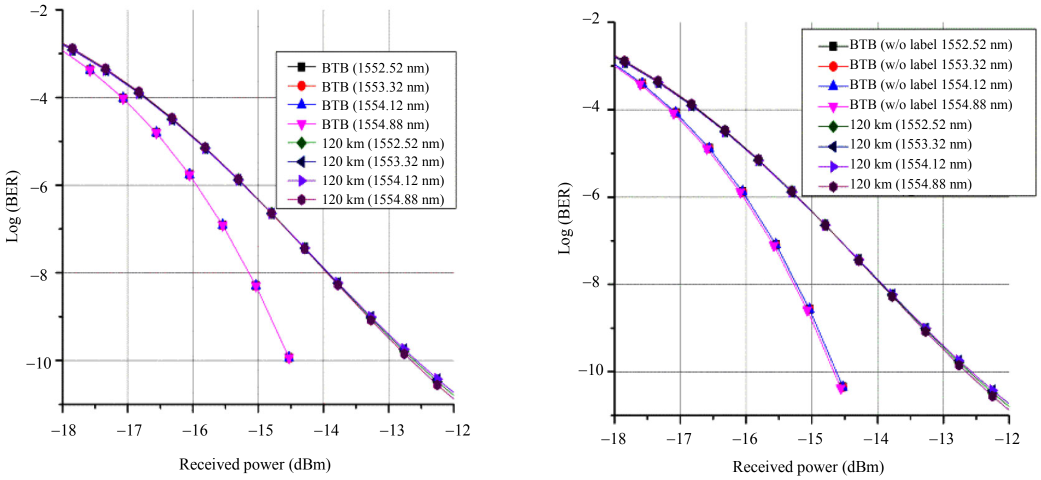
Fig. 6 Effects of the polarization tracker and PMD: (a) BER vs. ROP and (b) BER vs. OSNR.

As observed from Fig. 6, without the polarization tracker, all the four signals cannot be demodulated due to PMD and PDL impairments. With a big PMD in the fiber, the polarization tracker cannot fully recover PMD impairment and may cause some ROP and OSNR penalty. The eye diagram is a successful way of quickly and intuitively assessing the quality of a digital signal. The eye opening factor (*EOF*) is usually used to measure the received quality of SAC label. Its expression is

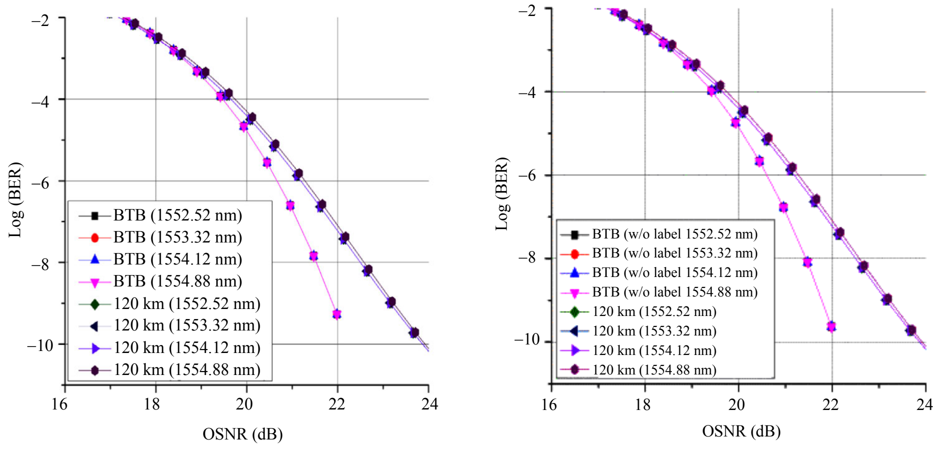
$$EOF=\left.{EA-\left(\sigma_1+\sigma_0\right)}\middle/{EA}\right. \qquad (1)$$

where EA is the eye amplitude, σ_0 and σ_1 are the standard deviations of the sample points of "0" bits and "1" bits within the sample range. In our transmission, the *EOF* of the BTB is better opened than transmission after 120 km. For BTB, the label's *EOF*s are 0.93, 0.93, 0.93, and 0.93 for each of the four 112 Gb/s payload channels, respectively; whereas the label's *EOF*s after 120 km are 0.90, 0.89, 0.90, and 0.89, respectively. A long distance transmission of the SAC label with a high speed payload is achieved with the method of frequency-swept coherent detection.

The transmission performance of the payload of each channel is shown in Figs. 7(a) and 7(b). Figures 7(a) and 7(b) show the transmission penalties for BTB with labels, BTB without labels and after 120 km. For BTB carrying the SAC label, the ROP and OSNR penalty for each of the four payload channels at wavelengths of 1552.52 nm, 1553.32 nm, 1554.12 nm, and 1554.88 nm are 0.2 dB, 0.2 dB, 0.2 dB, and 0.2 dB, respectively for ROP and 0.1 dB, 0.1 dB, 0.1 dB, and 0.1 dB, respectively for OSNR.



(a)



(b)

Fig. 7 Transmission performance of payload after 120 km: (a) performance with and without label: BER vs. ROP and (b) performance with label and without label: BER vs. OSNR.

The payload's ROP for BTB with label and after 120 km for each of the four channels at wavelengths of 1552.52 nm, 1553.32 nm, 1554.12 nm, and 1554.88 nm are −14.7 dBm, −14.7 dBm, −14.7 dBm, and −14.7 dBm, respectively for BTB and −13.3 dBm, −13.2 dBm, −13.3 dBm, and −13.3 dBm, respectively for 120 km at a BER of 10^{-9}. This results in a penalty of 1.4 dB, 1.5 dB, 1.4 dB, and 1.4 dB, respectively for ROP.

The payload's OSNRs for BTB with label and after 120 km for each of the four channels at wavelengths of 1552.52 nm, 1553.32 nm, 1554.12 nm, and 1554.88 nm are 21.9 dB, 21.9 dB, 21.9 dB, and 21.9 dB, respectively for BTB and 23.2 dB, 23.2 dB, 23.2 dB, and 23.3 dB, respectively for 120 km at a BER of 10^{-9}. This results in a penalty of 1.3 dB, 1.3 dB, 1.3 dB, and 1.4 dB, respectively for OSNR.

The payload's ROPs after 120 km without labels for each of the four channels at wavelengths of 1552.52 nm, 1553.32 nm, 1554.12 nm, and 1554.88 nm are −13.9 dBm, −13.9 dBm, −13.9 dBm, and −13.9 dBm, respectively. This results in a penalty for payload without/with the label system of 0.6 dB, 0.7 dB, 0.6 dB, and 0.6 dB. The payload's OSNRs after 120 km without labels for each of the four channels at wavelengths of 1552.52 nm, 1553.32 nm, 1554.12 nm, and 1554.88 nm are 22.8 dB, 22.8 dB, 22.8 dB, and 22.8 dB, respectively.. This results in a penalty for payload without/with the label system of 0.4 dB, 0.4 dB, 0.4 dB, and 0.5 dB. The power penalty and OSNR penalty for the above transmission scheme with label is less than 1 dB. The penalty of BTB/120 km transmission is less than 2 dB, and the penalty of payload without/with label system is less than 1 dB which indicates operational compatibility with 100-GHz WDM channel spacing with low performance penalty.

Lastly, we examine long haul transmission by creating loops to study the performance of the system. The loop consists of a standard single mode fiber (SSMF) with a length of 75 km, dispersion compensation fiber (DCF) with a length of 15 km adding up to a total length of 90 km per loop and an EDFA of 20.0 dB. Using the BER of 10^{-3} and forward error correction (FEC), a transmission distance of 900 km is achieved. The power gain margin can be used to increase the span of the optical link, which accounts for less number of amplifiers. Figures 8(a) and 8(b) show the transmissions using FEC while Tables 1 and 2 show the results obtained for the ROP and OSNR, respectively.

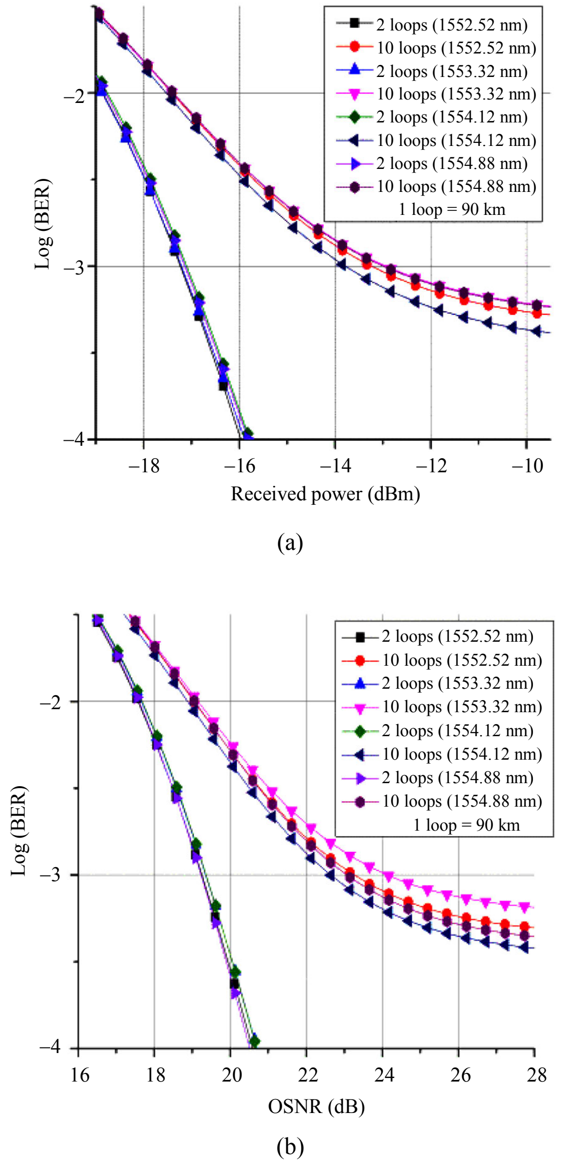


Fig. 8 Long haul transmission using loops and FEC: (a) BER vs. ROP and (b) BER vs. OSNR.

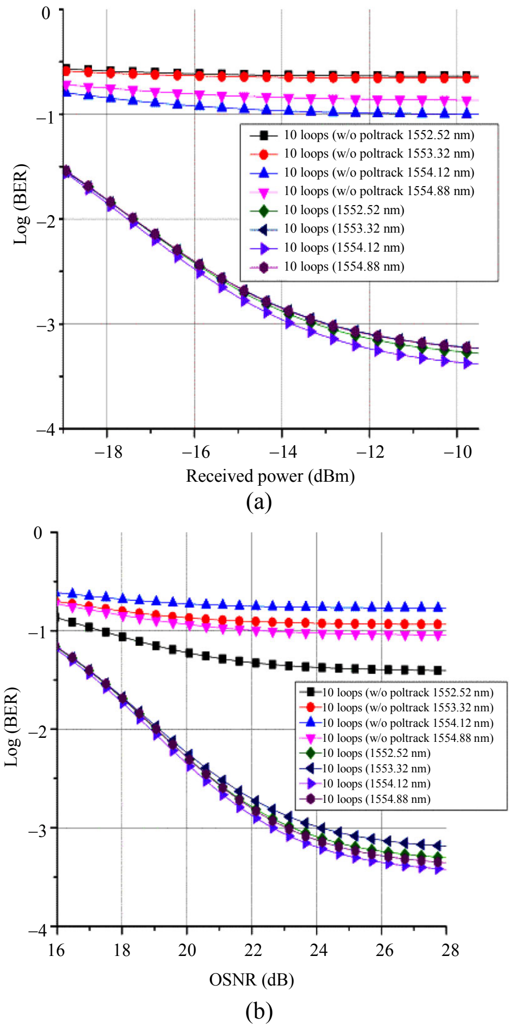
Table 1 Long haul transmission using (FEC): ROP.

Distance (km)	BER	Received power optical (dBm)			
		1552.52 (nm)	1553.32 (nm)	1554.12 (nm)	1554.88 (nm)
180	10^{-3}	−17.2	−17.2	−17.1	−17.1
900	10^{-3}	−13.2	−13.0	−13.7	−13.0

Table 2 Long haul transmission using (FEC): OSNR.

Distance (km)	BER	Optical signal to noise ratio (dB)			
		1552.52 (nm)	1553.32 (nm)	1554.12 (nm)	1554.88 (nm)
180	10^{-3}	19.3	19.4	19.4	19.2
900	10^{-3}	23.3	24.2	22.6	23.1

The effect of polarization tracker and PMD is examined using loops and forward error correction. The results obtained for ROP and OSNR after 10 loops are shown in Figs. 9(a) and 9(b).



(a)

(b)

Fig. 9 Effects of polarization tracker and PMD using loops and FEC: (a) BER vs. ROP and (b) BER vs. OSNR.

5. Conclusions

The performance analysis of 112 Gb/s ×4-channel PDM-DQPSK optical label switching system with spectral amplitude code labels is presented. The payload signal is demodulated using direct detection while the SAC label is detected using frequency swept coherent detection. The polarization tracker in direct detection brings an insertion loss of less than 0.5 dB to each channel and few Watts of power consumption. The laser linewidth of the payload is optimized to 10 MHz. Transmission performances of both the payload and label are good at a BER of 10^{-9}. A 900-km-long haul transmission of the payload is achieved using FEC at a BER of 10^{-3}. This result indicates that the high speed payload and SAC label are compactible. We have demonstrated the proof-of-principle of our proposed approach for 112 Gb/s×4-channel WDM PDM-DQPSK optical label switching system with SAC labels showing good performance with reduced complexity, indicating its potential application in future all optical labeled switching networks.

Acknowledgment

The authors acknowledge the National Natural Science Foundation of China (No. 61205067) for the support.

References

[1] G. H. Patel, R. B. Patel, and S. J. Patel, “Dispersion compensation in 40Gb/s WDM network using dispersion compensating fiber,” *Journal of Information, Knowledge and Research in Electronics and Communication Engineering*, 2013, 02: 662–665.

[2] K. G. Vlachos, I. T. Monroy, A. M. J. Koonen, and C. Peucheret, “STOLAS: switching technologies for optically labelled signals,” *IEEE Optical Communications*, 2003, 41(11): 9–15.

[3] G. P. Agrawal, *Nonlinear fiber optics*. New York: Academic Press, 2001.

[4] G. P. Agrawal, *Applications of nonlinear fiber optics*. New York: Academic Press, 2001.

[5] P. Seddighian, S. Ayotee, J. B. R. Fernandez, J, Penon, L. A. Rusch, and S. Larochelle, “Label stacking in photonic packet switched networks with spectral amplitude code labels,” *Journal of Lightwave Technology* , 2007, 25(2): 463–471.

[6] J. B. R. Fernandez, G. Huang, E. T. Aw, A. Wonfor, R. V. Penty, and I. H. White, “Ultrafast FWM self-routing between 10 ports of spectral amplitude coded 10 Gb/s packets set on 25 GHz grid with unequally spaced bins,” in *Proceeding of IEEE Optical Fiber Communication/National Fiber Optic Engineers Conference*, San Diego, USA, pp. 1–3, 2008.

[7]Z. A. El-Sahn, B. J. Shastri, M. Zeng, N. Kheder, D. V. Plant, and L. A. Rusch, “Experimental demonstration of a SAC-CDMA PON with burst-mode reception: local versus centralized source,” *Journal of Lightwave Technology*, 2008, 26(10): 1192–1203.

[8] J. J. V. Olmos, J. F. Zhang, P. V. H. Nielsen, I. T. Monror, V. Polo, A. M. J. Koonen, *et al.*, “Simultaneous optical label erasure and insertion in a single wavelength conversion stage of combined FSK/IM modulated signals,” *IEEE Photonics Technology Letters*, 2004, 16 (9): 2144–2146.

[9] Y. Cao, F. Chen, and Z. Yang “Frequency swept coherently detected spectral amplitude code for flexible implicit optical label switching,” *Chinese Optics Letters*, 2011, 9(7): 9–12.

[10] A. M. Alhassan, N. Badruddin, N. M. Saad, and S. A. Aljunid, “Beat noise mitigation through spatial multiplexing in spectral amplitude coding OCDMA networks,” in *IEEE 4th International Conference on Photonics*, Melaka, pp. 169–171, 2013.

[11] T. Eltaif, N. Nicholas, M. A. Alsaraj, and B. A. Hamida, “Multi premises network based on spectral amplitude coding optical CDMA systems,” in *IEEE/16th International Conference on Advanced Communication Technology*, Pyeongchang, pp. 1080–1083, 2014.

[12] B. Koch, V. Mirvoda, H. Grießer, H. Wernz, D. Sandel, and R. Noé, “Endless optical polarization control at 56 krads, over 50 gigaradian, and demultiplex of 112-Gbs PDM-RZ-DQPSK signals at 3.5 krads,” *IEEE Journal of Selected Topics in Quantum Electronics*, 2010, 16(5): 1158–1163.

[13] M. Ferrario, P. Boffi, L. Marazzi, P. Martelli, P. Parolari, and M. Martinelli, “Impact of PDL-induced crosstalk on 100-Gbs polarization multiplexed RZ-DQPSK in PMD-affected metro networks,” *Optics Communications*, 2011, 284(24): 5662–5664.

[14] Y. Xu, X. Li, and J. Yu, “Simple scheme for PDM-QPSK payload generation in an optical label switching network,” *Journal of Optical Communications and Networking*, 2016, 8(2): 53–57.

[15] Y. Cao, A. V. Osadchiy, X. Xin, X. Yin, C. Yu, and I. T. Monroy, “Recognition of spectral amplitude codes by frequency swept coherent detection for flexible optical label switching,” *Photonic Network Communications*, 2010, 20(2): 131–137.

[16] Y. Feng, H. Wen, H. Y. Zhang, and X. P. Zheng, “40-Gb/s PolMux-QPSK transmission using low-voltage modulation and single-ended digital coherent detection,” *Chinese Optics Letters*, 2010, 8(10): 976–978.

[17] R. S. Luis, B. J. Puttnam, J. M. D. Mendinueta, S. Shinada, M. Nakamura, Y. Kamio, *et al.*, “Digital signal processing for digital coherent self-homodyne detection,” in *19th OptoElectronics and Communication Conference and the 39th Australian Conference on Optical Fibre Technology*, Melbourne, pp. 904–906, 2014.

[18] J. K. Fischer, R. Elschner, F. Frey, J. Hilt, C. Kottke, C. Schubert, *et al.*, “Digital signal processing for coherent UDWDM passive optical Networks”, in *Photonic Networks; 15 ITG Symposium*, Leipzig, Germany, pp. 1–7, 2014.