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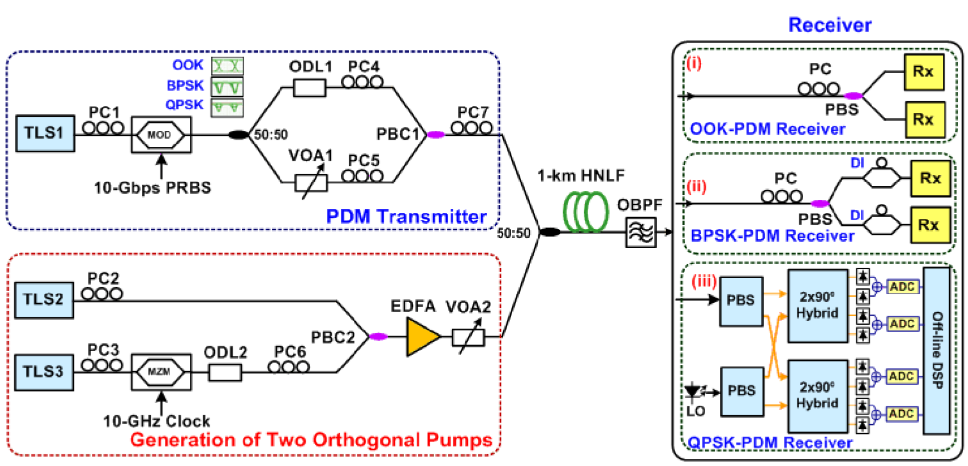

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Polarization-Insensitive and Receiver-Sensitivity-Gain Format Conversion for PDM Signals Based on Dual-Orthogonal-Pump Four-Wave Mixing in Highly Nonlinear Fiber

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Abstract: All-optical format conversion plays an important role in future transparent optical networks in order to enhance reconfigurability. On the other hand, the polarization-division multiplexing (PDM) technique has been extensively studied for achieving high-speed and high-spectral-efficiency optical networks. Since the state of polarization of PDM signals are randomly changed along the transmission optical link, it is important to elaborately design a polarization-insensitive conversion scheme in such a network. In this paper, we proposed and experimentally demonstrated an all-optical nonreturn-to-zero–return-to-zero format conversion for PDM on–off keying (OOK), binary phase-shift keying (BPSK), and quadrature phase-shift keying (QPSK) signals. Polarization-insensitive operation is achieved by utilizing the merit of the dual-orthogonal-pump four-wave mixing (FWM) process in a highly nonlinear fiber, and receiver-sensitivity-gain operation is observed in the conversion process. The bit error ratio (BER) results show that receiver-sensitivity gains of $\sim$1.5, $\sim$0.8, and 0.3 dB for the OOK, BPSK, and QPSK PDM signals at BER values of 10^{-9}, 10^{-9}, and 10^{-3} are obtained, respectively.

Index Terms: Format conversion, polarization division multiplexing (PDM), four-wave mixing (FWM), highly nonlinear fiber (HNLF).

1. Introduction

Various kinds of optical networks have been proposed for different requirements of network scaling, transmission distance and capacity, power consumption, communication security, and so on [1]. To satisfy these requirements of the optical networks, numerous types of modulation

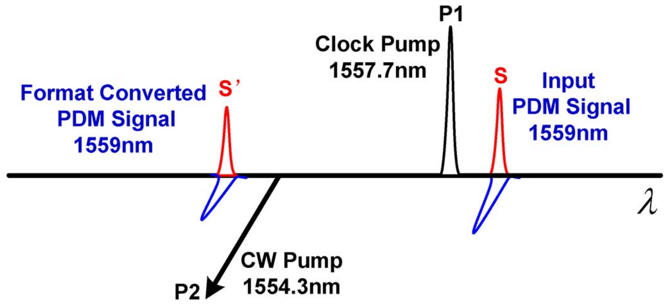

Fig. 1. Schematic illustration of format conversion based on dual orthogonal polarization pumps FWM.

formats have been introduced and studied nowadays, including conventional OOK formats as well as new advanced modulation formats. In the future, thus different networks may employ different modulation formats whose unique benefits satisfy their corresponding network's requirements [2]–[10]. Therefore, the function of all-optical modulation format conversion is an important interface technique in optical networks which can provide flexible management and interface, and enhance the reconfigurability for different optical networks. Over the past few years, numerous format conversion schemes have been proposed and demonstrated, such as RZ-OOK to NRZ-OOK [3], [11], [12], NRZ-OOK to RZ-OOK [13]–[15], OOK to multi-level phase shift keying (M-PSK) [6]–[8], OOK to quadrature amplitude modulation (QAM) [2]–[9]. Most of these schemes utilized nonlinear effects, such as cross-phase modulation (XPM) and FWM, generated in different nonlinear media, including nonlinear optical fiber, semiconductor optical amplifier (SOA), waveguide or others.

On the other hand, PDM technique is becoming a promising candidate for high-speed and high-spectral-efficiency optical communication systems as it can double the spectral efficiency (thus data capacity) directly by combing two polarization channels of same bit rate and same wavelength [16]–[19]. Therefore, all optical format conversion, especially polarization-insensitive format conversion, in such system may be desired. Additionally, it is important to elaborately design and optimize the scheme in order to avoid extra power penalty in the format conversion process. In our previous work [16], format conversion for NRZ-OOK to RZ-OOK PDM signals was successfully demonstrated by firstly performing polarization demultiplexing and then processing separately. However, this scheme required all-optical dynamic state of polarization (SOP) tracking and polarization demultiplexing techniques, and thus was sensitive to the polarization state of the input PDM signals. In this paper, we propose a polarization-insensitive all-optical NRZ-OOK to RZ-OOK, NRZ-BPSK to RZ-BSPK and NRZ-QPSK to RZ-QPSK format conversion scheme for PDM signals by utilizing the merit of dual orthogonal polarization pumps FWM process in HNLF. Receiver-sensitivity-gain conversion is achieved in this conversion process as well. The BER measurements results show that receiver-sensitivity gain of $\sim$1.5 dB, $\sim$0.8 dB, and $\sim$0.3 dB for OOK, BPSK and QPSK PDM signals at BER value of 10^{-9}, 10^{-9}, and 10^{-3} are obtained, respectively.

2. Operation Principle

Fig. 1 shows the principle of polarization-insensitive NRZ to RZ format conversion for PDM signals using dual orthogonal polarization pumps FWM. Two pumps, one clock pump (P_1) and one continuous wave (CW) pump (P_2), are orthogonally polarized $(P_1 P_2)$. If the input NRZ-PDM signals are well synchronized with the clock pump (P_1), one RZ-PDM signals will be generated after FWM in nonlinear medium. Denoting the angle frequencies of input NRZ-PDM signals (S) and pumps (P1 and P2) by ω_s, ω_{p1}, and ω_{p2}, respectively, and assuming that $\omega_{p1} < \omega_{p2}$, we can obtain the format converted RZ-PDM signals (S') at the angular frequency $\omega_{s'}$. The relationship between the pumps (ω_{p1} and ω_{p2}), and PDM signals is shown in equation (1).

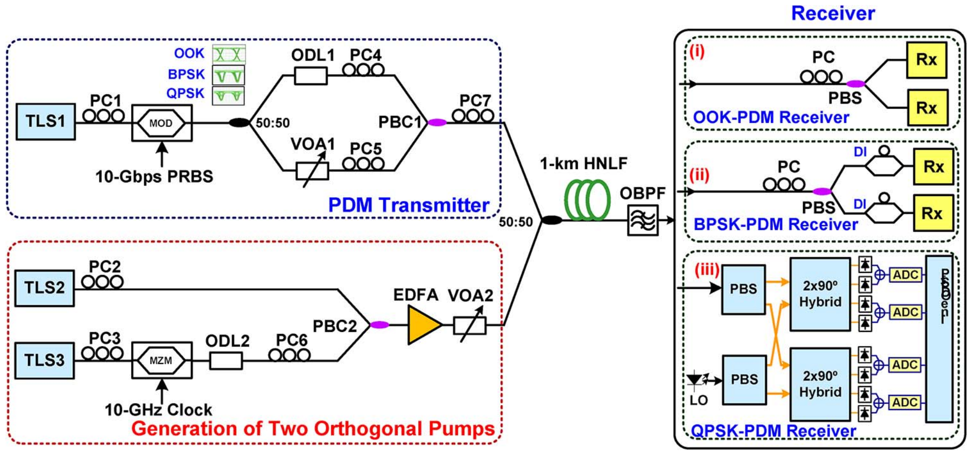

Fig. 2. Experimental setup: TLS: Tunable Laser, PC: Polarization Controller, MZM: Mach-Zehnder Modulator, MOD: Optical Modulator, ODL: Optical Delay Line, VOA: Variable Optical Attenuator, PBC: Polarization Beam Combiner, PBS: Polarization Beam Splitter, EDFA: Erbium-Doped Fiber Amplifier, HNLF: Highly Nonlinear Fiber, OBPF: Optical Band Pass Filter, LO: Local Oscillator laser, DI: Delay Interferometer, ADC: Analog-Digital Converter.

Polarization-insensitive conversion for the PDM signals can be achieved by utilizing the merit of dual orthogonal pumps FWM process [7]

$$\omega_{S'} = \omega_{P1} + \omega_{P2} - \omega_S. \quad (1)$$

3. Experimental Setup and Results

The experimental setup is shown in Fig. 2. It consist of a 2 $\times$ 10-Gb/s NRZ-OOK, 2 $\times$ 10-Gb/s NRZ-BPSK or 2 $\times$ 20-Gb/s NRZ-QPSK PDM signals transmitter, dual orthogonal polarization pumps generation block, a section of HNLF, a PDM signals receiver, as well as related test equipments. In the transmitter, the light from tunable laser (TLS1)oscillating at $\sim$1559.0 nm is modulated by an optical modulator (MOD) with10-Gb/s pseudorandom bit sequences (PRBS) to generate NRZ-OOK, NRZ-BPSK, or NRZ-QPSK signal. Then the 2 $\times$ 10-Gb/s NRZ-OOK, 2 $\times$ 10-Gb/s NRZ-BPSK, or 2 $\times$ 20-Gb/s NRZ-QPSK PDM signals are obtained employing an interleave scheme that is composed of a 50/50 coupler, two polarization controllers, a variable optical attenuator (VOA1), a optical delay line (ODL1: 1-km single mode fiber and a variable optical delay line) and a polarization beam combiner (PBC1). The OVA1 is used to balance the optical power of the two polarization tributaries of PDM signals. The ODL1 is used to decorrelate and synchronize the data stream of the two polarization tributaries of PDM signals. A polarization controller (PC7)is used to generate a random polarization direction for the PDM signals that is entirely independent of the polarization sated of the pumps.

The dual orthogonal polarization pumps generation block uses two TLSs (TLS2 and TLS3, oscillating at $\sim$1557.7 nm (P1) and $\sim$1554.3 (P2), respectively). As mentioned before, in order to achieve NRZ to RZ format conversion, P1 is intensity modulated by a 10-GHz clock signal. The two wavelengths are spaced almost symmetric to the zero dispersion wavelength of the HNLF. P1 and P2 are first combined by a 50/50 polarization beam combiner (PBC2). Then the two pumps are amplified by a high-power erbium-doped fiber amplifier (EDFA). Since P1 and P2 are coupled by a polarization beam combiner, their polarizations are made orthogonal to each other. The powers of two pumps are set to be the same at the input of HNLF while the total pump power can be adjusted by VOA2.

The two pumps and the input NRZ-OOK, NRZ-BPSK, or NRZ-QPSK PDM signals are combined by a 50/50 coupler and fed into 1-km HNLF subsequently. The zero dispersion wavelength, dispersion slope, and nonlinear coefficient of the HNLF are 1556 nm, 0.02 ps/nm2/km,

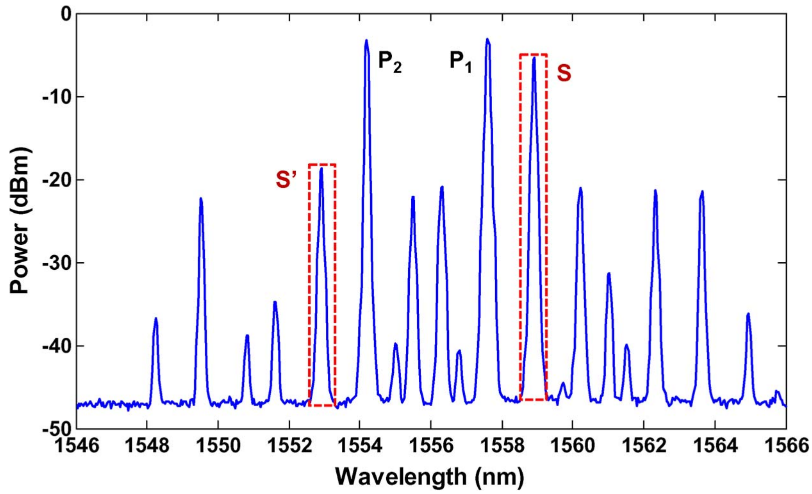

Fig. 3. Spectra of the two pumps, input signal, and FWM generated signal after HNLF. P_1: clock pump, P_2: CW pump, S: input PDM signals, S': format converted PDM signals. The wavelengths of the P_1, P_2, S and S' are at 1557.7 nm, 1554.3 nm, 1559.0 nm, and 1553.0 nm, respectively.

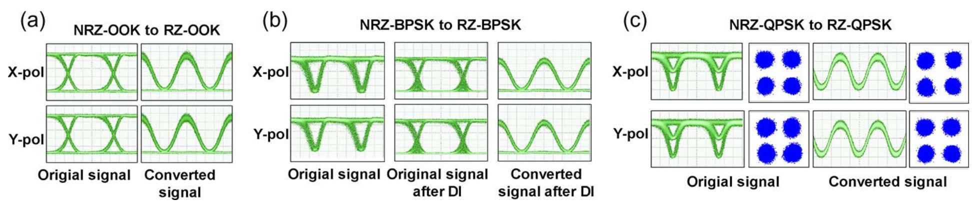

Fig. 4. Typical measured eye diagrams for the format conversion. (a) NRZ-OOK PDM signals to RZ-OOK PDM signals. (b) NRZ-BPSK PDM signals to RZ-BPSK PDM signals. (c) NRZ-QPSK PDM signals to RZ-QPSK PDM signals with corresponding constellations inserted.

and 30 ($W \cdot km^{-1}$), respectively. In order to achieve the format conversion, the clock pump (P1) and NRZ-OOK, NRZ-BPSK, or NRZ-QPSK PDM signals are adjusted to symbol synchronization through ODL2. At the HNLF output, the format converted PDM signals at ∼1553.0 nm are extracted by an optical band pass filter (OBPF). At the signal receiver side, we use the direct detection, delay interferometer (DI) detection, and coherent detection to demultiplex and demodulate the OOK-PDM, BPSK-PDM, and QPSK-PDM signals, respectively (see Fig. 2(i)–(iii), respectively).

Fig. 3 shows the optical spectra of the signals after HNLF, including the spectra of input two pumps (P1 and P2), input PDM signals (S), and format converted PDM signals (S'). In our measurement, the total power of the two pumps fed into the HNLF are adjusted at ∼15.8 dBm, and the power of the input PDM signal is set at ∼13.2 dBm (corresponding to ∼10.2 dBm for each polarization tributaries). Under the same condition, the eye diagrams of the proposed format conversion scheme are measured and presented in Fig. 4. Fig. 4(a) shows the eye diagrams of the original NRZ-OOK PDM signals and converted RZ-OOK PDM signals. Fig. 4(b) shows the eye diagrams of the original NRZ-BPSK PDM signals, original NRZ-BPSK PDM signals after DI, and format converted RZ-BPSK PDM signals after DI. The eye diagrams of original NRZ-QPSK PDM signals, format converted RZ-QPSK PDM signals, and corresponding constellations are presented in Fig. 4(c). Here, the polarization tributary without decorrelating ODL1 reference as X-pol and the other channel referenced as Y-pol. It is obvious that error free format conversion can be achieved under all these three conversion process.

The BER measurements are taken finally for evaluating the performance of the format conversion process. Fig. 5(a)–(c) show the BER results for the original NRZ-OOK PDM signals and

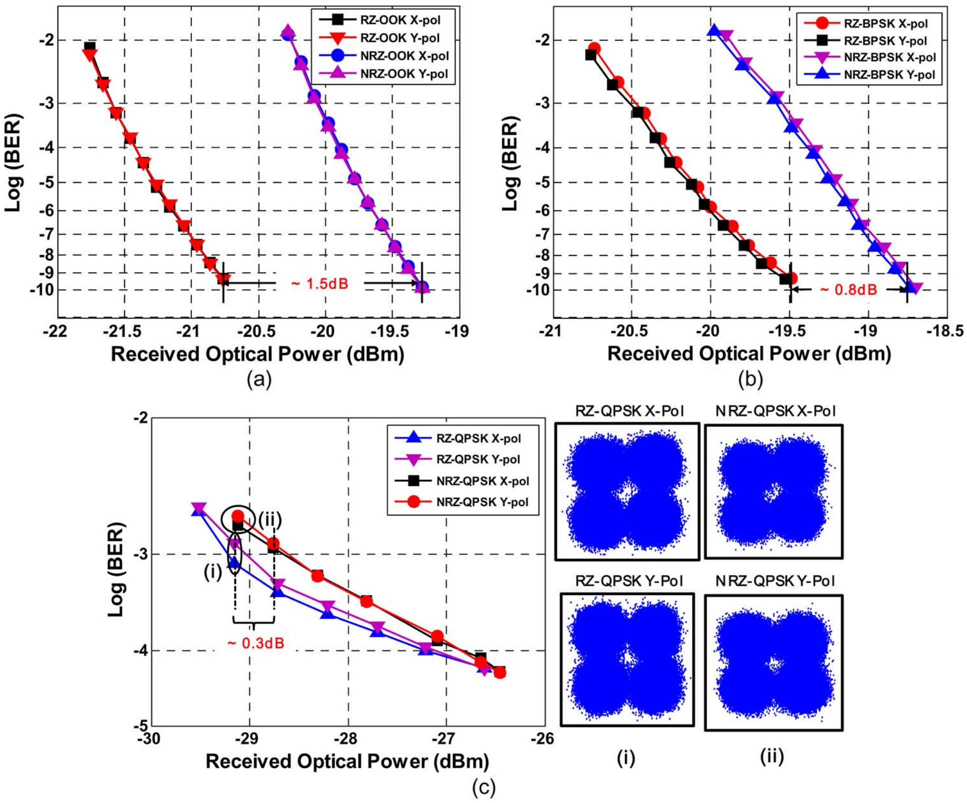

Fig. 5. Measured BER results for format conversion. (a) NRZ-OOK PDM signals to RZ-OOK PDM signals. (b) NRZ-BPSK PDM signals to RZ-BPSK PDM signals. (c) NRZ-QPSK PDM signals to RZ-QPSK PDM signals with corresponding constellations inserted.

converted RZ-OOK PDM signals, original NRZ-BPSK PDM signals and converted RZ-OOK PDM signals, and original NRZ-QPSK PDM signals and converted RZ-OOK PDM signals (both polarization tributaries of the PDM signals), respectively. As shown in Fig. 5, $\sim$1.5-dB receiver-sensitivity gain (at the BER value of 10^{-9}) is obtained for converted RZ-OOK PDM signals relative to original NRZ-OOK PDM signals, $\sim$0.8-dB receiver-sensitivity gain (at the BER value of 10^{-9}) is obtained for converted RZ-BPSK PDM signals relative to original NRZ-BPSK PDM signals, and $\sim$0.3-dB receiver-sensitivity gain (at the BER value of 10^{-3}) is obtained for converted RZ-QPSK PDM signals relative to original NRZ-QPSK PDM signals. Considering the receiver-sensitivity difference and different receiving schemes for different formats, and different degradation on different formats under the FWM process, the receiver-sensitivity-gain differences are reasonable.

4. Conclusion

We have successfully demonstrated a scheme of polarization-insensitive all-optical NRZ-OOK to RZ-OOK, NRZ-BPSK to RZ-BPSK, and NRZ-QPSK to RZ-QPSK format conversion for PDM signals by utilizing dual orthogonal polarization pumps FWM in HNLF. Receiver-sensitivity gain of $\sim$1.5 dB, $\sim$0.8 dB, and $\sim$0.3 dB for OOK, BPSK, and QPSK PDM signals at BER value of 10^{-9}, 10^{-9}, and 10^{-3} are obtained, respectively. Considering the receiver-sensitivity difference and difference receiving schemes for difference formats, and difference degradation on difference formats under the FWM process, the receiver-sensitivity-gain difference are reasonable. Theoretically, this scheme can be applied to multiple wavelengths simultaneously as well by elaborately synchronized all the multiple wavelengths signals with the clock pumps.

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