An all-optical polarization monitoring scheme for polarization division multiplexed transmission

Jia Ye (叶 佳)[1], Lianshan Yan (闫连山)[1*], Anlin Yi (易安林)[1], Wei Pan (潘 炜)[1],
Bin Luo (罗 斌)[1], Zhen Guo (郭 振)[1], and X. Steve Yao[2]

[1] *Center for Information Photonics and Communications, School of Information Science and Technology,*
Southwest Jiaotong University, Chengdu 610031, China
[2] *General Photonics Corp., 5228, Edison Ave., Chino, CA 91710, USA*
[*] *E-mail: lsyan@home.swjtu.edu.cn*

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A novel polarization monitoring scheme for polarization division multiplexed (PDM) systems is proposed. By using a tag light transmitted in different but close wavelength to the data signal as the feedback control, the scheme can demultiplex automatically two orthogonal polarizations in PDM systems. The effectiveness of the scheme is demonstrated experimentally in a 2×10-Gb/s on-off-keying (OOK) PDM transmission system.

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The greater demand for more system capacity has driven the conduct of research on the increased spectral efficiency of fiber communications based on dense wavelength division multiplexing (DWDM) techniques. Several approaches can satisfy this purpose, including reducing the wavelength spacing between adjacent channels, increasing the transceiver bit rate of each channel, etc. In particular, one promising candidate is polarization division multiplexing (PDM), wherein two orthogonally polarized signals with the same wavelength are transmitted simultaneously in a single fiber. Ideally, the operator only needs to add a polarization beam combiner (PBC) and a polarization beam splitter (PBS) at each end of the fiber link, while the other parts of the system can remain unchanged.

Despite the attractive features of PDM, its implementation faces significant challenges. One major issue is on monitoring the crosstalk of the two polarization channels in real time in order to separate them effectively by using PBS or other methods. Various schemes for the design of the receiver have been proposed: (1) addition of clock tones or pilot tones into the signal streams as monitor signals[1−3], (2) use of unbalanced optical power detection[4,5], (3) crosstalk correlation detection[6], (4) use of coherent detection schemes that combine PDM with phase-shifted-keying formats, as recently highlighted by digital signal processing[7−9], and (5) use of radio frequency (RF) power as feedback signal[10,11]. Electronic approaches are generally more cost-effective, but bit-rate-dependent. Meanwhile, optical approaches require automatic polarization tracking and a well-controlled optical power balance between channels.

In this letter, we propose and demonstrate a novel all-optical scheme to manipulate polarization in PDM systems. The scheme is capable of demultiplexing automatically two orthogonal polarizations. By combining one polarized signal with another tag light (TL) on the same polarization but at different wavelengths, at the receiver end we can easily use an optical filter and low-speed photodetector (LSPD) to detect the power of TL that can be used as feedback signal for the dynamic polarization controller as means of separating the two polarized signals. Moreover, the scheme does not require high-speed electronics or unbalanced optical power between two orthogonal channels. This approach is demonstrated in a 2×10-Gb/s on-off-keying (OOK) PDM transmission system over a 50-km single-mode fiber (SMF).

The conceptual diagram of the automated control scheme of the PDM system is shown in Fig. 1. An additive TL with different wavelength but the same polarization of one signal light (TX2) was launched onto one input port of the PBC. The wavelength difference between TL and the data streams was set within specified limits. At the receiver end, the state of polarization (SOP) of TL was approximately the same as the TX2 signal. We assumed that the birefringence along the fiber link was limited, and therefore, the polarization correlation between TL and the signals was kept constant. By using a specified fiber Bragg grating (FBG) and LSPD, we filtered with ease TL from one polarization channel and detected optical power. Then, TL was used as feedback for the PDM demultiplexer. When the optical power of TL reached its maximum value, optimal performance was gained by the polarization control block.

Figure 2 shows the PDM demultiplexing effectiveness of the proposed automated polarization monitor scheme in a 10-Gb/s PDM transmission system. Alternatively, for demonstration purposes, the multiplexed channel can be separated by PBS into two orthogonal polarizations, modulated by two independent modulators, and then combined by PBC. However, due to the equipment limitations, we used a single modulator and a coupler to obtain two 10-Gb/s $2^{31}-1$ pseudo-random binary sequence (PRBS) data streams. A spool of 2-km SMF was inserted onto one of its paths to decorrelate two data

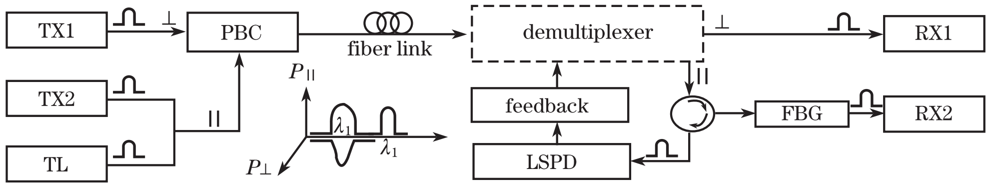

Fig. 1. Conceptual diagram of the PDM system using the proposed polarization monitor scheme. TX: transmitter, RX: receiver.

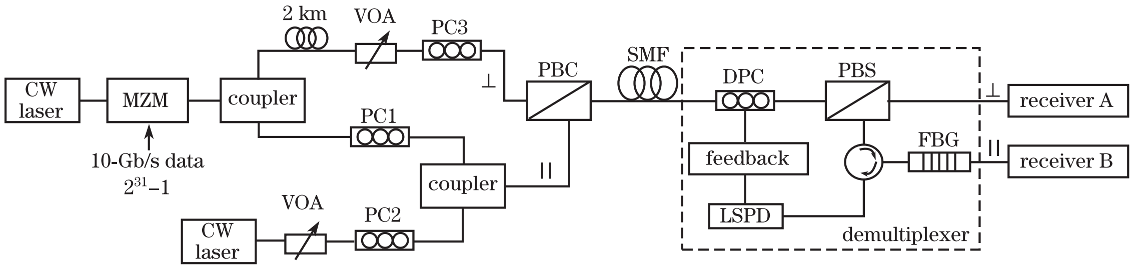

Fig. 2. 10-Gb/s PDM transmission system using the proposed PDM demultiplexing method. MZM: Mech-Zenhder modulator; CW: continuous wave; PC: polarization controller.

channels. Three polarization controllers were used to align the polarization states of the two modulated signals and TL to the PBC. The input optical power of the two modulated signals and TL transmitted onto the PBC was set to −4 dBm. Subsequently, this was adjusted by two variable optical attenuators (VOAs).

After transmitting through a 50-km fiber link, the data stream was demultiplexed using the proposed polarization monitor scheme, particularly, with a polarization control block. The block was composed of a data acquisition (DAQ) card (250 kS/s, 16 bits A/D), dynamic polarization controller (DPC), PBS, circulator, FBG, and LSPD (response bandwidth of about the order of MHz). TL was reflected by a FBG filter (~0.1 nm in bandwidth) and then inputted onto the LSPD using the circulator. The photodetector converted TL into voltage signals. Next, voltage signals were converted into digital signals, transferred onto the DAQ card, and then transmitted to the computer. To control for SOP, our software was arranged such that it could adjust automatically the polarization controller, thereby maximizing the optical power of TL. The two polarization channels seemed detached when the voltage reached its maximum value and maintained thereafter.

We then employed non-return-to-zero (NRZ) and return-to-zero (RZ) signals to prove the effyectiveness of the proposed demultiplexer. Figure 3(a) shows the power penalties of the demultiplexed NRZ signals as a function of the wavelength spacing between signal light and TL. Power penalties were compared to the back-to-back case without the PDM scheme (i.e., there was about 0.5 dB of additional power penalty in the back-to-back case with the PDM scheme). After transmission at 50 km and PDM demultiplexing, the power penalty for PDM(⊥) (without TL) was kept relatively constant (−2 dB). Meanwhile, for the PDM(||) channel, because of the overlap in the filtering spectrum between FBG and the 0.5-nm optical filter between erbium-doped fiber amplifier (EDFA) and the PDM receiver, TL could not be totally filtered from the PDM(||) signal. At wavelength spacing larger than 0.4 nm, the power penalties of PDM(⊥) and PDM(||) were approximately equal. Conversely, at less than 0.4-nm spacing, the PDM(||) signal was affected by the residual TL, with its wavelength in the range of the filter passband. In particular, at the channel wavelength spacing of 0.2 nm, additional power penalty increased to 0.7 dB. This can be reduced further by optimized filtering selection. Figure 3(b) shows the bit error rate (BER) curves and eye diagrams

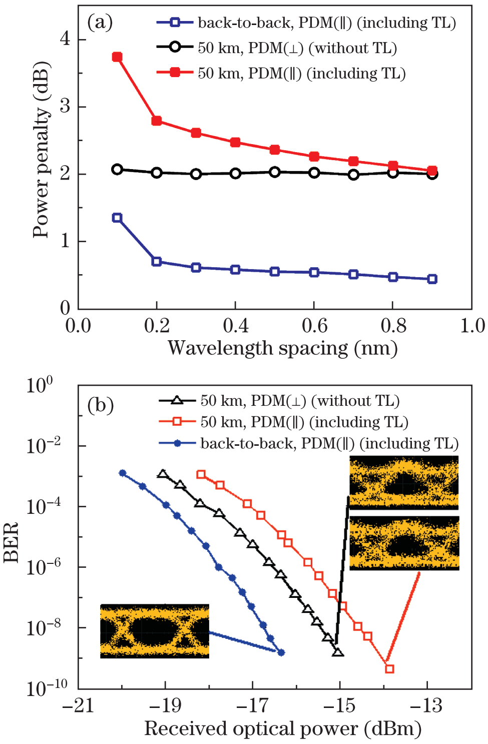

Fig. 3. Power penalty versus. wavelength spacing between the NRZ signal and tag signal of two orthogonal channels after 50-km PDM transmission (compared with the back-to-back case without the PDM scheme and measured at 10^{-9} sensitivity); (b) typical BER curves and eye diagrams of two polarized NRZ signals with 0.2-nm wavelength spacing.

of the polarized channels with 0.2-nm wavelength spacing between signal light and TL.

RZ signal is sensitive to chromatic dispersion (CD); however, the module for CD compensation was not employed due to equipment limitations. We therefore used 25-km SMF as transmission link when RZ signal was employed in the PDM system. Figure 4(a) shows the power penalty of the demultiplexed RZ signal as a function of wavelength spacing. Compared with the back-to-back case without the PDM scheme, power penalty for PDM(⊥) decreased to 1 dB, a result of the change in fiber link length, without which the performance of RZ signal would have been approximately the same as that of the NRZ signal. For reference, the BER curves and eye diagrams of the received RZ signal with 0.2-nm wavelength spacing between signal light and TL is shown in Fig. 4(b).

A legitimate concern is that optical power levels might affect the effectiveness of the monitor due to nonlinear polarization rotations, sometimes referred to as cross-polarization modulation (XPolM)[12]. Nonlinear polarization rotation could decrease the effectiveness of optical PMD compensators in long-haul systems[13]. In theory, XPolM is caused by the pattern dependence of the adjacent channel. Therefore, the inserted TL with constant power would not cause bit pattern-dependent variations in the SOP of signal light. To verify this, we investigated the influence of launch power on transmission capability. With power fixed onto the receiver end at −15 dBm, we gradually increased launch power in the 50-km fiber from −4 to 6 dBm. Consequently, the BERs of the two demultiplexed channels were measured. Figure 5 shows BER versus the launch power of the two channels at a wavelength spacing of 0.3 nm. The BER of each demultiplexed signal was kept very flat, confirming that increases in the launched TL power have limited effect on system performance at a certain level. We did not measure BER at the higher power levels.

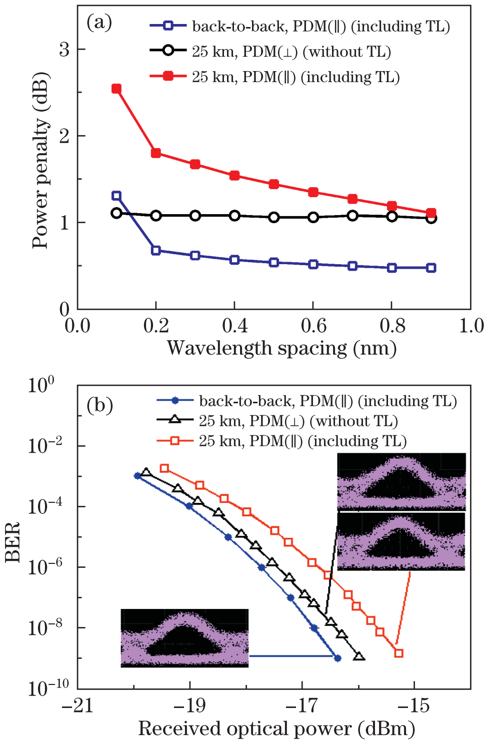

Fig. 4. Power penalty versus wavelength spacing between the RZ signal and tag signal of two orthogonal channels after 25-km PDM transmission (compared with the back-to-back case without the PDM scheme and measured at 10^{-9} sensitivity); (b) typical BER curves and eye diagrams of two polarized RZ signals with 0.2-nm wavelength spacing.

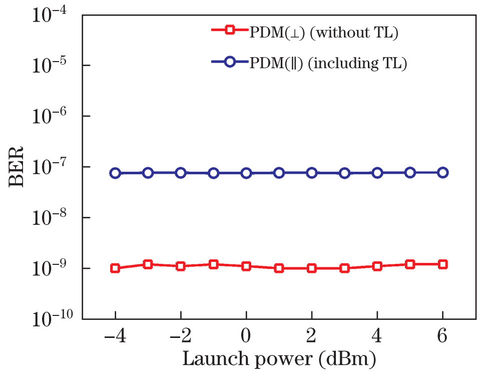

Fig. 5. BER curves of two polarized signals versus launch power with power of −15 dBm at the receiver end and 0.3-nm wavelength spacing.

Our approach is effective for PDM transmission systems. However, apart from limitations like the need for a dummy monitor wavelength, it also faces major gaps, such as polarization-mode dispersion or PMD in PDM transmissions[14−17]. Generally, PDM systems, unlike non-PDM systems, are sensitive by five or more factors in relation to PMD[15]. Future studies can find solutions that can facilitate PMD mitigation using our proposed scheme. As an example, because the polarization rotation relationship between TL and signal channels can be used to monitor PMD effect, we can obtain PMD information through power detections of the monitor channel and the two signal channels. This topic is worthy of further investigation.

In conclusion, we have described a novel polarization monitoring scheme that uses TL, combined with the signal streams, as a feedback to separate two polarized channels. Such feedback scheme is cost-effective because it uses LSPD and has no specific requirements on the optical power of the two polarized channels. This scheme has been demonstrated in a 2×10-Gb/s NRZ/RZ OOK PDM system. Experimental results show that TL with wavelength spacing of 0.2 nm only induces a power penalty of 0.8 dB (i.e., worst case).

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