Influence of the interaction PMD and SPM in the polarization shift keying (PolSK) modulation using ultrashort pulse as carrier

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Resumen: *La modulación por polarización (PolM) es una alternativa para la transmisión a altas tasas de bits en enlaces de fibra óptica metropolitano. En el presente artículo, se propone realizar un sistema de comunicaciones ópticas con PolM y una fuente de pulsos ultracortos como portadora óptica en un enlace de 190 km de fibra óptica estándar (SSMF). El principal objetivo del artículo es mostrar el impacto de la interacción de la dispersión por modo de polarización (PMD) y la automodulación de fase (SPM) en la etapa de recepción. Las pruebas de simulación se aplicaron a una tasa de bit de 10 y 40 Gb/s y una potencia desde 1 hasta 50 mW. Se analizó el desempeño del sistema de comunicaciones ópticas a través de la medida del ancho de pulso (portadora), las esferas de Poincaré por cada fenómeno y su interacción, los diagramas de ojo y las curvas de BER vs potencia. Los resultados obtenidos muestran el gran impacto del PMD y SPM a 40 Gb/s y 50 mW, donde se dispersan los estados de polarización (SOP) con respecto al SOP inicial y el VER es lo suficientemente alto para disminuir la calidad del enlace de recepción. Las simulaciones permitieron determinar que la interacción PMD y SPM no se debe ignorar en los sistemas de comunicaciones ópticas con PolM y el desarrollo de nuevas técnicas de mitigación son necesarias.*

Palabras clave: Modulador de Polarización, dispersión de modo de polarización, modulación de fase, pulso ultracorto, ecuación de Manakov-PMD, Poincaré sphere, BER.

Abstract: *Polarization modulation (PolM) is an interesting alternative for generating transmissions at high bit rate in metropolitan-fiber optical link. In this paper, an optical communications system with PolM and an ultrashort pulse source as carrier are proposed to carry out a transmission at 190 km in standard single-mode fiber (SSMF). The goal is to observe the impact of the interaction of polarization-mode dispersion (PMD) and self-phase modulation (SPM) in the reception. The simulation tests are carried out for a bit rate of 10 and 40 Gb/s, and a power peak ranging from 1 to 50 mW. The optical communications system performance is analyzed by pulse width measurement (carrier), Poincaré spheres for each phenomenon and with the interaction, eye diagrams and BER vs power curves. The obtained results show the interaction PMD and SPM is strong at 40 Gb/s and 50 mW where the polarization states (SOP) are spread with respect to the initial SOP and BER is sufficiently high to reduce the quality of the reception link. The simulations allow corroborating that the interaction PMD and SPM must not be ignored in optical communications systems with PolM and the need for developing new mitigation techniques are required.*

Keywords: Polarization modulator, polarization-mode dispersion, self-phase modulation, ultrashort pulse, Manakov-PMD equation, Poincaré sphere, BER..

1 Introduction

The polarization shift-keying (PolSK) is an interesting method for increasing the transmission rate and to create modulation formats at high level. The useful of PolSK was demonstrated for long-haul fiber transmission at 10 Gb/s, with amplifiers each 50 km by using a simulation package OptSim [Carena98]. The advances of polarization modulation (PolM) allowed developing four-level detection polarization modulated systems through the 4-PolSK constellation, which was proposed to reduce transceiver architecture [Hu03]. A PolM based on LiNbO3 Mach-Zehnder modulator (MZM) were tested over a 50 km by using standard single-mode fiber (SSMF) at 40 Gb/s, demonstrating its viability for high-transmission rate [Chi05]. Recently, PolM has been used to create ultrafast polarization modulation in vertical cavity surface emitting lasers (VECSEL) by changing the states of polarization (SOP) with RF modulation [Barve12]. Other approach was two-stage feed forward carrier phase estimation algorithms for dual-polarization 16-ary QAM (DP 16-QAM) with coherent detection [Zhong13]. In addition, a recent study of efficiency of modulation formats for optical communications proposes to use dual polarization quadrature phase shift keying (DP-QPSK) due to its excellent energy performance between 0.8 (2.5 b/s/Hz) and 1.6 dB (2.8 b/s/Hz) [Khodakarami13]. The above shows the importance of PolSK development for finding new modulation formats oriented to at high-transmission rate.

On the other hand, it is important to consider the PolSK performance with linear and nonlinear phenomena in SSMF. An analysis about the PolSK found that the depolarization induced by polarization mode dispersion (PMD) generates an excess sensitivity penalty compared with intensity modulations and therefore, an active control of the input SOP is necessary [Lepley00]. A similar research analyzed the influence of PMD for dual-channel PolSK system limits of bit rate until 22 Gb/s [Cui11]. Other research work carried out experiments to monitor PMD and dispersion chromatic in 40 Gb/s by using two in-band PolM pilot tones at different frequencies in order to separate both phenomena and compensate simultaneously [Shi06].

Considering self-phase modulation (SPM), a format based on a chirped duobinary PolSK transmission implemented through simulation, mitigated the signal distortion and spectral broadening, increasing the dispersion tolerance and reduces SPM [Yang05]. A research about return zero (RZ) format pulse and Differential Polarization-shift Keying (DPolSK) found that the performance is degraded by presence of PMD (0.05 ps/Km1/2) but the system has a better BER (< 10-3 at 5 dBm of peak launch power) than DPSK (10-2 at 3 dBm) [Chen10]. However, when peak launch power is increased above 5 dBm, DPolSK has a high BER. These works show the need for studying and understanding the interaction PMD and nonlinearities with respect to the peak power.

In this paper, the main goal is to carry out several simulations in VPI photonics of a PolSK using an ultrashort pulse source as carrier in order to observe the impact of the interaction of PMD and SPM explained by the Manakov equation (SPM is relevant for one channel in SSMF [Yousaf09]). The simulation tests with PMD and SPM are considered independently and after taking into account its interaction. The used bit rates are 10 and 40 Gb/s and SSMF has a distance at 190 km. The above configuration is selected to identify the critical condition that affects the reception with balanced PIN detectors. The result analysis will be discussed through eye diagram and BER vs Power curves obtained from VPI photonics simulator.

The structure of this paper is organized as follows: in section 2, the theory about PMD, SPM, the interaction PMD and SPM, and ultrashort pulses are presented. In section 3, the polarization modulation and its mathematical expressions are explained. The simulation experiments of optical communications system and results are shown and discussed in section 4. Finally, conclusions and future works are mentioned.

2 Theory

2.1 Interaction between PMD and SPM

The birefringence in a fiber is due to the loss of symmetry in the index of refraction of the fiber caused by molecular changes of the material (anisotropy), efforts, and changes in the geometric shape of the optical fiber core. This effect due to the material, significantly affects the propagation of signals through the fiber by the phenomenon known as polarization mode dispersion of light.

PMD or Polarization-Mode Dispersion is a limiting factor in transmission systems of high-speed fiber-optic Gbps and long distance. PMD causes widening of optical pulses transmitted by an optical fiber, causing interference among symbols and, therefore, an increase of the erroneous bit rate. The PMD effect occurs when the two orthogonal polarization components- called HE11 fundamental mode propagation polarization modes- travel at different group velocity, arriving at different times at the end of the fiber, broadening and distorting pulses. The difference in arrival times between the polarization modes is called differential group delay (DGD: Differencial Group Delay. This parameter is used to determine the PMD. The variation of the group velocity is produced by the birefringent characteristics of the transmission medium of the optical fiber. The birefringence is the change in refractive index, n, of the transversal axes of the optical fiber, called birefringence axes [Zapata12].

Many different phenomena occur in the propagation by optical fiber, among which the most important are the nonlinear phenomena and PMD. These phenomena affect the performance on communication optical links. The phenomena nonlinear modify the power signal, while the PMD causes widening of pulses optical transmitted, causing interference among symbols. The polarization effects are difficult to analyze because they generate random variations in the birefringence in optical fibers, as well as polarization dependent loss and gain in the amplifiers. On the other hand, one the most important nonlinear phenomena is the Kerr effect, which affects the signal phase becoming in a big challenge of research for the communication optical links.

The great majority the studies on the nonlinear Schrodinger equation considered the part scalar, where one single state polarization for the light is studied. However, the long scope is essential to analyze the vector equation Schodinger, where the terms of coupling the PMD and nonlinear effect Kerr are known. In this case, both can interact in order to produce effects that are potentially harmful like polarization rotation, which can alter the polarization states of the bits, so that they vary from one bit to the next a way that is difficult to predict.

The nonlinearity induces a chirp in the signal, which in combination with higher order PMD can lead to pulse compression and a reduction in the eye-opening penalty that would be present in the absence of PMD. Moreover, the nonlinear interaction between two channels generates a nonlinear rotation in the principal states of the bits in each channel that varies bit to bit. While this rotation does not directly induce an eye-closing penalty, it makes impossible to use current PMD compensation techniques since these techniques typically rely on each bit having the same principal states and therefore, the same polarization variation as a function of time within a bit slot. The above explanation that governs our investigation is the Manakov-PMD equation, defined as [Menyuk06]:

$$j\frac{\partial U(z,t)}{\partial z}+j\Delta\beta^{(1)}(z)\bar{\sigma}_3(z)\frac{\partial U(z,t)}{\partial z}-$$
$$\frac{1}{2}\beta^{(2)}(z)\frac{\partial^2}{\partial t^2}U(z,t)+\frac{8}{9}\gamma\left|U(z,t)\right|^2U(z,t)=0 \tag{1}$$

where U(z,t) is the field amplitude, γ is the nonlinear parameter, β(1) and β(2) are the first and second order dispersion chromatic in function of z-direction, respectively, and σ3 refers to Pauli matrix. The nonlinear PMD term is not included and the pulses will be considered in the picoseconds range, typical in optical communications systems. In addition, the nonlinear PMD term is negligible in this range. The Manakov-PMD equation is the mathematical model that describes the interaction PMD and nonlinear effects, that in our case is SPM phenomenon. In the next section, an explanation about ultrashort pulses is presented.

2.2 Ultrashort pulse

An ultrashort pulse is an electromagnetic wave represented by the electrical field, ***E***(*t*), defined by spectral components in terms of Fourier inverse transform [Monmayrant10]:

$$E(t)=\frac{1}{\sqrt{2\pi}}\int_{0}^{\infty}\varepsilon(\omega)\cdot\exp[-i\omega t]d\omega \qquad (2)$$

where $\varepsilon(\omega)$ is the electrical field in the spectral domain. Considering the complex Fourier transform in terms of amplitude and phase, a mathematical model of the ultrashort pulse dynamical is expressed in time domain [Dorrer05]:

$$E(t)=\left|E(t)\right|\cdot\exp\left[i\phi_i(t)\right]\cdot\exp\left[i\phi_0\right]\cdot\exp\left[-i\omega_o t\right] \qquad (3)$$

where $|E(t)|$ is the electrical field magnitude, ω_0 represents the nearest central frequency of the pulse spectrum, $\square_i(t)$ is the phase depend on time, and $\square_0$ is a constant phase. The phase allows determining the amount of frequency components of a pulse in different intervals of time. On the other hand, ω_0 generates phase variations of pulse in time (chirp). One aspect that many scientists seek is to measure the duration of a pulse [Antonicini06]; considering Eq. (2), the duration of a pulse can be determined by a statistical model (in this case, $<\Delta t>$ represents the average or media of the duration of pulse), as shown in Eq. (4):

$$\langle\Delta t\rangle=\frac{\int_{-\infty}^{+\infty}t\left|E(t)\right|^2dt}{\int_{-\infty}^{+\infty}\left|E(t)\right|^2dt} \qquad (4)$$

Other important information about the ultrashort pulse is the spectral width (the term $<\Delta\omega^2>$ is defined as the standard deviation of the spectral width), as shown in Eq. (5):

$$\left\langle\Delta\omega^2\right\rangle=\frac{\int_{-\infty}^{+\infty}\omega^2\left|\varepsilon(\omega)\right|^2d\omega}{\int_{-\infty}^{+\infty}\left|\varepsilon(\omega)\right|^2d\omega} \qquad (5)$$

Equations (4) and (5) are useful to find the pulse duration and spectrum width. In this case, it is used the two measures well-known as half-width at half-maximum (HWHM) and full-width at half-maximum (FWHM). The latter is the most applicable in the test lab [Rullière05]. Relating Eq. (4) and Eq. (5), Heisenberg's uncertainly is taken into account where the product $\Delta t\Delta\omega$ defines that:

$$\Delta t\Delta\omega\geq\frac{1}{2} \qquad (6)$$

In Eq.(6), the product has a limit ½ in order to create a ultrashort pulse [Fermann05]. This characteristic allows obtaining different pulses shape (e.g. triangular, Gaussian, Lorentzian, etc.), generated by the initial sequence of a pulses train and the maximum amplitude of its envelope. In FWHM case, the limit can change according to the shape and characteristic of the pulse, as shown in Eq. (7):

$$\Delta t\Delta\upsilon\geq K \qquad (7)$$

where $\Delta\upsilon$ is the bandwidth FWHM and K is a factor of pulse shape. In several applications, Gaussian pulse (K = 0.441) and Sech (K = 0.336) are the most popular in lab test. For these pulses shape, if τ_p is the pulse duration when the peak power is known, the Gaussian and Secant Hyperbolic shapes can be defined by:

$$E(t)=E_0\exp\left[-\left(\frac{t}{\tau_G}\right)^2\right] \qquad (8)$$

and

$$E(t)=E_0\mathrm{sech}\left(\frac{t}{\tau_s}\right) \qquad (9)$$

where $\tau_G = \tau_s / (2\ln 2)^{1/2}$ and $\tau_s = \tau_p / 1.76$. The above description will be useful to create an ultrashort pulse source as carrier for PolM by means of VPI photonic simulator.

3 Polarization modulation

A polarization modulation (PolM) is a method to increase the transmission rate and spectral width without affecting the optical signal power. Usually, PolM carries out a transformation of a linear polarization state though an arbitrary polarization state. The above allows modulating the angle of polarization according to the used modulation signal. If the modulation signal is 1-binary then the output will be polarized at -45°; otherwise, if the modulation signal is 0-binary then the output will be at +45°. To reach this modulation, PolM needs an ultrahigh-speed mode converter and a static polarization controller to find a polarization state, represented by a point on the Poincaré sphere [Bull05]. This polarization state is switched to any other state into sphere. The changes of polarization state depend on the phase modulations realized by polarization maintaining fibers (PMF), LiNbO3 modulator [Chen06]. A mathematical expression of PolM in function of Jones matrix is defined below:

$$\begin{bmatrix}E_o(x)\\E_o(z)\end{bmatrix}=\begin{bmatrix}\exp\left(i\phi_x(\text{-}1)^n\right) & 0\\ 0 & \exp\left(\text{-}i\phi_z(\text{-}1)^n\right)\end{bmatrix} \qquad (10)$$
$$\begin{bmatrix}\cos(\pi/4) & \text{-}\sin(\pi/4)\\ \sin(\pi/4) & \cos(\pi/4)\end{bmatrix}\cdot\begin{bmatrix}E_i(x)\\E_i(z)\end{bmatrix}$$

where Ei and Eo are the input and output electric field, respectively, n is a positive integer that indicates the n-th polarization modulation and ϕ refers to the phase modulation. Usually, PolM uses a LiNbO3 modulator which Pockel's effect is generated to achieve phase modulation. When the electrical field is excited onto the crystal, variations of the refraction index are induced and the maximum change occurs in the z-direction [Wilberg07]. For the PolM case, the propagation light will provide several phase modulations in the x- and z-modulation if the propagation direction is assumed in y-direction. In LiNbO3 phase-matching, z-direction or extraordinary wave has a high phase modulation although the x-direction could be presented a small phase modulation if it is an ordinary wave. Considering LiNbO3 modulator as phase modulator, the output electric field for Ex = Ez in terms of Stokes parameters is given by:

$$\mathbf{E_o}(\phi) = \begin{bmatrix} E_x^2 + E_y^2,\ 0,\ 2E_xE_y\cos(\phi(t)), \\ 2E_xE_y\sin(\phi(t)) \end{bmatrix} \qquad (11)$$

where □(*t*) = □*z*(*t*) – □*x*(*t*). To control the polarization states observed on the Poincaré sphere, an angle □(*t*) = π is recommended to guarantee an optimal modulation [Hu04].

One important aspect of PolM is its detection after reception. One approach was proposed by [Sköld09], where an ideal horizontal polarizer and a vector, $\boldsymbol{P} = [p_o \;\; p_1 \;\; p_2 \;\; p_3] = [p_o, \; \boldsymbol{p}]$ are defined in order to indicate four-component of polarization in Stokes's space. The mathematical expression of the detected power in the reception, $D(t)$, is shown below:

$$D(t) = \left(p_o + p_1\cos\left(\phi_{45^o}(t)\right)\right) - p_2\sin\left(\phi_{0^o}(t)\right) \sin\left(\phi_{45^o}(t)\right) - p_3\cos\left(\phi_{0^o}(t)\right)\sin\left(\phi_{45^o}(t)\right) \qquad (12)$$

Eq. (12) describes the amount of detected power if the amplitudes depend linearly on the components of the polarizer vector *P*.

4 Simulation and discussion

The goal of the simulation is to show the polarization modulation behavior when PMD, SPM and the interaction between them are presented in SSMF at 190 km (0.2 dB/km of attenuation). In Figure 1, a schematic representation of the simulation is illustrated. The first part represents an ultrashort pulse source (carrier), where it is used an impulse function generator, a four-order Gaussian lowpass filter at 200 GHz (electrical), and a pulse laser at 1 MHz of linewidth and initial power of 1 mW (wavelength of 1550 nm). The second part is a code-word generator, where uses a Gaussian filter at 10 ns (for 10 Gb/s) of full width half maximum (FWHM) and at 10 ps of FWHM (for 40 Gb/s). On the other hand, the polarization modulator contains inside a polarization controller (PC) at 45°, a phase modulator (PM) at 180° fixed, two splitter polarizations after PC, and the main output (to see the PolM representation in VPI, go to [User-12]). The optical link has three erbium-doped-fiber amplifiers (EDFA) with gain of 30 dB, each one connected to a SSMF where PMD, SPM and the interaction between them are independently simulated. It is important to clarify chromatic dispersion is not considered because the paper is focused on the impact of PMD, SPM and its interaction with respect to PolM propagation. For the reception, balanced PIN detectors (BER measured and second-order Gaussian lowpass filter include) and an electrical amplifier with gain at 50 dB are applied. The simulations are carried out in VPI transmission market V9.0.

To observe the impact of PMD, SPM and its interaction, the pulse laser power is varied from 1 mW to 50 mW. In addition, the transmission rate is used at 10 Gb/s and 40 Gb/s, respectively, to study the eye diagram behavior. In Figure 2, Poincaré sphere and optical spectrum of PolM input are shown, where the states of polarization (SOP) are located at an angle of 45° and -45° (it is important to consider linewidth of pulse laser in the point distribution on the sphere). The code-word has a length of 14 bits, where the choice sequence is {1 0 1 0 0 1 0 1 0 1 0 0 1 0}. In order to analyze the propagation behavior of polarization modulation through SSMF, the pulse laser power is fixed in 1 mW and the PMD coefficient is established at 0.5 ps/km$^{1/2}$ and 0.125 ps/km$^{1/2}$ for 10 and 40 Gb/s [Leiva07].

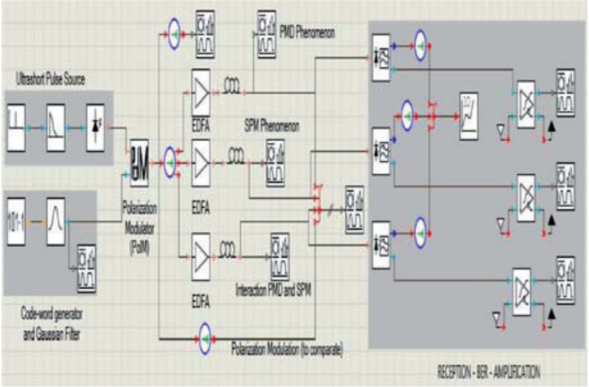


Figure 1. General scheme of simulation built up in VPI transmission market V9.0.

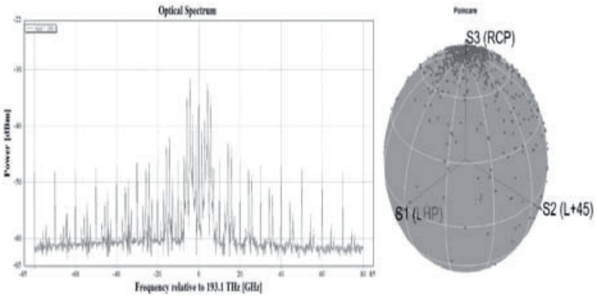
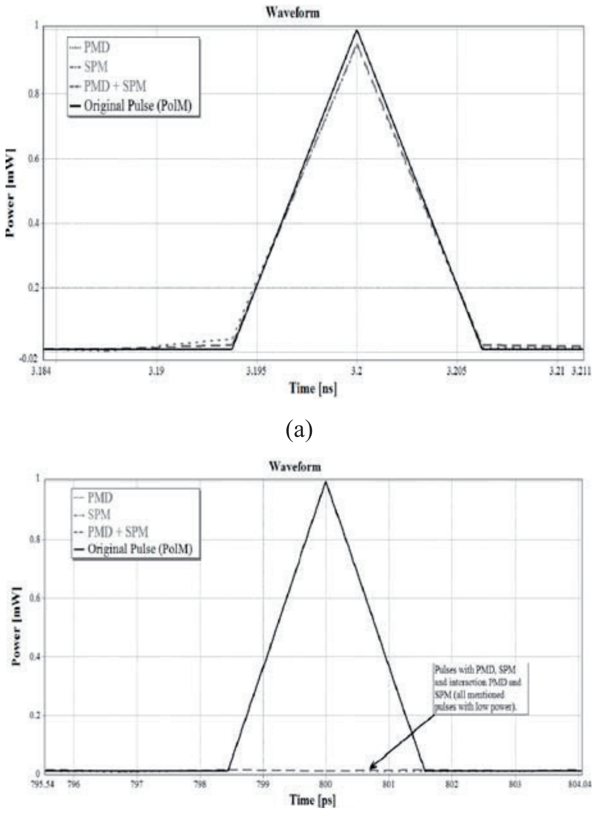


Figure 2. Optical spectrum and Poincaré sphere of PolSK at 1 mW (carrier) and 10 ns (information).

Figure 3 illustrates the ultrashort pulse when PMD, SPM and its interaction are taken into account (due to the bandwidth and Gaussian order used in the simulation, the pulse shape is approached to a triangular shape). Figure 4 illustrates different changes of Poincaré sphere with the mentioned phenomena. By analyzing Figure 3, the pulse width for original PolM is 5 ps (FWHM), with PMD is 6.082 ps, and with SPM is 6.045 ps (for 10 Gb/s). However, the interaction PMD and SMP increases the pulse width at 6.416 ps. Considering 40 Gb/s, the interaction PMD and SPM is strong which the pulse power decreases and the pulse width is increased too. In this case, the pulse width measurements are complicated to establish. In Figure 4, comparing independently PMD and SPM with respect to its interaction, the SOP for PMD-SPM change drastically the phase when the transmission rate is 40 Gb/s. Therefore, high-transmission rate increases the interaction PMD and SPM for metropolitan-fiber transmission and SOP are spread.

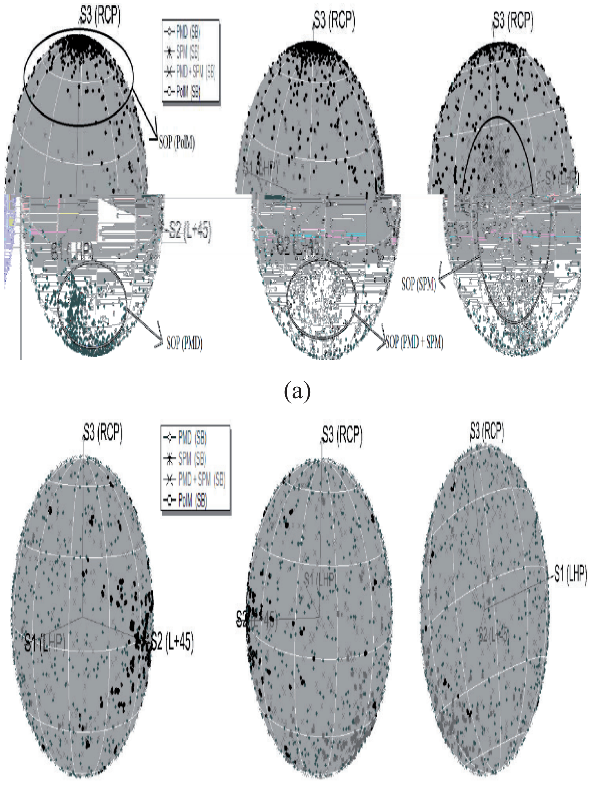
To analyze other aspects of the interaction PMD and SPM, the eye diagrams in the reception and BER estimation are considered. In Figure 5, several eye diagrams for 10 Gb/s and 40 Gb/s at 50 mW are shown. In Figure 6, two measurements, BER vs Power, are illustrated at 10 and 40 Gb/s. Comparing Figures 5 and 6, the interaction PMD and SPM for 10 Gb/s is similar to 40 Gb/s and the increase of power has little variation of BER. Nevertheless, BER begins to rise when the power is increased and therefore, the interaction PMD-SPM will be considerable. Thus, the interaction is strong after 30 mW if the transmission rate is 40 Gb/s. The critical point of the interaction is found at 50 mW and 40 Gb/s with BER = 0.2626591. This condition causes a much closed eye for high-transmission rates and at high power. The above is sufficient to truncate the reception but the interaction PMD and SPM could change its behavior due to the birefringence random of PMD. However, BER values of PMD and SPM will be low with respect to BER of the interaction PMD and SPM if the power and transmission rate are high.



(a)

(b)

Figure 3. Ultrashort pulse behavior with polarization modulation by considering PMD, SPM, and their interactions for: a) 10 Gb/s and b) 40 Gb/s.



(a)

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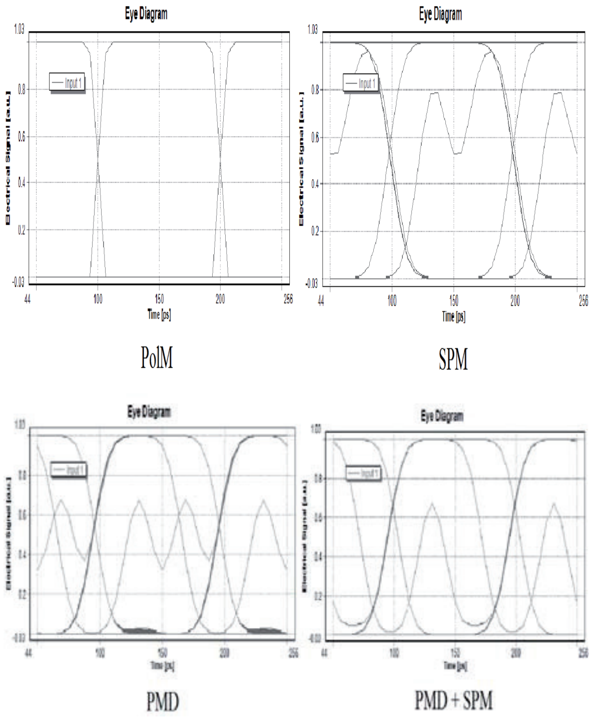
Figure 4. Poincaré sphere to analyze the SOP with PMD, SPM, and their interactions, for: a) 10 Gb/s and b) 40 Gb/s.



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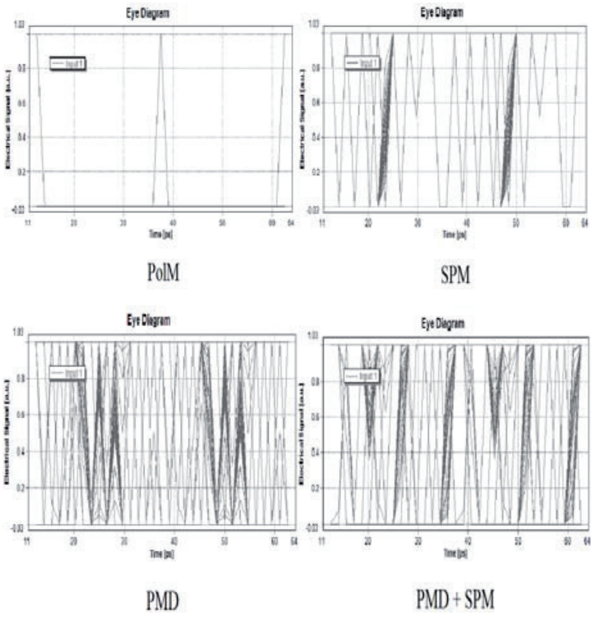
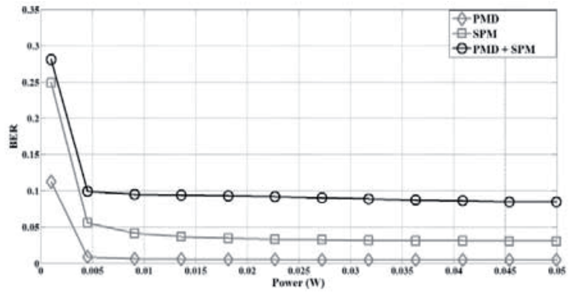
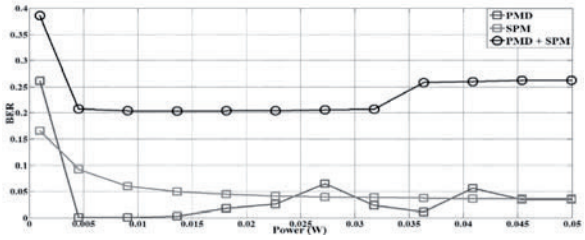


(b)

Figure 5. Eye diagrams in reception step considering a peak power at 50 mW, if the transmission rate is: a) 10 Gb/s and b) 40 Gb/s.



(a)



(b)

Figure 6. BER vs Power if: a) 10 Gb/s and b) 40 Gb/s.

5 Conclusions and future works

In this paper, a simulation experiment and its analysis with PolM and ultrashort pulse source as carrier for an optical link of SSMF at 190 km are presented. The results show that the pulse width is increased for a bit rate at 10 Gb/s when the interaction PMD and SPM are taken into account and it is greater than PMD and SPM seen separately. Nevertheless, the pulse width is difficult to measure at 40 Gb/s due to the interaction PMD and SPM is strong and the attenuation is high. Analyzing from another viewpoint, BER vs power curves with bit rate at 40 Gb/s and high peak power generate many problems in the reception and the interaction PMD and SPM is considerable. The above was corroborated in the eye diagrams since the eye is more closed with the interaction than considering the phenomena separately. Moreover, the influence of the interaction is also observed in Poincaré sphere where the SOPs are more spread than the initial SOP from PolM (40 Gb/s).

As future works, the interaction PMD and SPM will be studied when wavelength-division multiplexing (WDM) and polarization multiplexing (PolMux) are used for long-haul fiber transmission. On the other hand, the cross-polarization modulation (XPolM) will be simulated and analyzed with respect to the interaction PMD and SPM in WDM and PolMux applications, taking into account the ultrashort pulses trains as carriers, polarization controllers (PC) and spatial light modulators (SLMs). These studies will allow proposing experimental setup in a real application.

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