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A New Orthogonal Labeling Scheme Based on a 40-Gb/s DPSK Payload and a 2.5-Gb/s PolSK Label

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***Abstract*—In this letter, we propose and experimentally demonstrate a new orthogonal labeling scheme based on a 40-Gb/s differential phase-shift keying payload and a 2.5-Gb/s polarization-shift keying label, which entirely eliminates the modulation crosstalk between the payload and label and shows negligible swapping penalty.**

***Index Terms*—Differential phase-shift keying (DPSK), optical label swapping, polarization-shift keying (PolSK).**

I. Introduction

Future Internet routers will need optical label switching to route and forward a massive number of packets per second independently of IP packet length and payload bit rate [1]. Several labeling schemes based on orthogonal modulation [2]–[6] have recently been experimentally demonstrated as a competitive approach to subcarrier labeling proposed previously [1], including amplitude-shift keying (ASK)/differential phase-shift keying (DPSK) [3], ASK/frequency-shift keying [4], DPSK/ASK [5], and ASK/polarization-shift keying (PolSK) [6]. Orthogonal labeling schemes have better spectral efficiency compared to the subcarrier multiplexing methods, leading to good resilience to fiber chromatic dispersion. Additionally, the labeling processing can be kept intact when upgrading the payload speed in contrast to the traditional subcarrier multiplexing method where it is necessary to change the radio frequency (RF) if the payload bit rate is increased. However, there is a common modulation problem in present orthogonal labeling schemes, namely that the extinction ratio (ER) of the ASK signal should be very low because a certain amount of optical power on ASK space bits is required to carry the phase/frequency/polarization information and thereby enable detection. The ERs used in all demonstrated systems are in any case less than 4.5 dB [3]–[6]. Such low ER will obviously degrade the system performance and give rise to problems for multihop scalability and all-optical processing on the payload such as 2R/3R regeneration and wavelength conversion. Therefore, it is important for orthogonal labeling to find effective ways to remove this ER limitation.

In this letter, we propose and experimentally demonstrate a new orthogonal labeling scheme based on a 40-Gb/s DPSK payload and a 2.5-Gb/s PolSK label, which entirely eliminates the modulation crosstalk between the payload and label[1].

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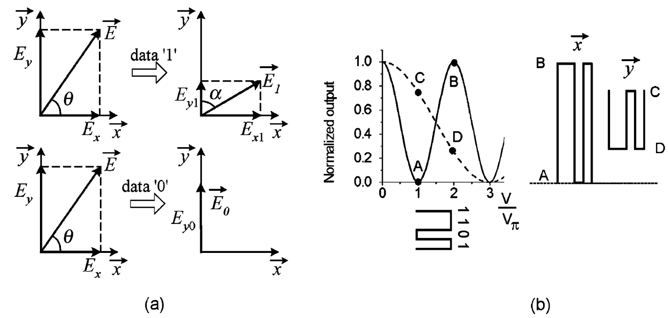

Fig. 1. (a) Schematics of the polarization states at the input and output of the MZM. (b) Transfer function of the horizontal (solid line) and vertical (dash line) polarization states.

II. Principle

Based on lithium niobate ($LiNbO_3$) material, various designs of polarization modulators have been proposed [6]–[8]. In [6] and [7], a single $LiNbO_3$ crystal waveguide is employed to implement polarization modulation based on the anisotropy of the electrooptic coefficient of the $LiNbO_3$ crystal. In these schemes, polarization rotation is achieved by imposing a relative π phase change of one of the principle axes. However, for DPSK/PolSK labeling systems, the phase variation induced in the polarization modulator may degrade the DPSK payload and should, thus, be avoided.

In our experiment, polarization modulation is achieved by a standard LiNbO3-based Mach–Zehnder modulator (MZM) operating in a special but simple way [9]. We assume $\vec{x}$ and $\vec{y}$ axis are the principal axis of the crystal, and the reference plane $\vec{x}, \vec{y}$ normal to the $\vec{z}$ propagation axis of the electrical field $\vec{E}$. Light linearly polarized at an angle θ with respect to the $\vec{x}$ axis is launched into the MZM, yielding horizontal and vertical polarization linear states with different amplitude and zero phase difference. Given the fact that the phase shift of the axis with smaller electrooptic coefficient, namely the $\vec{y}$ axis, is around 1/3 of that of the $\vec{x}$ axis [7], the transfer function of the two polarization states versus applied voltage can be depicted as Fig. 1(b). If we set the working point at A and set the data voltage equal to V_π (the voltage that is required in the $\vec{x}$ axis for a π-phase shift), the output field at $\vec{x}$ axis has a maximum ER, while the vertical polarization state has a nonoptimal ER and inverted data. Therefore, the output of a logic "1" is a combination of a $\vec{x}$ vector and a $\vec{y}$ vector, and the output of a logic "0" is a pure $\vec{y}$ vector. In this way, the binary data is encoded in two linear states of polarization (SOP). In order to maintain the constant power for "1"s and "0"s, angle θ is calculated to be 54.7°.

Assuming that two 3-dB couplers are used in the dual-drive MZM with perfect ER and omitting the loss, the output signal $\vec{E}(t)$ of the polarization modulator can be obtained

$$\begin{aligned}\vec{E}(t) = &\hat{x}E_x \exp(i\varphi_{\mathrm{DPSK}} + i\phi_x) \exp\left[i\pi\frac{u_1(t)+u_2(t)}{2V_{x\pi}}\right] \\ &\times \cos\left[\pi\frac{u_1(t)-u_2(t)}{2V_{x\pi}} + \phi_x\right] \\ &+ \hat{y}E_y \exp(i\varphi_{\mathrm{DPSK}} + i\phi_y) \exp\left[i\pi\frac{u_1(t)+u_2(t)}{2V_{y\pi}}\right] \\ &\times \cos\left[\pi\frac{u_1(t)-u_2(t)}{2V_{y\pi}} + \phi_y\right] \qquad (1)\end{aligned}$$

where $E_{x(y)}$ is the amplitude of the optical field in $\vec{x}$ ($\vec{y}$) axis, φ_{DPSK} represents the DPSK information of the input signal, ϕ (a constant value) is the relative optical phase between the two arms in the absence of RF drive voltage. $u_1\ (t)$ and $u_2\ (t)$ are the RF drive voltages to the two modulator arms, respectively. For chirp-free operation, $u_1\ (t) = -u_2\ (t)$.

As shown in (1), the polarization modulation index is solely determined by the cosine factor that defines the power transfer coefficients, which is independent to the DPSK phase. In addition, a dual-drive MZM using a push–pull driving mechanism can in principle generate a chirp-free signal, meaning that there is no residual phase modulation and the DPSK information is safely preserved. It should be noted that the constant phase shift ϕ can be factored out after differential DPSK demodulation. Based on the above discussion, it is then clear that using the MZM-based polarization modulation scheme, the DPSK payload and the PolSK label are completely isolated and, thus, no modulation crosstalk or limitation of the ER exist. At the receiver, we obtain amplitude detection of the PolSK label by use of a polarization beam splitter (PBS) that performs the conversion from polarization modulation to amplitude modulation. The detected label signal is then passed through a low-pass filter that suppresses frequency components higher than the label bit rate. Therefore, the DPSK information has no impact on the label detection. As to the detection of the DPSK payload, a label eraser can be employed to remove any polarization modulation that may influence the DPSK detection since DPSK demodulators are in most cases based on fiber and are polarization sensitive to some degree. Hence, the DPSK payload and the PolSK label can be detected independently without any interactions.

It is worth noting that this scheme is polarization sensitive. In practice, how to control the SOP packet by packet needs to be investigated in the future work. The random birefringence of buried optical fibers in networks typically causes only 2°–10° fluctuations in the polarization angles of the propagating signals; hence, dynamic polarization control can be used to compensate for the polarization fluctuations [10].

III. Experimental Results

The experimental setup for the DPSK/PolSK labeling system is shown in Fig. 2. An external cavity laser generates continuous-wave light at 1545 nm that is DPSK modulated by a phase modulator with payload data at 40 Gb/s. The DPSK signal is then amplified to a power level of 15 dBm and afterwards passes through a 3.5-nm optical bandpass filter before coming into

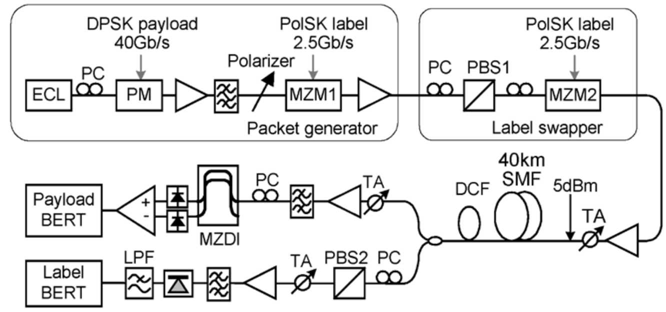

Fig. 2. Experimental setup for DPSK (40 Gb/s)/PolSK (2.5 Gb/s) labeling system. ECL: External cavity laser. PM: Phase modulator. TA: Tunable attenuator. MZDI: Mach–Zehnder delay interferometer.

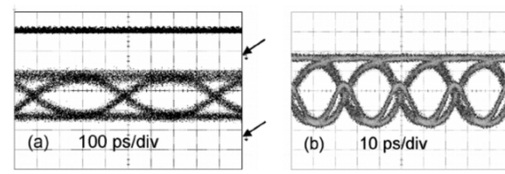

Fig. 3. Eye diagrams of the labeled signal [(a) upper] and the detected label at 2.5 Gb/s [(a) lower] and the detected payload at 40 Gb/s (b) in back-to-back case.

a polarization modulator (MZM1), where the PolSK label at 2.5 Gb/s is encoded generating a DPSK/PolSK dually modulated signal. A rotatable polarizer is inserted before the MZM1 to obtain the exactly required input SOP. The insertion loss MZM1 is 5.6 dB, which is almost the same compared to the intensity modulation. The label swapper performs two basic functions, i.e., label erasure and label reinsertion. The DPSK/PolSK signal is first launched into the label eraser that consists of a polarization controller (PC) and a PBS, where the old polarization label is removed by adjusting the PC so that the mark and space bits have the same optical power at the output of the PBS, thus maintaining constant amplitude. The new label is encoded in another polarization modulator (MZM2) through PolSK modulating the incoming pure DPSK signal. Label swapping is, thus, accomplished. The label-swapped signal is then amplified to a power level of 5 dBm and transmitted through a 40-km spool of standard single-mode fiber (SMF) and a matching 6-km spool of dispersion-compensating fiber. Label detection is implemented by suppressing one of the shifted polarizations using the same device as that for label erasure, and a 1.8-GHz electrical low-pass filter is used to suppress high frequency noise. The DPSK payload is detected by a balanced detector, which comprises an optical delay interferometer and a two-port differential electrical amplifier.

The eye diagrams of the labeled signal, the detected label, and the detected payload in a back-to-back case are shown in Fig. 3. The zero level is indicated by an arrow line. The top line in Fig. 3(a) is the DPSK/PolSK labeled signal, below which is the eye diagram of the demodulated label. The detected DPSK payload is displayed in Fig. 3(b). To investigate the transmission suitability of this new labeling format, transmission through 40-km SMF with dispersion-shifted fieber is first carried out before investigation of label swapping. The eye diagrams after transmission, as shown in Fig. 4, are clear and open, indicating that the proposed labeling format is suitable for transmission.

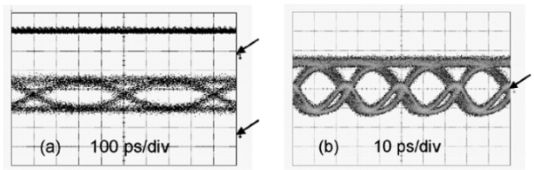

Fig. 4. Eye diagrams of the labeled signal [(a) upper] and the detected label at 2.5 Gb/s [(a) lower] and the detected payload at 40 Gb/s (b) after transmission through 40-km SMF.

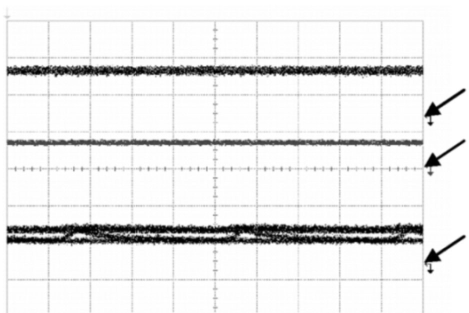

Fig. 5. Oscilloscope traces (100 ps/div) of the original labeled signal (top), label-erased signal (middle), and label-swapped signal (bottom) based on 40-Gb/s DPSK payload and 2.5-Gb/s PolSK label.

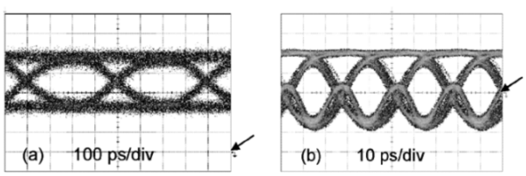

Fig. 6. Eye diagrams of (a) PolSK label at 2.5 Gb/s and (b) DPSK payload at 40 Gb/s after label swapping.

The oscilloscope traces recorded during label swapping are shown in Fig. 5. The top line is the old PolSK labeled DPSK signal. The middle one is the pure DPSK payload after label erasure. The one at the bottom is the output of the label swapper containing the old DPSK payload and the new PolSK label. Because a PC (which is not as accurate as a polarizer) is used before the MZM2 to adjust the input SOP, it is seen that the amplitude of the label-swapped signal is not perfectly constant, which is due to an imbalance between the mark and space. It is envisaged that this nonconstant signal could become a limiting factor for multihop operation. The eye diagrams of the detected payload and label after label swapping are shown in Fig. 6.

The measured BER curves are shown in Fig. 7. The receiver sensitivities for the payload and label in the back-to-back case are about -20 and -24 dBm, respectively. After 40-km transmission, power penalties for the payload and label are 0.52 and 0.96 dB, respectively. Label swapping penalties for the payload and label are 0.15 and 0.6 dB; penalties stemming from label swapping and 40-km SMF transmission are 2.2 dB for the payload and 2.9 dB for the label. The relative large penalty for swapping plus transmission is because a single-drive MZM is used in the label insertion which led to a higher chirp. The negligible swapping penalty makes the proposed labeling approach very promising in real network applications.

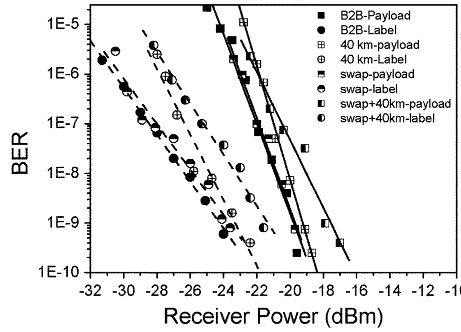

Fig. 7. BER curves of DPSK payload at 40 Gb/s and PolSK label at 2.5 Gb/s for various cases. B2B denotes the back-to-back case. Dashed and solid lines represent the label and payload, respectively.

IV. Conclusion

A new orthogonal labeling scheme based on a 40-Gb/s DPSK payload and a 2.5-Gb/s PolSK label is proposed and experimentally demonstrated. The most striking feature of this new labeling format is that there is no modulation crosstalk between the payload and label, in contrast to previously reported orthogonal modulation formats. Swapping penalties are only 0.15 and 0.6 dB for the payload and label, respectively. Penalties due to swapping and 40-km SMF transmission are 2.2 dB for the payload and 2.9 dB for the label.

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