Label swapping and packet transmission of DPSK-labeled PPM signal in optical label switching

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A label swapping scheme of an optical labeled signal with differential phase shift keying (DPSK) for label at 2.5 Gb/s and pulse position modulation (PPM) for payload at 40 Gb/s is demonstrated by simulation. Power penalties of ~1.8 and ~0.8 dB are achieved for both the payload and label over 80-km single mode fiber (SMF) transmission. This labeling scheme allows the use of four-wave mixing (FWM) in semiconductor optical amplifier (SOA) to perform label erasure, with advantages of transparence for bit rate, high processing rate, simple architecture, and low cost. Label swapping is demonstrated with appropriate penalties of −3.5 and 0.8 dB for PPM payload and new DPSK label, respectively. To further prove the effectiveness of the proposed scheme, label swapping in the case of using 10-Gb/s DPSK label is also investigated with the power penalties of 6 and 2 dB for PPM payload and new DPSK label.

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Optical packet switching (OPS) has been the focus of next-generation network for its potential for seamless integration of data and optical networks[1]. In particular, optical label switching (OLS) is a promising switching method of OPS, which can perform the ultra-fast packet routing and forwarding in IP over wavelength-division multiplexing (WDM) networks[2−13]. In OLS, the payloads are forwarded and routed directly in the optical layer at an ultra-fast bit rate so that electronics bottlenecks can be solved. Only labels with the routing information are processed in the core nodes. Thus far, several optical labeling schemes have been proposed, including time-serial labeling, sub-carrier multiplexing (SCM) labeling, and orthogonal modulation labeling.

Among these, orthogonal modulation labeling scheme is recognized as a competitive method for its highest spectral efficiency; particularly, differential phase shift keying (DPSK) format has been widely investigated for its good tolerance for fiber nonlinear effect. However, the main disadvantage of orthogonal modulation labeling scheme is the limited extinction ratio (ER) of label and payload. The ER of amplitude-shift keying (ASK) modulated payload should not be too high in order to avoid the long string of "0"s causing the lost of label information. However, the low ER of ASK-modulated signal will worsen the system performance. Here, pulse position modulation (PPM) is used to solve the problem about the ER of ASK-modulated signal, as data are described by the position of pulse within the bit slot so that each bit slot will have equalized energy. In this letter, binary PPM is adopted, where pulses in the first half of the bit slots represent "0" signals and pulses in the second half of the bit slots represent "1" signals, as illustrated in Fig. 1.

In the core node, it is required that the old label be erased and a new label with the routing information of the next node is reinserted. Currently, some methods of wavelength conversion are used to realize label erasure and insertion in the orthogonal modulation labeling, such as a semiconductor optical amplifier Mach-Zehnder interferometer (SOA-MZI)[8] for frequency-shift keying (FSK)/ASK labeling scheme, non-linear optical loop mirror (NOLM)[9] for optical carrier suppression and separation (OCSS) labeling scheme, and a saturated SOA for the ASK/DPSK labeling scheme[10]. For the DPSK label of the orthogonal modulation labeling scheme, the cross gain modulation (XGM) in SOA has been reported to erase the DPSK label[11], and the inversion in the logic of payload is the scheme's weakness. In addition, the DPSK label can also be erased by cross phase modulation (XPM) in SOA-MZI; however, a MZI and two SOAs should be adopted, resulting in a complex architecture.

In this letter, all-optical label swapping and packet transmission for a 40-Gb/s PPM payload with 2.5-Gb/s DPSK label is demonstrated to solve the conflict of the ER of the label or payload. Simultaneous error-free transmission of the payload and label is obtained over 80-km single mode fiber (SMF). Label erasure of the DPSK label is demonstrated based on the four-wave mixing (FWM) process in a SOA, with advantages of transparence for data rate, high processing speed, simple architecture, and low cost.

In this letter, FWM effect is used to realize DPSK label erasure with its transparence for data rate. When two

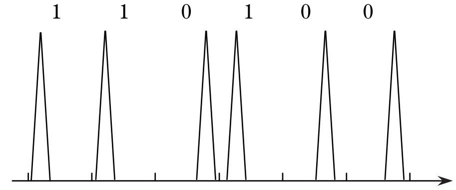

Fig. 1. Spectrum of binary PPM in the time domain.

optical signals co-propagate inside a fiber or SOA, the degenerate FWM process will produce new sidebands due to the nonlinearity effect. If the two signals have the same polarization and the power depletions are negligible, the electric fields of the two FWM products can be expressed as

$$\mathbf{E}_{112} = kA_1^2 A_2 \exp \mathrm{j}[(2\omega_1 - \omega_2)t + (2\phi_1 - \phi_2)], \quad (1)$$

$$\mathbf{E}_{221} = kA_2^2 A_1 \exp \mathrm{j}[(2\omega_2 - \omega_1)t + (2\phi_2 - \phi_1)], \quad (2)$$

$$\omega_{221} = 2\omega_2 - \omega_1, \quad (3)$$

$$\omega_{112} = 2\omega_1 - \omega_2, \quad (4)$$

where $\mathbf{E}_{112}$ and $\mathbf{E}_{221}$ are the corresponding fields of the generated FWM products at the angular frequencies of ω_{112} and ω_{221}, respectively; A_i, ω_i, and $\phi_i\,(i = 1, 2)$ are the corresponding input field amplitude, angular frequency, and phase of amplified optical input signals, respectively; k is a proportional constant related to FWM efficiency. The input lights at ω_1 and ω_2 are DPSK modulated signal and continuous wave (CW) light, as illustrated in Fig. 2, according to Eqs. (1)–(4); the phase relationship of the FWM products is listed in Table 1. It is shown that the phase information of the DPSK signal is transparently transferred to the left sideband at ω_{112}, which has the same phase modulation depth with the original DPSK signal. When the phase modulation depth for the phase information carried at ω_1 is doubled in the resultant phase pattern at ω_{221}, i.e., $\phi_{221} = 2\phi_2 - \phi_1$, the phase information at ω_{221} will be zero for neither data "0" nor data "1", which means that the original DPSK signal is lost. In summary, the left FWM sideband obtains the same phase information with the DPSK input signal, while the phase information of the right FWM sideband is gone. Therefore, the FWM effect can perform label erasure of the DPSK label in the orthogonal modulation-based label switching.

Label erasure is a crucial procedure in all-optical label swapping. The architecture of DPSK/PPM labeling scheme is presented in Fig. 3. At the ingress edge router, the incoming IP packets are assigned with a DPSK label, orthogonally modulated to the PPM payload. At the core router, the received optical power is split into two parts. The first portion is used for label extraction in the label extracted unit (LEU). The demodulated label is then converted into electrical signal by the photodiode (PD). The electrical signal can be fed into a label processor for label clock recovery, label information retrieval, forwarding information lookup, and new label generation. For the remaining part, the label signal is removed by the label removal unit (LRU), where the old DPSK encoded label information is erased and the PPM payload from the incoming packet is preserved. New label information intended for the next routing node will be differentially precoded and then reinserted orthogonally onto the optical packet using phase remodulator. Fiber delay line (FDL) is used to synchronize the LEU with LRU and label insertion unit (LIU).

Figure 4 shows the schematic diagram of the simulation setup for the transmission of a DPSK-labeled PPM signal, as well as label erasure and insertion. A CW from LD1 (laser diode) at frequency of 193.1 THz with launched power of 5 mW is modulated in a phase modulator (PM) with a 2.5-Gb/s pseudorandom binary

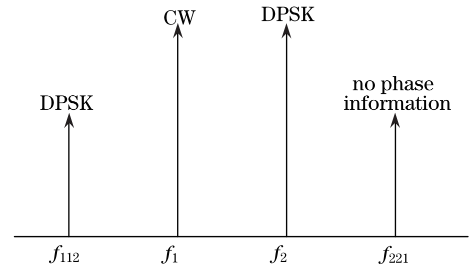

Fig. 2. Frequency spectrum of FWM between the DPSK signal and CW.

Table 1. Phase Relationship of FWM Sidebands and the Two Input Signals

Signal	DPSK Input	CW	Left Sideband	Right Sideband
Wavelength	ω_1	ω_2	ω_{112}	ω_{221}
Phase	ϕ_1	ϕ_2	$2\phi_1 - \phi_2$	$2\phi_2 - \phi_1$
Phase	π(1)	0(1)	π(1)	0(1)
Symbol	0(0)	0(0)	0(0)	0(0)

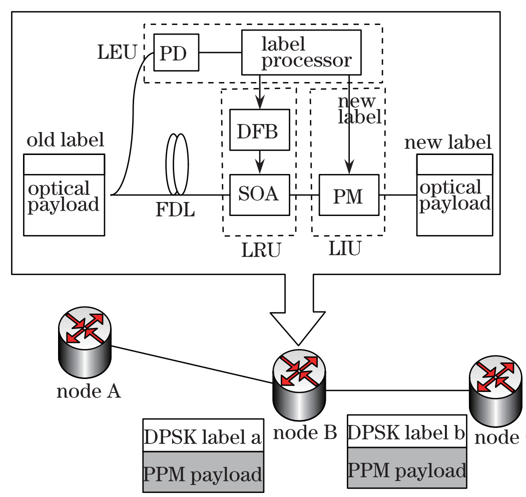

Fig. 3. System architecture for orthogonal DPSK/PPM labeling. DFB: distributed feedback.

sequence (PRBS) with lengths of $2^7 - 1$ to generate the DPSK label. The DPSK label is split into two parts by a 3-dB optical coupler. One part is modulated by 40-Gb/s PRBS data, "Data", with lengths of 2^7-1. A return zero (RZ) pulse generator with low duty cycle is used to create the pulse trains in the PPM signal with pulse width of 2.5 ps. Another one is modulated by the inverted data, "Data". The signals with complementary data are then combined with a 3-dB coupler after an offset of 50 ps, i.e., half a bit period. The orthogonal modulated DPSK/PPM signal is then generated. The DPSK/PPM signal is amplified by an erbium-doped fiber amplifier (EDFA) and then transmitted through 80-km SMF and 16-km dispersion compensation fiber (DCF). The dispersion coefficient and dispersion slope of SMF are 16 ps/(nm·km) and 0.08 ps/(nm^2·km), respectively, whereas the dispersion coefficient and dispersion slope of DCF are –80 ps/(nm·km) and 0.28 ps/(nm^2·km), respectively. After the fiber transmission, the DPSK/PPM signal is coupled with LD2 at frequency of 193.05 THz

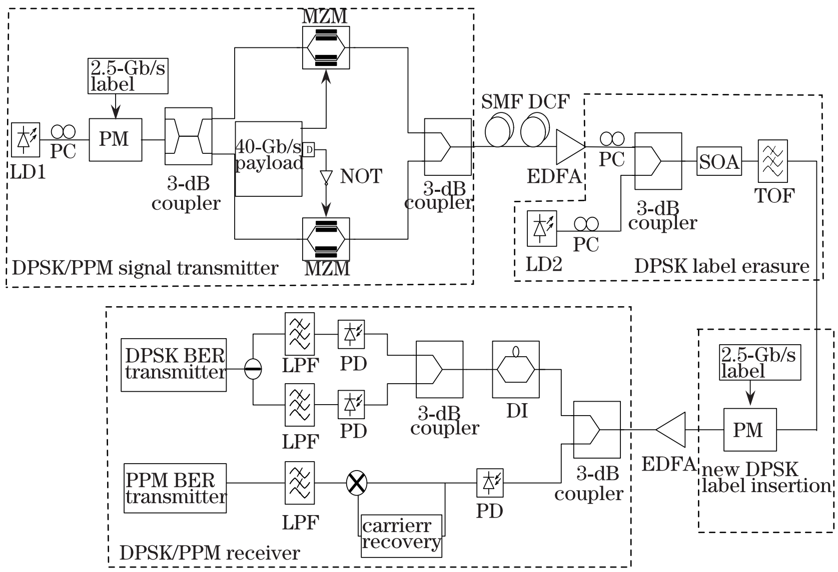

Fig. 4. Simulation setup for the transmission of DPSK-labeled PPM signal and label erasure by SOA and TOF. LPF: low pass filter.

with launched power of 1 mW. Due to the polarization dependence of FWM, two polarization controllers (PCs) are inserted to ensure that the two input signals are copolarized. The combined lights are launched into the SOA biased at about 250 mA. The average power launched into the SOA is about 6 dBm, with the two inputs at similar power level. From the output of the SOA, the FWM-generated signal at 193.15 THz has an optical signal-to-noise ratio (SNR) of 19.6 dB. The center frequency of the tunable optical filter (TOF) is tuned to 193.15 THz to filter the corresponding FWM sideband. After filtering the right FWM sideband, the phase information of the DPSK label is lost and the label erasure can be achieved. A new DPSK label can be remodulated with another PM.

At the receiver node, the DPSK/PPM signal is split into two branches with a 3-dB optical coupler. One branch goes to a Mach-Zehnder delay interferometer (MZDI) followed by a 10-GHz PD for the DPSK label detection. The other branch goes to another 10-GHz PD, and the PPM payload can be detected by multiplying it by the RZ clock, which is recovered from the original RZ signal.

Figure 5 shows the spectrum of time domain of the DPSK/PPM signal. The "Data" is delayed offset of 50 ps and then combined with "Data". Each bit period of 100 ps is divided into two parts-the first slot of 50 ps and the second slot of 50 ps. The pulse in the first slot represents "1", and the pulse in the last slot represents "0". It is realized that the position of pulses presents the data information, i.e., PPM format.

In order to detect the DPSK label, a limited ER of the payload is necessary. An increase in the ER will result in better transmission performance of the payload, but will cause a detrimental effect on the DPSK label. Figure 6 shows the ER versus bit error ratio (BER) with 40-Gb/s PPM payload and 2.5-Gb/s DPSK label in the case of 80-km SMF transmission, compared with the DPSK/ASK labeling scheme at the same bit rate. As

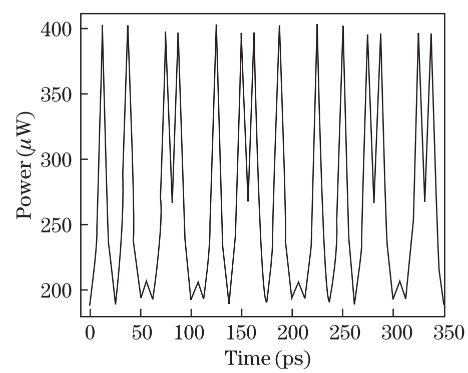

Fig. 5. Spectrum of the time domain of DPSK/PPM.

shown in Fig. 6, a tradeoff between the ER requirements for the payload and the label can be observed. The ER is chosen to be about 4.5 dB in order to obtain the BER of ASK payload and DPSK label of 10^{-9}. As the PPM payload is adopted in this letter, the ER of the payload can be enhanced to be 9.3 dB. The increased ER of the payload is mainly due to the fact that with PPM, data are represented via the temporal placement of the pulse within every bit slot, ensuring a constant energy per bit and avoiding a long string of "0"s, which will cause the lost of the DPSK-encoded label information.

The BER performance for back-to-back (B2B) and after 80-km SMF transmission of 40-Gb/s PPM payload labeled with 2.5-Gb/s DPSK label is illustrated in Fig. 7. At the B2B configuration, receiver sensitivities of ∼22 and ∼12 dBm are achieved for the payload and label, respectively, with BER of 10^{-9}. Both the payload and the label can be obtained error-free after 80-m transmission. The DPSK label shows a low power penalty of 0.8 dB due to the good dispersion tolerance of the DPSK modulation format. The power penalty of PPM payload after transmission through the 80-km SMF is 1.8 dB, owing to the noise and dispersion during the transmission.

Figure 8 is the spectrum of the frequency domain after FWM in SOA and after TOF with bandwidth of 20 GHz. Due to the wavelength conversion of FWM, the PPM payload on the frequency of 193.1 THz is converted on the light wave of the frequency of 193.15 THz, plotted with the dash lines in Fig. 8, with label erasure.

Figure 9(a) shows the PPM eye diagram after label erasure. After label erasure in SOA without new label rewriting, the 2.5-Gb/s DPSK label is suppressed, as shown in Fig. 9(b). Clearly, the label is successfully removed, while the frequency of the corresponding PPM payload is converted to 193.15 THz through the FWM in SOA without introducing noticeable eye closure for the payload, as illustrated in Fig. 9(c). By remodulating another phase modulation, a new DPSK label at 2.5-Gb/s is inserted on the original payload for further transmission in the network. Figures 9(c) and (d) show the signal with a new label and the corresponding DPSK eye diagram, respectively.

Figures 10 and 11 show the BER performance of the 40-Gb/s PPM payload with 2.5- and 10-Gb/s DPSK labels after label erasure and insertion, respectively. After label swapping, the ER of the payload is degraded, and power penalty of payload (at BER = 10^{-9}) of 3.5 and 6 dB are observed in the case of 2.5- and 10-Gb/s DPSK labeling schemes, respectively. This can be attributed to the residual modulation of the original label and the conversion efficiency of FWM in SOA. In addition, the

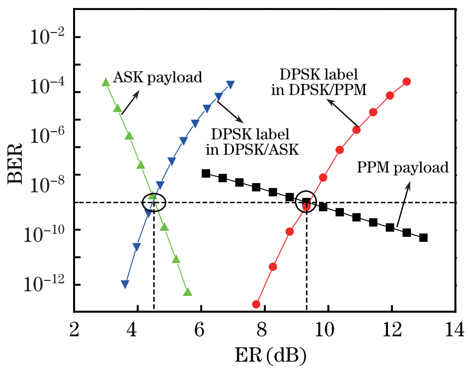

Fig. 6. Measured B2B BER versus payload ER for the DPSK/ASK labeling scheme and DPSK/PPM labeling scheme with the same bit rate.

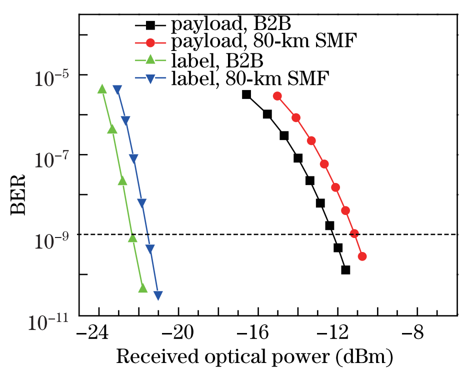

Fig. 7. BER performance of 40-Gb/s PPM payload and 2.5-Gb/s DPSK label at B2B and after 80-km SMF transmission.

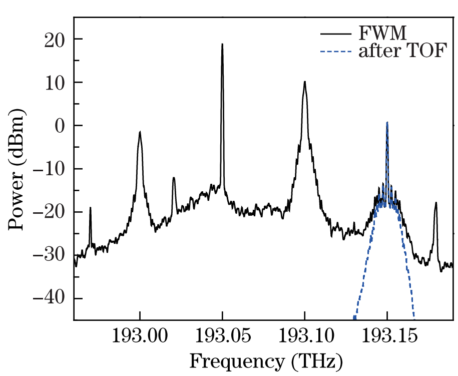

Fig. 8. Spectra of frequency domain with FWM and after TOF.

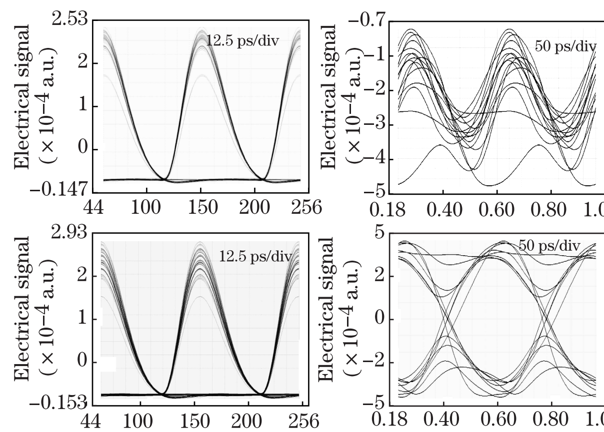

Fig. 9. PPM eye diagrams after the label erasure.

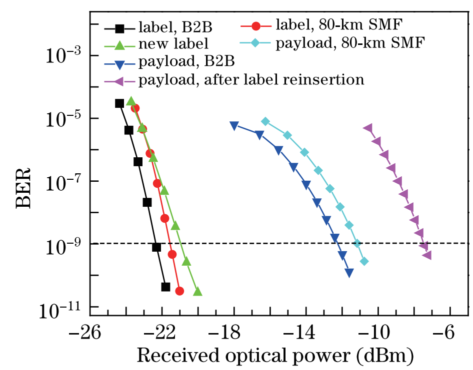

Fig. 10. BER versus received optical power with 40-Gb/s PPM payload and 2.5-Gb/s DPSK label in the case of B2B, 80-km SMF transmission, and label erasure and reinsertion.

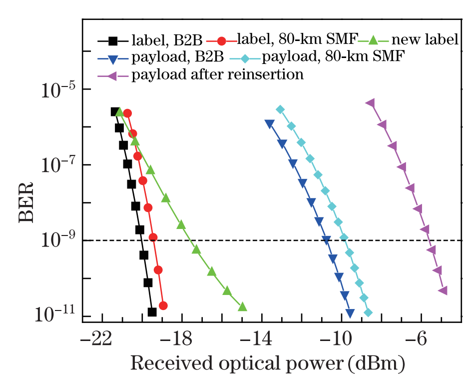

Fig. 11. BER versus received optical power with 40-Gb/s PPM payload and 10-Gb/s DPSK label in the case of B2B, 80-km SMF transmission, and label erasure and reinsertion.

performances of the new labels for 2.5- and 10-Gb/s DPSK labels are ∼0.8 and ∼2 dB (at BER = 10^{-9}) worse than that of the original label, respectively, due to the same reason.

In conclusion, a novel optical label swapping scheme is demonstrated based on FWM in SOA, implementing 2.5-Gb/s DPSK label erasure and upgrading to a bit rate of 10-Gb/s; it has the advantages of having transparent bit rate, simple configuration, and low cost. The 40-Gb/s payload is PPM modulated and used to solve the ER contradiction between the label and payload, and received by multiplying the recovered clock from the original RZ signal. The DPSK label erasure and reinsertion is achieved with appropriate power penalties, which are mainly caused by the residual modulation and the conversion efficiency of FWM.

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References

1. G.-K. Chang, J. Yu, Y.-K. Yeo, A. Chowdhury, and Z. Jia, Proc. IEEE **94,** 892 (2006).
2. J. Zhang, N. Chi, P. V. Holm-Nielsen, C. Peucheret, and P. Jeppesen, Electron. Lett. **39,** 388 (2003).
3. J. Zhang, N. Chi, P. V. Holm-Nielsen, C. Peucheret, and P. Jeppesen, IEEE Photon. Technol. Lett. **15,** 984 (2003).
4. J. Zhang, N. Chi, P. V. Holm-Nielsen, C. Peucheret, and P. Jeppesen, IEEE Photon. Technol. Lett. **15,** 1174 (2003).
5. N. Chi, L. Xu, J. Zhang, P. V. Holm-Nielsen, C. Peucheret, Y. Geng, and P. Jeppesen, IEEE Photon. Technol. Lett. **17,** 1325 (2005).
6. E. N. Lallas, N. Skarmoutsos, and D. Syvridis, IEEE Photon. Technol. Lett. **14,** 1472 (2002).
7. L. Wei, X. Xin, and C. Yu, Proc. SPIE **6783,** 678342 (2007).
8. K. G. Vlachos, I. T. Monroy, A. M. J. Koonen, C. Peucheret, and P. Jeppesen, IEEE Commun. Mag. **41,** 31 (2003).
9. J. Yu, G.-K. Chang, and O. Akanbi, J. Lightwave Technol. **24,** 271 (2006).
10. X. Liu, X. Wei, Y. Su, J. Leuthold, Y.-H. Kao, I. Kang, and R. C. Giles, IEEE Photon. Technol. Lett. **16,** 1594 (2004).
11. N. Chi, L. Xu, L. Christiansen, K. Yvind, J. Zhang, P. Holm-Nielsen, C. Peucheret, C. Zhang, and P. Jeppesen, in *Proceedings of OFC'2003* **2,** 792 (2003).
12. Z. Long, X. Xin, R. Zhou, Z. Zhang, and D. Xu, Chin. Opt. Lett. **8,** 642 (2010).
13. R. Rui, X. Xin, Q. Zhang, K. Zhao, T. Zhao, and C. Yu, Chin. Opt. Lett. **8,** 464 (2010).