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Total Polarization-Dependent Loss of Cascaded Optical Components for Optical Space Applications

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ABSTRACT

Photonics-based communication systems can provide increasing data rates to meet the users' requirements. Coherent optical communication system was implemented to satisfy the current and future applications, in which the transmission of optical signal over two polarizations can mainly achieve a double Baud rate as compared to a single polarization. However, dual polarization systems have some hindrances which are represented by polarization rotation, polarization-dependent loss (PDL), and polarization mode dispersion (PMD). In this paper, those impairments are demonstrated and investigated for either a single component or multiple components in the optical system. The theoretical and mathematical discussions reveal that the polarization rotation and PDL can cause a loss in the optical signal power and loss in the orthogonality between two polarization tributaries. Furthermore, simulations are carried out for 10 GBaud dual-polarization-quadrature phase shift keying (DP-QPSK) as an example of optical application. The simulation measurements in term of bit-error-rate (BER) show how the polarization impairments can significantly degrade the system performance.

Keywords: Dual-polarization-quadrature phase shift keying (DP-QPSK), free space optics, microwave photonics (MWP), orthogonality between two polarization tributaries, polarization dependent loss (PDL), polarization rotation.

1. INTRODUCTION

Microwave photonics (MWP) is considerably evolved and employed for various applications in telecommunications, internet of things, radars, remote sensing, and astronomy [1]-[5]. In tandem with the continuous growth of the services, some issues such as high-speed link, large bandwidth, very low latency, cost-effective, and less complexity are the imperative purposes in the transmission systems. The use of only electronic components prevents from achieving all those requirements, and thus, the incorporation of electronic and photonic means with exploiting optical fiber has become of great interest [5],[6]. For internet applications, the fiber access network based on passive optical network (PON) technology is implemented to carry 50 Gb/s for downlink and 25 Gb/s for uplink [7],[8]. In a transmission part of PON, the electrical broadband data modulates the optical carrier generated by a mono-mode laser using an electro-optic modulator. Then, the optical spectrum is sent over a long fiber length with very low attenuation as compared to the huge attenuation of the wireless RF transmission, in particular at higher frequency bands. At the receiver part, the photodiode (PD) is utilized to recover the electrical data. The 5G era and beyond depend on another leading MWP structure known by radio-over-fiber (RoF). The main idea behind RoF is an optical heterodyne technique for generating a frequency carrier at millimeter-wave (mm-wave) or terahertz (THz) frequencies to avail of large un-allocated bandwidths [9]. The heterodyne signal can be obtained through photo-mixing between two optical carriers with a frequency offset equal to the desired frequency [10].

Moreover, several techniques like higher-order modulation formats, wavelength division multiplexing (WDM), and multiple-input multiple-output (MIMO) have been performed using MWP components. Coherent optical system is a fundamental way to provide high-Baud-rate [11]. In the coherent systems, the polarization of the optical field can be harnessed in order to massively increase the system capacity, where the data is transmitted over different polarizations such as dual-polarization quadrature amplitude modulation (DP-QAM) [12]. However, optical components which produce phase and intensity noise, phase shift, fiber dispersion, and non-linearity, can reduce the system performance [13]-[16]. In fact, the most important issue for dual-polarization is polarization-dependent loss (PDL) that can destroy the balance in the power levels of the two polarization tributaries [17]-[19]. Hence, both optical signal to

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noise ratio (OSNR) and signal to noise ratio (SNR) are imbalanced between two polarizations.

At a system architecture level, the PDL occurs at different stages of the transmission/reception chain, and modeling the total PDL is of high interest to perform system analysis. Computing the equivalent PDL is not straightforward. In other words, when the number of the optical elements is high, one can resort to different asymptotic approximations, but in case of low number of the optical elements, as can be shown in free space optical communications (FSO), those approximations do not hold anymore. In this paper, we focus on how the total PDL with considering the polarization rotation can be calculated for a single or multiple PDL elements in optical space applications, in which each PDL element can induce own effect of the PDL and the polarization rotation. The theoretical study and mathematical derivations are presented and reveal that both polarization rotation and PDL can result in two main effects (i) inequality in power and (ii) destroying the orthogonality between of two polarization components. The latter can generate crosstalk components that can be either in-phase or out-of-phase with the main polarizations, and this subsequently varies the peak power. Therefore, this paper presents a method to compute the total PDL and also examines the loss in the power and orthogonality between two polarization tributaries by implementing a simulation setup for a 10 GBaud dual polarization-quadrature phase shift keying (DP-QPSK). The simulation results are evaluated in term of bit-error-rate (BER), where the difference in the BER results are obviously detected due to polarization issues.

The rest of the paper is organized as follows. After the introduction, the theoretical principles and mathematical derivations for a single or multiple PDL elements with respect to the impact of the polarization rotation are demonstrated in Section 2. Section 3 and 4 present the simulation setup and measurements using DP-QPSK modulation format. Finally, the conclusion of this paper is given in Section 5.

2. THEORITICAL AND MATHEMATICAL DISCUSSION OF A SINGLE AND CASCASED PDL ELEMENTS

The transmission of optical signals over two polarization axes (horizontal and vertical polarization) must be taken into account the polarization rotation, PDL, and polarization mode dispersion (PMD). In optical space communications, the uplink and downlink between ground station and satellite are free optics, and this allows to neglect the effects of chromatic dispersion and PMD induced by optical fiber. Therefore, the polarization rotation and PDL play the key roles in the FSO system degradation. The PDL is the ratio between the minimum and maximum intensities, as can be defined in:

$$\mathrm{PDL(dB)} = 10\ \log\left(\frac{1+\eta}{1-\eta}\right) \tag{1}$$

where η is a linear PDL coefficient which its value is between [0,1]. While the polarization rotation is dependent on the angle (θ) between a signal polarization and coordinate system (PDL axes).

In this work, the PDL effect is studied with respect to the rotation angle for three different cases, as can be presented in Fig. 1 (a) $\theta = 0°$ (b) $\theta = 45°$ and (c) $\theta = -45°$. The simplest configuration is designed employing a single PDL element. In general, the electric field of the optical carrier at the laser output consists of two orthogonal components (E_x and E_y). When the two electric components are passed across PDL element which possesses a lossy PDL on x-axis and loss-less on y-axis, the resultant two electric components after a PDL element are modified in power and orthogonality.

For $\theta = 0°$ in Fig. 1 (a), as E_x and E_y components are aligned with x-and y-axes respectively, both components at the output of the PDL element are still orthogonal, but they have power inequality due to high-loss PDL on x-axis. This explains why OSNR of one of the polarizations is different as compared to the other polarization. In the second case from Fig. 1 (b), when the optical signal is rotated by an angle of 45° with system coordinate, both E_x and E_y after PDL element have the same power (same OSNR). However, the most important outcome is that the resultant E_x and E_y are no longer orthogonal, lower than 90° [17]. From two cases (a) and (b), it can be seen that the polarization rotation and PDL can contribute to power imbalance and loss of orthogonality between two polarization tributaries. The last case for $\theta = -45°$ in Fig. 1 (c) demonstrates the same analysis of case (b), whereas here the orthogonality angle is larger than 90° since the orientation of polarization is changed.

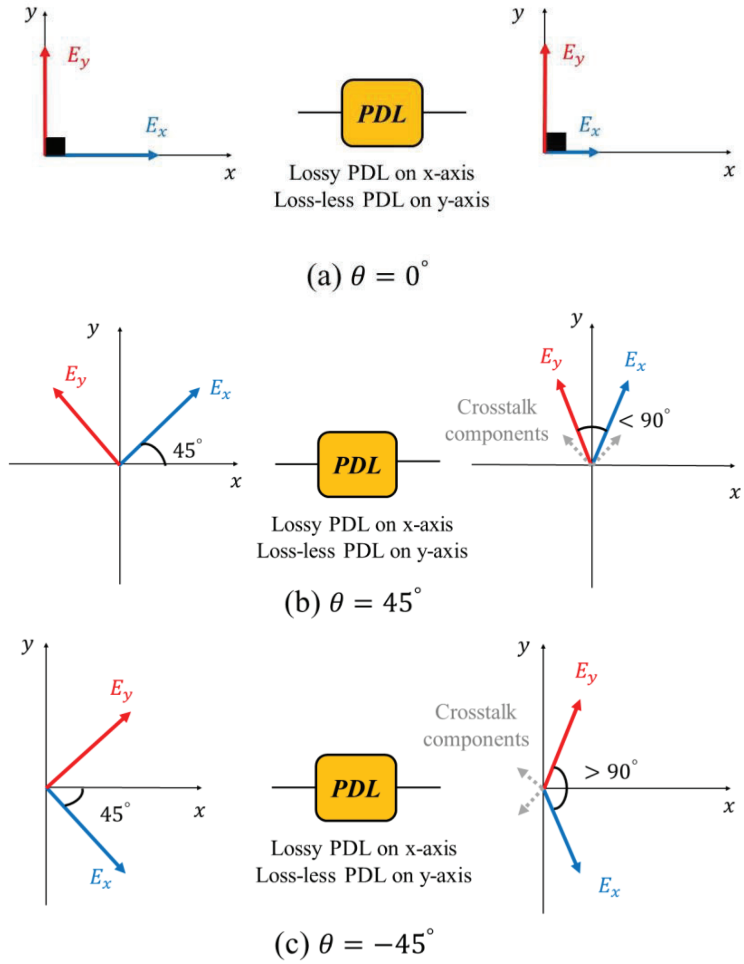


Figure 1: Configuration of two orthogonal electrical fields when passing through a single PDL element with three different cases of the polarization rotation effect.

On the other hand, the loss of orthogonality can generate polarization crosstalk components in the system, as can been seen by grey vectors in Fig. 1 (b) and (c). Those crosstalk components can alert the optical peak power. For emphasizing the polarization impairments, the mathematical model is derived according to the system described in Fig. 2 for a single PDL element. The electric field of the optical carrier ($E_{in}(t)$) is transmitted to an optical PDL element. Then, the output electric field ($E_{out}(t)$) is suffered from polarization rotation with an angle θ and PDL. The $E_{out}(t)$ can be expressed using Jones matrix representation as:

$$E_{out}(t) = R(\theta)\, D\, R(-\theta)\, E_{in}(t) \tag{2}$$

where R denotes the rotation by an angle θ, and D is the PDL matrix. Once substituting R and D by their matrices in eq. (2), the electric field at the output of the PDL element can be written as:

$$E_{out}(t) = \begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \sqrt{1+\eta} & 0 \\ 0 & \sqrt{1-\eta} \end{bmatrix} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} E_{in}(t) \tag{3}$$

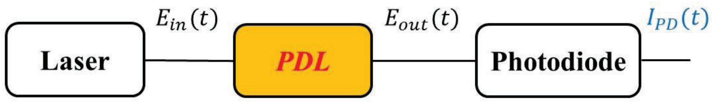


Figure 2: Simplest setup of a single PDL component.

Multiplying the three matrices ($R(\theta)\, D\, R(-\theta)$) can result in the final electric field before the PD as:

$$E_{out}(t) = \begin{bmatrix} \sqrt{1+\eta}\cos^2\theta + \sqrt{1-\eta}\sin^2\theta & \sqrt{1+\eta}\cos\theta\sin\theta - \sqrt{1-\eta}\cos\theta\sin\theta \\ \sqrt{1+\eta}\cos\theta\sin\theta - \sqrt{1-\eta}\cos\theta\sin\theta & \sqrt{1+\eta}\sin^2\theta + \sqrt{1-\eta}\cos^2\theta \end{bmatrix} E_{in}(t) \tag{4}$$

Afterwards, the PD with its responsitivity (r) can perform an optic-electro conversion to give the electrical photocurrent as can be calculated in:

$$I_{PD}(t) = rP_{opt} \propto r|E_{out}(t)|^2 \tag{5}$$

where P_{opt} defines optical power while $|E_{out}(t)|^2$ is the optical intensity of the signal before the PD. Some manipulations are applied to calculate the optical intensity, and hence, the photocurrent is given in the following form:

$$I_{PD}(t) = r|E_x(t)|^2 + r|E_y(t)|^2 + r\eta\cos(2\theta)\left(|E_x(t)|^2 - |E_y(t)|^2\right) + 2r\eta\sin(2\theta)\,|E_x(t)||E_y(t)| \tag{6}$$

From eq. (6), the photocurrent emerges the impact of PDL (η) associated to the polarization rotation (θ), and this directly translates on the system performance. The last term of $|E_x(t)||E_y(t)|$ is arising because the loss of orthogonality occurs. This term generates the peak power variation as mentioned before in the theory.

Three scenarios for θ and η are studied to verify the photocurrent obtained in eq. (6);

1) ***$\theta = 0°$ and $\eta = 0$:***

This represents an ideal scenario without polarization rotation and PDL. When those values are substituted in eq. (6), the photocurrent has solely the two orthogonal electric field, as can be seen in:

$$I_{PD}(t) = r|E_x(t)|^2 + r|E_y(t)|^2 \tag{7}$$

2) ***$\theta = 0°$ and $\eta \neq 0$:***

As the polarization rotation is null, the photocurrent can be written as:

$$I_{PD}(t) = r|E_x(t)|^2 + r|E_y(t)|^2 + r\eta\left(|E_x(t)|^2 - |E_y(t)|^2\right) \tag{8}$$

It can be observed that the last term of eq. (6) is suppressed in which the photocurrent in eq. (8) only suffers from PDL. This finding is logic since the E_x and E_y components are still orthogonal after the PDL element, and thus, the crosstalk polarization components are vanished. This scenario is exactly agreement with our discussion in the theory as in Fig. 1 (a).

3) ***$\theta = \pm 45°$ and $\eta \neq 0$:***

This scenario considers the both effects, and the photocurrent can be expressed as:

Figure 3: Simplest setup of multiple PDL components.

$$I_{PD}(t) = r|E_x(t)|^2 + r\left|E_y(t)\right|^2 \pm 2r\eta|E_x(t)|\left|E_y(t)\right| \tag{9}$$

As the term of $|E_x(t)||E_y(t)|$ appears in the outcome of eq. (9), this refers that the polarization crosstalk components are generated in the system because of the loss of orthogonality after the PDL element. It can be noticed that the eq. (9) is also matched with our explanation in the theory as in Fig. 1 (b) and (c) with respect to the polarization orientation. The previous three scenarios verify the mathematical model of the photocurrent which shows the effects of the polarization rotation and PDL as well as their consequences on the power inequality and orthogonality loss.

Fig. 3 depicts the optical system with multiple PDL elements. The steps to derive the mathematical model for this configuration are the same as a single PDL element with one main difference in calculating the matrices of ($R(\theta)\ D\ R(-\theta)$) [19]. The total effects of the polarization rotation and PDL (U_{total}) can be presented as:

$$U_{total} = \prod_{i=1}^{N} R(\theta_i)\ D_i\ R(-\theta_i) \tag{10}$$

where i is an index of the PDL element and N is the total number of the PDL elements. Then, the electric field at the last PDL element ($E_{out}(t)$) can be written using Jones matrix representation as:

$$E_{out}(t) = \begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} = \prod_{i=1}^{N} \begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix} \begin{bmatrix} \sqrt{1+\eta_i} & 0 \\ 0 & \sqrt{1-\eta_i} \end{bmatrix} \begin{bmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{bmatrix} E_{in}(t) \tag{11}$$

The PD detects this electric field including the total effect of the polarization rotation and PDL in order to generate the photocurrent, as can be seen in eq. (6).

3. SIMULATION SETUP

The simulation arrangement of a DP-QPSK coherent optical system is presented in Fig. 4. A transmitter part is shown in Fig. 4 (a). A laser emanates a single optical carrier which is sent to a polarization beam splitter (PBS). The PBS separates the optical carrier into two polarizations (x and y polarizations). The carriers on two polarizations are modulated by data. After the modulation, the both modulated signals are summed by a polarization beam coupler (PBC) for generating DP-QPSK in the optical domain. Then, the DP-QPSK signal is propagated over either optical fiber or free space optic, and this is dependent on the application.

Afterwards, a receiver part is demonstrated in Fig. 4 (b) where the optical modulated signal is received by the PBS to have the signal on the two polarizations. Using DP-QPSK means that the receiver output has four components, I and Q on x and y polarizations. For detecting the four components, a laser is employed as a local oscillator (LO) with a 90° optical hybrid. The LO can also boost the optical power. As stated in the transmitter, the PBS is utilized to split the optical carrier of the LO into x and y polarizations. Then, the received optical modulated signal and optical carrier from

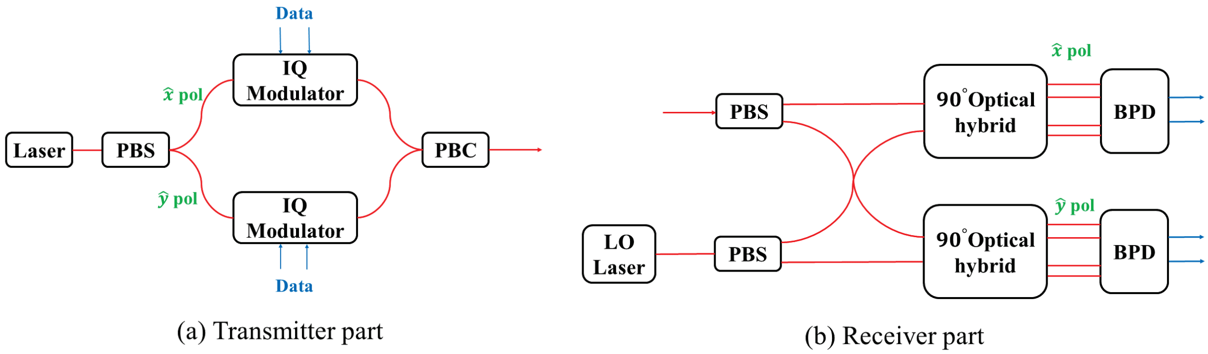


Figure 4: A simulation setup of a coherent optical system.

the optical LO are transmitted to two 90° optical hybrid components. The two balanced photodiodes (BPDs) detect the optical modulated signals and convert them to the DP-QPSK in the electric domain, I_x and Q_x components and I_y and Q_y components. The electrical amplifiers and analog to digital converters can be used after the BPD to apply the digital signal processing (DSP) or to analyze the system performance in term of BER.

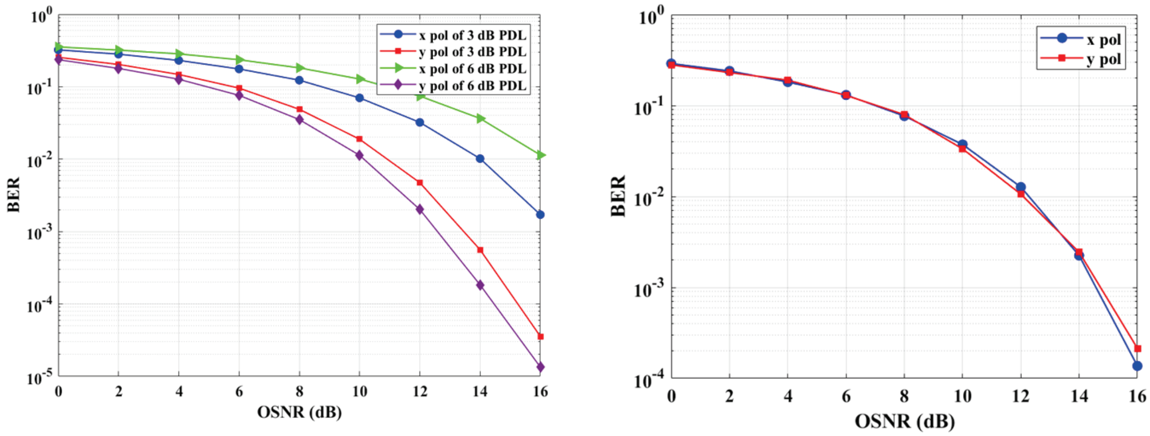
4. RESULTS AND DISCUSSION

The schematic setup of the coherent optical system in Fig. 4 is emulated by using OptiSystem Software in which a 10 GBaud of QPSK is applied along two polarization components. The simulation results are measured in absences of phase and intensity noise, frequency offset, and nonlinearity because the key role of these simulations is to only examine the polarization rotation and PDL in a dual polarization system. In addition, the simulation is designed for FSO, and thus, the chromatic dispersion and PMD are neglected as well. Fig. 5 depicts simulation measurements in term of BER as a function of OSNR for two polarization rotation angles (θ) of 0° (a) and 45° (b).

In Fig. 5 (a), two values of PDL are applied, PDL of 3 dB for a single PDL element and PDL of 6 dB for cascaded PDL elements (three elements). For θ = 0° and 3 dB PDL, the BER measurements on x polarization (blue curve) are different from y polarization (red curve), and the degradation in BERs on x polarization is higher than other polarization component. For instance, the BER values at a 10 dB OSNR are -1.15 and -1.72 on x and y polarizations, respectively. This difference is obtained because the PDL element has high-loss PDL on x-axis as compared to low-loss PDL on y-axis. It can be noticed that these findings confirm the demonstration in Fig. 1 (a) and in eq. (8). On the same figure (a), the green and violet curves represent the BER results on x and y polarizations for θ = 0° and total PDL of 6 dB for three PDL elements. The total PDL is calculated using eqs. (10) and (11). As in the single PDL element, the difference between two BERs (x and y polarizations) are detected due to lossy PDL on x and loss-less PDL on y. From Fig. 5 (a), an increase in the PDL value leads to increase in the BER difference. Therefore, in case of absence of polarization rotation in the system, the PDL causes the loss in the power between two polarization components.

Furthermore, as soon as the polarization rotation with PDL is considered in the system, the power values on two polarization components are the same, but the orthogonality is destroyed. This scenario is demonstrated in Fig. 5 (b) in which the simulation results are carried out for rotation angle of 45° and PDL of 6 dB (high loss PDL on x polarization). Since the loss of orthogonality occurs, polarization crosstalk components emerge, which generate the variation in the peak power, as explained in Fig. 1 (b) and last term in eqs. (6) and (9). The most notable outcome in the simulation results on Fig. 5 (b) is that the BER measurements on both polarizations are identical. In other words, the impact of orthogonality loss is not affected on the system. This result is logic where the coherent optical receiver used in the simulation setup can separately handle each polarization component alone. Therefore, the peak power variation has no impact on the BER measurements.

It is worthy to mention that the peak power variation induced by rotation and PDL can substantially impair the system performance when the nonlinearity of optical fiber or optical components such as amplifier is employed in the system.



(a) $\theta = 0°$ and PDL of 3 dB and 6 dB

(b) $\theta = 45°$ and PDL of 6 dB

Figure 5: BER versus OSNR for different cases of rotation angle and PDL.

This is an important next step that will be to examine for optical space applications, and in particular in the optical amplifiers which are used in the optical link to compensation the huge losses of free space propagation.

5. CONCULSION

In this paper, a coherent optical system is used to convey DP-QPSK in FSO applications. The polarization degradations which are represented by polarization rotation and PDL are theoretically and mathematically demonstrated. These impairments can lead to loss in power balance and orthogonality between two polarization components. For examining these degradations, the simulations are performed for various scenarios of rotation angle and PDL. The results of BER show the difference in the BER for a single or multiple PDL elements when neglecting the rotation effect. While with considering the rotation angle, the BERs possess the same behavior, thanks to coherent optical receiver which can mitigate the consequences of the polarization rotation effect.

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