Effects of pattern dependence on high-power polarization-division-multiplexing applications

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High-power polarization-division-multiplexing (PDM) systems or functional modules, such as self-phase-modulation (SPM)-based all-optical regenerators, cross-phase-modulation (XPM)-based wavelength convertors or format convertors, all-optical logical gate, and so on, may suffer from the effects of pattern dependence. Such effects are experimentally investigated using relative time delay variation between bit sequences with orthogonal polarization states in a 2×10.65 Gb/s high-power on-off keying (OOK) PDM system. Eye-diagram-based signal-to-noise ratio (SNR) and bandwidth of broadened spectrum are measured and compared. An eye-diagram-based SNR fluctuation of up to 4 dB may occur as the delay changes.

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Some current optical communication systems or functional modules, such as self-phase-modulation (SPM)-based all-optical regenerators, cross-phase-modulation (XPM)-based wavelength convertors or format convertors, all-optical logical gate, and so on, may require the signal power to be pumped sufficiently high[1−3]. Such systems or functional modules mostly work for one single data channel with a fixed polarization state or for several channels with different wavelengths.

In contrast, the polarization-division-multiplexing (PDM) scheme is being widely used at present, especially in numerous experiments, because it can double system capacity and spectral efficiency directly without complicated hardware modifications[4]. Some functional modules (i.e., all-optical regeneration and wavelength conversion) may find application in the PDM system[5,6]. However, obstacles may arise when transplanting existing single-channel or limited-wavelength channel functional modules directly into PDM systems (i.e., the pattern dependence effect).

In this letter, we investigate one possible problem that may be a challenge for high-power function modules in PDM systems if one single functional module is simultaneously applied to both polarizations. Pattern dependence effects caused by fiber/semiconductor optical amplifier (SOA) nonlinearities or nonlinearities in PDM systems have been previously investigated[7] either as deleterious or beneficial factors, but not as both in such systems.

The problem with high-power functional modules for PDM systems is identified as pattern dependence because, although two data streams with orthogonal polarization states are totally random, any possible bit pattern match or mismatch may cause performance fluctuation.

This effect is experimentally investigated in a 2×10.65 Gb/s on-off keying (OOK) PDM system. In the experiment, pattern dependence effects are emulated using a variable time delay element between two polarization tributaries of the PDM signal channels. Both special bit sequences and pseudorandom bit sequences (PRBSs) are applied and evaluated. Performance deviations are compared in terms of eye-diagram-based signal-to-noise ratio (SNR) and the bandwidth of SPM broadened optical spectrum. Results indicate that an eye-diagram-based SNR difference of up to 4 dB may occur as the delay value is varied for different bit sequences. Such dramatic performance variations should be taken in account or eliminated when applying such kindred high-power functional modules into PDM systems.

Figure 1 shows the experimental setup. An external-cavity laser (ECL) oscillating at 1 555.3 nm is modulated by two cascaded Mach-Zehnder modulators (MZMs) with certain bit sequences to generate a return-to-zero (RZ) OOK signal. MZM1 is driven at 10.65 Gb/s through the output data from the bit error rate (BER) tester, whereas MZM2 is driven by the synchronized clock signal. The 2×10.65 Gb/s OOK-PDM signals are generated using a coupler, two polarization controllers (PCs), a variable optical attenuator (VOA), and a polarization beam coupler (PBC). VOA is used to balance the optical power of the two channels. A variable delay line (VDL) is placed in another path to generate the relative time delay between the two polarization tributaries of the PDM signal.

A 1-km single-mode fiber (SMF) is also inserted into the VOA path to reduce interference. The relative length of the two paths is especially designed; thus, more than 4 bit relative time delay between two polarization tributaries of the PDM signal is obtained by controlling VDL.

The high-power functional module, a fundamental structure for SPM-based optical regenerators, XPM-based signal processors, and all-optical logical units, is composed of a high-power erbium doped fiber amplifier (EDFA) and 1-km highly nonlinear fiber (HNLF). An optical filter with a 3-dB bandwidth of 0.6 nm is also used after the high-power EDFA to reduce the amplified spontaneous emission (ASE) noise.

After the high-power functional module, the two polarization tributaries of the PDM signal are separated

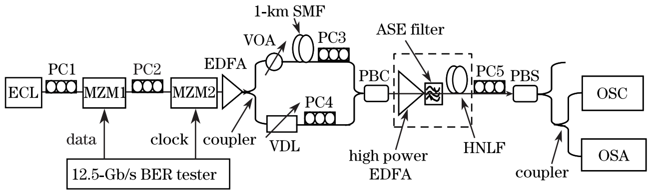

Fig. 1. Experimental setup. PBS: polarization beam splitter; OSC: high-speed oscilloscope; OSA: optical spectrum analyzer.

using a polarization beam splitter (PBS). The bit/eye/optical spectrum is monitored using a high-speed oscilloscope (OSC, 86100C) and an optical spectrum analyzer (OSA, MS9710C). The input power to the HNLF is ~27 dBm. The zero-dispersion wavelength, dispersion slope, and nonlinear coefficient of the HNLF are 1 556 nm, 0.02 ps/(km·nm^2), and 30 (W·km)$^{-1}$, respectively.

The driving bit sequences are changed and VDL is varied to generate different relative patterns between the two polarization tributaries of the PDM signal. The oscilloscope is used to measure the bit sequences and eye-diagram-based SNR values. Here, the eye-diagram-based SNR is defined as

$$\mathrm{SNR} = 10\lg\left(\frac{I_1 - I_0}{\sigma_1 + \sigma_0}\right),$$

where I_1 and I_0 are the histogram means at the one and zero levels, respectively; σ_1 and σ_0 are the standard deviation of the histogram at the one and zero levels, respectively. The measurements are made over the middle 5% of the eye-diagram. As we concentrate on the pattern-dependent parameters (e.g., eye-diagram-based SNR, spectrum bandwidth), note that (i) the original signals are not degraded; (ii) unlike some whole functional modules for a single-channel or several-wavelength channel, the signal performance is only evaluated after the HNLF (whereas for some whole functional modules, optical filters are often used after the HNLF, i.e., SPM-based regenerator); (iii) a manually adjusted PC5 is used to separate the two channels (practical demultiplexing schemes are available[4,8]).

Figures 2(a)–(c) show the measured eye-diagram-based SNR results (at the received power ~–2.0 dBm). First, an alternate 10-bit sequence is applied and the relative delay is changed between the two channels (i.e., the percentage of bit overlap between the two channels changes). The best performance (best eye-diagram-based SNR) is the case of a 100% overlap (see bit sequences and corresponding eye diagrams in Fig. 2(a) with an eye-diagram-based SNR value of ~14 and ~7.8–8.2 dB for other cases with bits not fully overlapped. We then change the number of 1 bit (followed by the same number of 0 bit) and tune the overlapping parameter as well (Fig. 2b).

Generally and similarly, the case of a full overlap always has the best performance because as the number of 1-bit increases, the performance variation reduces (within 1–2 dB). In the case of PRBS, only the best and worst performances in the proposed setup are determined because the delay can only be varied up to 4 bit. For different PRBSs (2^7–1, 2^{10}–1, 2^{15}–1, 2^{23}–1, and 2^{31}–1), the best and worst eye-diagram-based SNR values are quite similar to the ~4 dB difference between the best and worst values.

Figure 2(d) shows the BER results for the best and worst cases when a 2^{31}–1 length of PRBS is applied. A ~2.4 dB power penalty exists between the worst and best cases.

In fact, not only does the output eye diagram change, the broadened spectrum also changes. Figure 3 shows measured spectrum parameters. As the overlap increases, the spectrum bandwidth increases accordingly because of the increased peak power of the signals (i.e., stronger nonlinear effect). As an example, for a 10-dB spectral bandwidth (too many spectral ripples for the 3-dB bandwidth), the spectrum bandwidth may vary from 0.4–0.5 to 1.0–1.3 nm for different PRBS series. Therefore, considering the above two major variations (eye-diagram-based SNR and spectrum), the pattern dependence effects must be taken into account when applying such a kindred high-power functional module into PDM systems.

One major contributor to the performance variation is the peak optical power variations in the HNLF, whereas another contributor may be the nonlinear polarization rotation[9] in the HNLF cased by the high-power pump. To evaluate this effect, the signal polarization state (by PC, see Fig. 4(a)) is fixed, and the input power to the HNLF is changed. The polarization crosstalk into the orthogonal polarization state is then measured using the PC (see Fig. 4(a)). After the measurements, the nonlinear polarization rotation angles are calculated at different amounts of input power, as shown in Fig. 4. As previously mentioned, the input power of both polarization states is ~27 dB, and the induced rotation angle (corresponding to the input power of one polarization state ~24 dB) is only ~4°–5°. Therefore, the

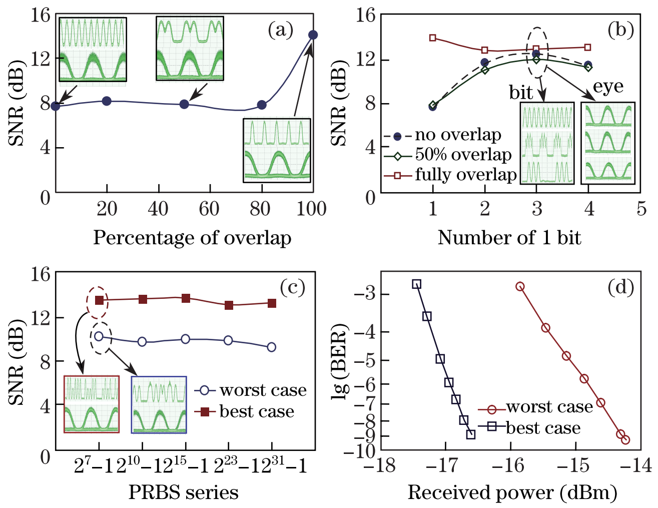

Fig. 2. Eye-diagram-based SNR and BER results: (a) alternate 10-bit sequence versus different amounts of bit overlapping; (b) different numbers of 1-bit followed by the same numbers of 0 bit as the bit overlap varies; (c) PRBS signals with different pattern lengths; (d) BER results for the worst and best cases with 2^{31}–1 PRBS. Insets: the upper traces are the bit streams before PDM demultipelxing (to show the overlap values between the two polarization components) and the lower traces are the eye diagrams for the signal after PDM demultiplexing.

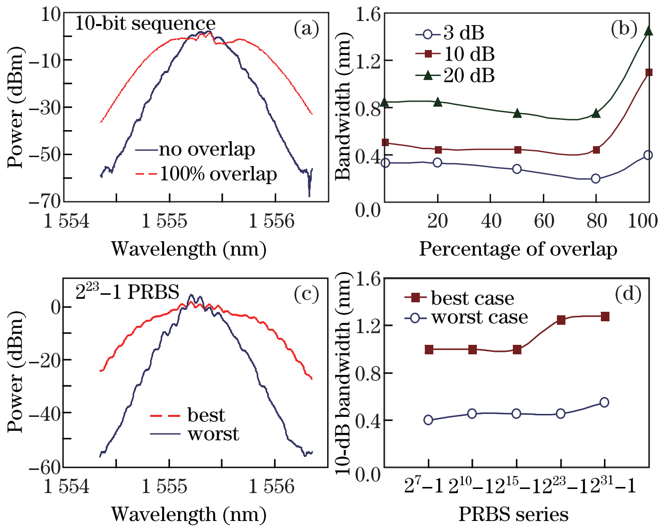

Fig. 3. Spectrum measurement results after demultiplexing: (a) optical spectrum of the alternate 10-bit sequence with different amounts of bit overlapping; (b) bandwidths at 3, 10, and 20 dB for the 10-bit sequence with different amounts of bit overlapping; (c) optical spectrum of 2^{23}–1 PRBS; (d) 10-dB bandwidth variations for different PRBS signals.

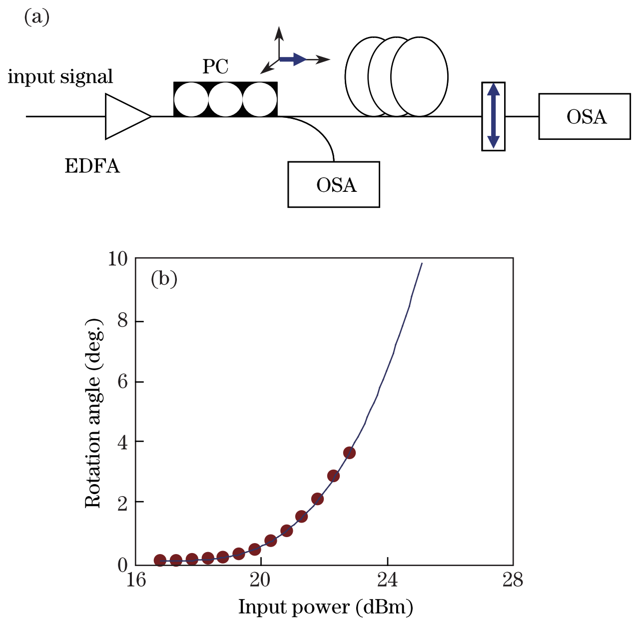

Fig. 4. Measured polarization rotation angle as a function of the input power into the HNLF: (a) concept diagram for measurement; (b) measurement results.

contribution of nonlinear polarization or polarization crosstalk is not a significant factor in the proposed setup.

Pattern dependence effects for high-power functional modules in PDM systems have been evaluated. However, several points should be stressed: (i) such an effect may combine with other polarization-related impairments (e.g., polarization mode dispersion (PMD) or polarization-dependent loss (PDL)) to be a more challenging issue[10,11]; (ii) the pattern (bit) information may be monitored or estimated for performance optimization or nonlinearities mitigation[12]; (iii) modifications to reduce such effects are desired once some high-power required functional modules for a single channel are transplanted into PDM systems. As an example, bidirectional modules may be effective candidates[13,14].

In conclusion, the pattern dependence effects in high-power functional modules for a 2 × 10.65 Gb/s OOK-PDM system are experimentally investigated. Such effects are considered for performance optimization, or even for systems wherein high fiber nonlinearities or high power may occur. Results show that an eye-diagram-based SNR fluctuation of up to 4 dB occurs as the delay changes.

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