Analysis of DOP in the Presence of PMD and PDL for NRZ/RZ-DPSK Signals in High-Rate Optical Transmission Link

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Abstract— **This work analyzed numerically the relationship between DOP, PMD and PDL dispersion effects in high-rate optical communication systems for differential phase-shift-keying modulation. It was considered 10 Gb/s and 20 Gb/s transmission rates for NRZ-DPSK and RZ-DPSK (duty cycle 50% and 33%) signals.**

Key words: DOP, DPSK, PDL, PMD.

I. INTRODUCTION

In optic communications, when is desired to work with high rates (10 Gb/s or more) it is necessary to study birefringent effects which occurs in optical fibers due imperfections on fiber fabrication, temperature changes and winds, this last on air fibers. It can also occur in some other components like birefringent crystals and polarizers [1].

The light transmitted on this kind of communications is already polarized and is desirable that should be delivered the same way. However, dispersive effects and polarization loss can happen. The dispersive effects are polarization mode dispersion (PMD). Otherwise the polarization loss is caused by polarization dependent loss (PDL).

In recent years, several works have studied the effects of PMD and/or PDL in optical communication systems. In [2] it was studied the relation between degree of polarization (DOP) and PMD for different formats of modulation. The compensation of PMD is analyzed in [3]. In [4] it was studied the mitigation generated by PMD and CD (chromatic dispersion) at 10 Gb/s for DPSK (differential phase shift keying) and DQPSK (differential quadrature phase-shift keying) modulations using Viterbi equalization. In [5] it was studied performance of fiber optical system transmission in the presence of PMD, PDL and CD. In [6] it was examined PMD impairment of optical DPSK systems. In [7] it was shown the impact of PDL on DOP including PMD for NRZ Gaussian pulse. In [8] it was detailed and described optical polarization mode dispersion compensators (PMDCs) for high-speed optical communication systems. In [9] it was studied the evaluation of the moment-generating function (MGF) for a linear optical communication system consisting of distributed amplified spontaneous emission (ASE), PMD and PDL. The bit error rates (BERs) were evaluated for DPSK and OOK systems with PMD and PDL in [10,11,12]. An analytic model is reported in [13] to evaluate the electric output signals and their variance (Eye Diagram) for multi channel high-speed DPSK fiber optical system in presence of PMD, PDL and chromatic dispersion (CD).

This paper analyses the effects of PMD and/or PDL on DOP for modulation NRZ (non-return-to-zero)-DPSK and RZ (return-to-zero)-DPSK in fiber optical communication systems of 10 Gb/s and 20 Gb/s transmission rates.

In the Section II is shown a short review about PMD and PDL effects in optical fibers. The relationship among DOP, PMD and PDL is described in the Section III. The description of the simulational model for optical communication systems used in this work is presented in Section IV. The results are presented in the Section V. Finally, the conclusions are shown in the Section VI.

II. REVIEW OF PMD AND PDL EFFECTS

The polarization of the light is characterized by the distribution of its energy in two orthogonal modes (axes), it is called principal states of polarization (PSP). The degenerate nature of the orthogonally polarized modes holds only for an ideal single-mode fiber with a perfectly cylindrical core of uniform diameter. Real fibers exhibit considerable variation in the shape of their core along the fiber length. They may also experience nonuniform stress such that the cylindrical symmetry of the fiber is broken. Degeneracy between the orthogonally polarized fiber modes is removed because of these factors, and the fiber acquires birefringence.

In conventional single-mode fibers, birefringence is not constant along the fiber but changes randomly, both in magnitude and direction, because of variations in the core shape (elliptical rather than circular) and the anisotropic stress acting on the core. As a result, light launched into the fiber with linear polarization quickly reaches a state of arbitrary polarization. Moreover, different frequency components of a pulse acquire different polarization states, resulting in pulse broadening. This phenomenon is called *polarization-mode dispersion* (PMD) and becomes a limiting factor for optical communication systems operating at high bit rates. Due PMD, the orthogonally polarized modes propagate with different velocities resulting in a delay between the modes. The delay is called as differential group delay (DGD). The time average of those delays characterizes the PMD effect. According the DGD and the modulation used it is possible that happen a reduction on DOP, which is undesirable due the pulses spread on the fiber.

Losses of a fiber link often depend on state of polarization (SOP) of the signal propagating through it. This dependency is known to the *polarization-dependent loss* (PDL). Even though silica fibers themselves have relatively little PDL, the signal passes through a variety of optical components such as isolators, modulators, amplifiers, filters, and couplers, most of which exhibit loss (or gain in the case of optical amplifiers) whose magnitude depends on the SOP of the signal.

Moreover, the combination of PDL and PMD leads not only to large random variations in the signal power but also to signal distortion that invariably affects the performance of all long-haul lightwave systems [1].

III. The Relation of DOP, DGD and PDL

The DOP can be described from Stokes parameters. They are measured by optical field intensity contribution on the two orthogonal bases H/V (horizontal/vertical), +45º/-45º (right diagonal/left diagonal), and $\sigma+/\sigma-$ (left-hand circular /right-hand circular). Each one of these parameters S_1, S_2 and S_3 represents respectively the difference between linear, circular and diagonal polarizations. Together, the four parameters, represents the Stokes vector $\boldsymbol{S}= [S_0\ S_1\ S_2\ S_3]'$. Therefore, DOP é defined by [1]

$$DOP = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0} \quad (1)$$

In the frequency domain, the relationship of average Stokes vector and the field vector $\vec{\mathbf{E}} = [E_{0x}\ E_{0y}]'$ is described by [2]

$$S_0 = \int_{-\infty}^{+\infty} (|E_{0x}(\omega)|^2 + |E_{0y}(\omega)|^2) d\omega \quad (2)$$

$$S_1 = \int_{-\infty}^{+\infty} (|E_{0x}(\omega)|^2 - |E_{0y}(\omega)|^2) d\omega \quad (3)$$

$$S_2 = 2\int_{-\infty}^{+\infty} \mathrm{Re}[E_{0x}(\omega)E_{0y}(\omega)] d\omega \quad (4)$$

$$S_3 = -2\int_{-\infty}^{+\infty} \mathrm{Im}[E_{0x}(\omega)E_{0y}(\omega)] d\omega \quad (5)$$

where E_{0x} and E_{0y} represents respectively the field components on polarization axes x and y. The output optical field on fiber can be modeled by

$$\vec{\mathbf{E}}_{out}(\omega) = T(\omega)\vec{\mathbf{E}}_{in}(\omega) \quad (6)$$

where T and $\vec{\mathbf{E}}_{in}$ are the Jones transfer matrix fiber link and input optical field, respectively. They are described by [2]

$$T(\omega) = e^{(-\alpha(\omega)L - j\overline{\beta}(\omega)L)} U(\omega) \quad (7)$$

$$\vec{E}_{in} = \begin{bmatrix} \sqrt{r} \\ \sqrt{1 - re^{j\theta}} \end{bmatrix} f(\omega) \quad (8)$$

where $\alpha, \overline{\beta}$, L, r, θ and f are attenuation, the average propagation constant, the length of the fiber link, the optical power splitting ratio, the phase difference of two orthogonal polarization directions and the pulse format, respectively. The matrix U models the first order PMD and PDL effects [1,2,14]

$$U(\omega) = \begin{pmatrix} e^{\alpha_{PDL}/2} u_1 & u_2 \\ u_2 & e^{-\alpha_{PDL}/2} u_1^* \end{pmatrix}, \quad (9)$$

where α_{PDL} is the loss coefficient of PDL, $u_1 = \cos(\omega DGD/2) + j\cos(2k\omega)\sin(\omega DGD/2)$ and $u_2 = j\sin(2k\omega)\sin(\omega DGD/2)$. The coefficient k is defined by the depolarization rate, $|2\boldsymbol{k}|=|\partial \boldsymbol{s}/\partial \omega|$. The parameter $\boldsymbol{s}$ is direction of one of two orthogonal eigenvectors of PSP of the fiber. Therefore, using (6) in (1) – (5), we obtain DOP of output state [14].

IV. Simulational Analysis

In order to verify the impact of PMD and PDL effects on DOP in the optical communication systems, the simulation setup shown Fig. 1 was used for NRZ-DPSK and RZ-DPSK signals.

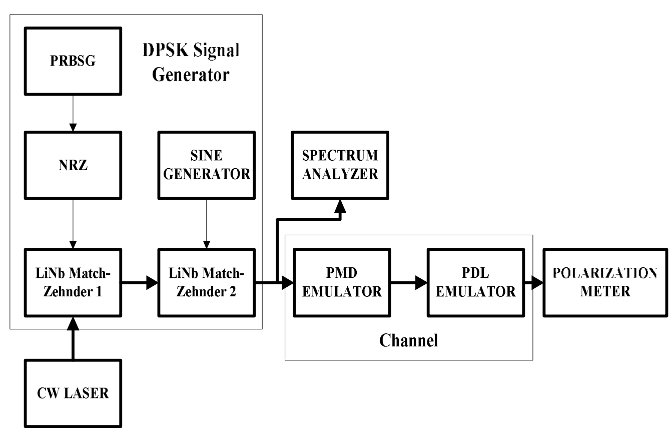

Figure 1. Simulation setup to measure the DOP in the presence of PMD and PDL effects.

In Fig. 1, one pseudo random bit sequence generator (PRBSG) is used to generate signal of 128 bit length at 10 Gb/s and 20 Gb/s rates that it will be modulated on NRZ/RZ-DPSK pulse generator consisting by LiNb Match-Zehnder modulators and CW laser at 1550 nm wavelength. The optical spectrum analyzer is used, channel input, to verify the chosen spectrum modulation. The optical channel is modeled by PMD and PDL emulators.

The PMD and PDL effects on DOP of transmitted signal were analyzed for NRZ-DPSK, RZ-DPSK (50% and 33%) modulations. Figs. 2, 3 and 4 show the optical power spectrums of NRZ-DPSK, RZ-DPSK 50% and RZ-DPSK 33% generated in Fig. 1 at optical channel input, respectively.

V. RESULTS

Firstly, it was analyzed the behavior of DOP in function of the DGD and PDL for the NRZ-DPSK, RZ-DPSK (50%) and the RZ-DPSK (33%) signals. The results were obtained varying the DGD value for 0 to 100 ps (0 to 50 ps) for 10 Gb/s (20 Gb/s). The PDL had fixed for values 0 and 0.5 dB when DGD is varied. In the simulation, it was considered 64 samples per bit generated, r = 1, α = 0.2 dB/km, $2k$ = 10.8 degree/GHz and zero chromatic dispersion [14].

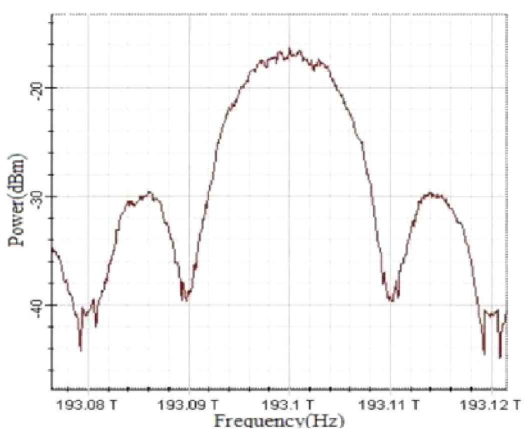

Figure 2. The optical spectrum of NRZ-DPSK format signal.

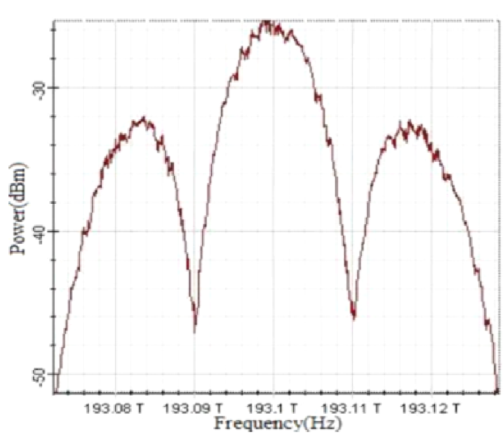

Figure 3. The optical spectrum of RZ-DPSK 50% format signal.

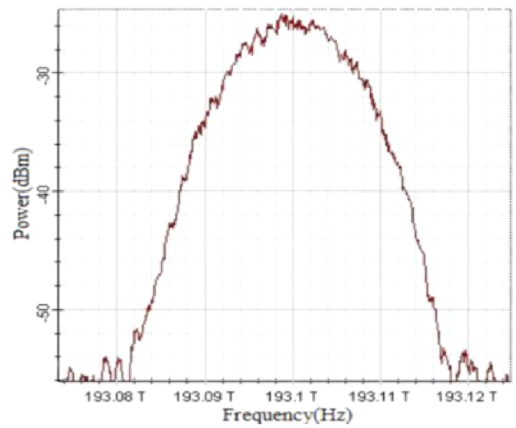

Figure 4. The optical spectrum of RZ-DPSK 33% format signal.

Figs. 5 and 6 show the DOP as function DGD for signals studied at 10 Gb/s and 20 Gbs/s without PDL effects, respectively.

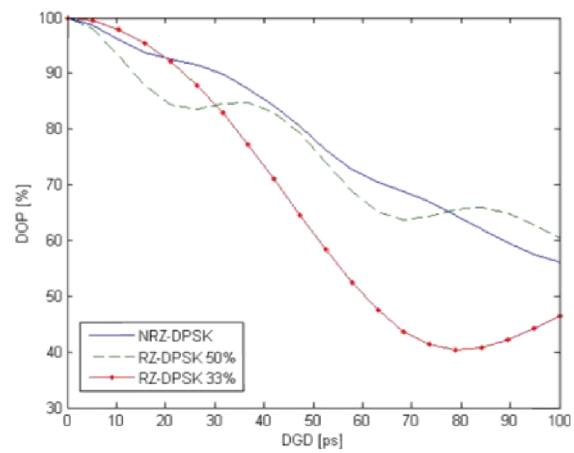

Figure 5. DOP versus DGD for the NRZ-DPSK, RZ-DPSK 50% and RZ-DPSK 33% at 10 Gb/s with PDL 0 dB.

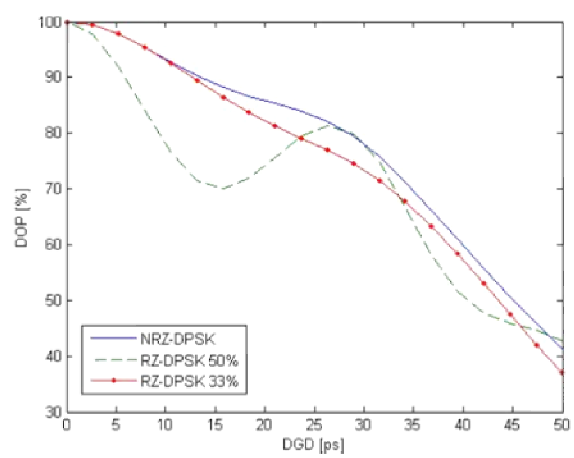

Figure 6. DOP versus DGD for the NRZ-DPSK, RZ-DPSK 50% and RZ-DPSK 33% at 20 Gb/s with PDL 0 dB.

It is noted in Figs. 5 and 6 that the relationship between DOP and PMD for NRZ-DPSK signal is practically monotonic behavior. The DOP is less sensitive to variation of DGD for this type signal than RZ-DPSK signals. The DOP varies no monotonically with DGD for RZ-DPSK signals. The state of polarization of RZ-DPSK 33% signal showed more sensitivity to PMD effect in comparison to other signals for 10 Gb/s rate. While the SOP of RZ-DPSK 50% signal suffered more variation for 20 Gb/s.

Now the PDL effect was added to the channel with PMD. It was considered PDL 0.5 dB and the behavior of DOP for signals studied at 10 Gb/s and 20 Gb/s is shown in the Figs. 7 and 8. The same behavior of DOP is shown in Figs. 5 and 6. However, the PDL effect improves the DOP for all cases analyzed. This is expected since the PDL element acts as a polarizer.

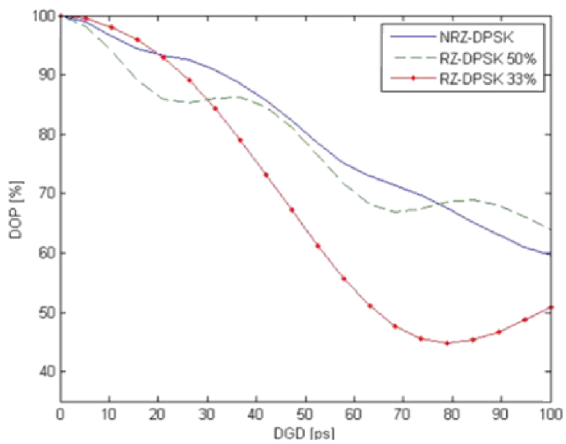

Figure 7. DOP versus DGD for the NRZ-DPSK, RZ-DPSK 50% and RZ-DPSK 33% at 10 Gb/s with PDL 0.5 dB.

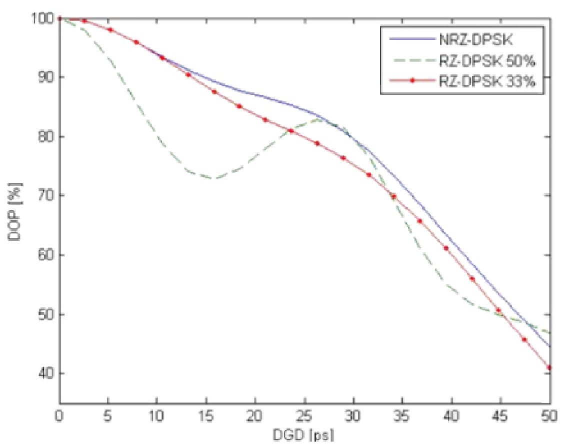

Figure 8. DOP versus DGD for the NRZ-DPSK, RZ-DPSK 50% and RZ-DPSK 33% at 20 Gb/s with PDL 0.5 dB.

Finally it was fixed the value of DGD in 10 ps and PDL was varied for 0 to 1 dB. The results of DOP versus PDL were shown in Figs. 9 and 10 for 10 Gb/s and 20 Gb/s rates, respectively. It was observed that the DOP has a monotonic increasing relationship with the PDL for the three types of signals studied.

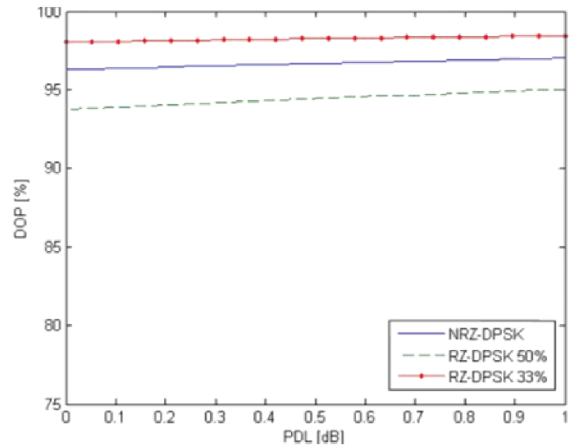

Figure 9. DOP versus PDL for DGD 10 ps at 10 Gb/s.

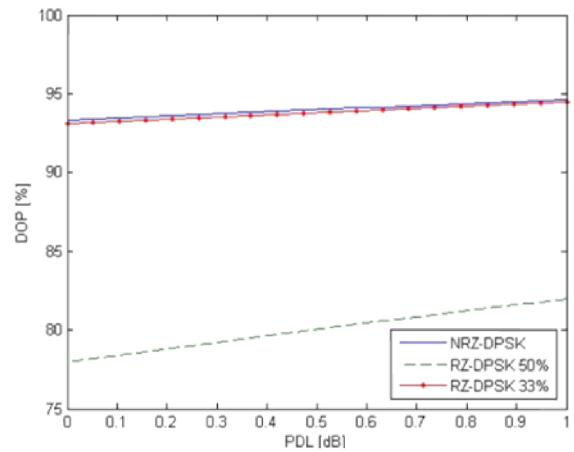

Figure 10. DOP versus PDL for DGD 10 ps at 20 Gb/s.

VI. CONCLUSION

Initially it were introduced the concepts and mathematical analyzes of PMD and PDL effects in optical fibers, what can origin these effects, what they affect and lastly simulations and shown of the results, thus reaching to determinates conclusions.

During an optical communication, using high rates (10 Gbs/s or 20 Gb/s), and according to any modulation, as might be seen, the PMD effect appears like a problem to light polarization on this kind of communication. However the addition of PDL can significantly improve the DOP variation caused by PMD. When the DGD had fixed value and the DOP varies monotonically increasing with PDL. It was noted that for fiber optic link which has a DGD average less than 10 ps, the degradation of DOP caused by the PMD effect could be compensated by PDL effect for differential phase-shift-keying modulations analyzed.

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