Polarization Dependent Loss Emulator Built with Computer-driven Polarization Controllers and Single Mode Fibre

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Keywords: Polarization Dependent Loss, Polarization Components Positioning.

Abstract: In this paper, a polarization dependent loss emulator is designed with computer-driven polarization controllers and single mode fibre. It proves that PDL obeys Maxwellian distribution when it is expressed in decibels. By positioning the polarization controllers at different places in the emulator link, it also proves that positions of PDL components have a significant effect on the statistics of PDL in a fixed length communication system. As the number of polarization components involved and the communication fibre length remain as constants, the longer the uninterrupted fibre is, the smaller the PDL mean value is produced.

1 INTRODUCTION

Optical fibre communication networks are playing an important role in the area of high-speed, high-volume and ultralong-distance data transmission. With the growth in demand for greater data, greater bandwidth has been applied, this has made polarization become an effect which cannot be ignored in the system. For example, polarization has been considered as a major obstacle in the development of polarization-division-multiplexing digital coherent transmission systems when it is operating at more than 100Gb/s (Mori et al., 2011). Polarization happens because of the asymmetry of optical fibre factors on the two orthogonal axes, such as the asymmetry of dispersion parameters which introduce polarization mode dispersion and the asymmetry of loss parameters which introduce polarization dependent loss. In the effect of polarization, signals in the optical fibre transmission systems will be distorted by a bigger bit error rate, and a lower signal-to-noise ratio.

As the optical pulse becomes narrower, polarization impairs transmission signals in two ways. Polarization mode dispersion (PMD) can cause the signal distortion due to the differential group delay (DGD) on the two perpendicular axes in the fibre, and polarization dependent loss (PDL) can introduce additional loss because of the difference of loss factor of the two perpendicular axes in the fibre. Moreover, PMD and PDL always exist together in real optical transmission systems, which generates combined effects. For example, due to the loss of orthogonality between the two principal states of polarization, PDL distorts the statistics results of PMD away from the theoretical distribution (Musara et al., 2013).

Even though PDL is limited to a relatively small value in the latest produced fibre (about 0.02dB/km at 1550 nm), its time-dependent randomness makes it a factor of reducing signal-to-noise ratio which cannot be ignored (Lichtman, 1995), especially in those old deployed fibre communication systems. In order to improve the performance of a long-distance optical transmission system, it is significant to deploy a proper number of polarization dependent amplifiers in the proper positions. To achieve this target, a reliable PDL emulator is essential.

In this paper, a PDL emulator is built with computer-driven polarization controllers and sections of single mode fibre. It is aimed to provide a continuous statistical result which obeys the Maxwellian distribution, as concluded by previous researchers. Another goal of building this emulator is to find out how the PDL components work with communication fibres. To achieve this, the fibre length of this emulator is fixed to a constant length (7×15 metres) and two polarization controllers are used to provide random states of polarization. One of the controllers is constantly deployed between the laser source and the first link of fibre and the other one is deployed at different places in the emulator in different cases. The results are used to compare how the statistical results are affected by the position changes of the second polarization controller.

Liu Y., Shepherd P. and Allsopp D..
Polarization Dependent Loss Emulator Built with Computer-driven Polarization Controllers and Single Mode Fibre.
DOI: 10.5220/0005563700420047
In *Proceedings of the 6th International Conference on Optical Communication Systems* (OPTICS-2015), pages 42-47
ISBN: 978-989-758-116-8

2 POLARIZATION DEPENDENT LOSS (PDL)

2.1 Definition

Polarization dependent loss is a measure of the peak-to-peak difference in transmission of an optical component or system with respect to all possible states of polarization. It is defined as the ratio of the maximum and the minimum transmission of an optical device with respect to all polarization states, as shown in Eq. (1)

$$PDL_{dB} = 10 \times log(\frac{P_{Max}}{P_{Min}}) \quad (1)$$

In Stokes space, a polarized light beam can be written in the form of Stoke vector $\vec{S} = (S_0, S_1, S_2, S_3)^T$, where

$$\begin{aligned} S_0 &= I \\ S_1 &= Ip\cos 2\psi \cos 2\chi \\ S_2 &= Ip\sin 2\psi \cos 2\chi \\ S_3 &= Ip\sin 2\chi \end{aligned}$$

Here Ip, 2ψ and 2χ are the spherical coordinates in Stokes space, so the Stoke vector $\vec{S}$ can present any polarization state of the polarized light beam.

After passing through a device which changed the state of polarization, the Stoke vector of this light beam can be described as $\vec{S_{out}} = M\vec{S}$ where M is the Muller Matrix used to describe the polarization device

$$M = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix}$$

The output power of this light beam

$$P_{out} = m_{11}S_0 + m_{12}S_1 + m_{13}S_2 + m_{14}S_3 \quad (2)$$

By the definition of Stokes vector, there is

$$S_0^2 = S_1^2 + S_2^2 + S_3^2 \quad (3)$$

and P_{out} can come to the extrema with the condition of $\frac{m_{12}}{S_1} = \frac{m_{13}}{S_2} = \frac{m_{14}}{S_3} = k$. Maximum or minimum values are achieved respectively when k is positive or negative. Therefore, Eq. (1) can be rewritten as

$$PDL_{dB} = 10 \times log(\frac{m_{11} + \sqrt{m_{12}^2 + m_{13}^2 + m_{14}^2}}{m_{11} - \sqrt{m_{12}^2 + m_{13}^2 + m_{14}^2}}) \quad (4)$$

2.2 The Statistical Theory

As polarization is a time-dependent element in transmission systems, PDL plays its role as a random attenuator. It generates irregularities in the power evolution along the link and may cause a significant degradation in the optical signal-to-noise ratio. Previous research showed that for all the relevant range of parameters the PDL of a communication system has Maxwellian distribution when it is expressed in decibels.

Even though the distribution of PMD obeys Maxwellian distribution as well, the distribution of PDL is independent of the system's PMD (Mecozzi and Shtaif, 2002). The dependence of the mean-square PDL (in decibels) on system length is linear in most cases, but it may become exponential in systems extending over transoceanic lengths.

The polarization dependent component of the power gain of a generic optical element can be described as $1 + \vec{\Gamma} \cdot \vec{S_0}$, where $\vec{S_0}$ is a unit Stokes vector corresponding to the polarization state of the incident optical field and $\vec{\Gamma}$ represents the vector of PDL. Therefore, the highest and lowest gains are $1 \pm \Gamma$ with $\Gamma = |\vec{\Gamma}|$ and the high gain is achieved when $\vec{S_0}$ is parallel to $\vec{\Gamma}$ in Stokes space, and the lowest gain is achieved when $\vec{S_0}$ is anti-parallel to $\vec{\Gamma}$. Based on the definition of PDL, it can be described as $PDL \equiv 10log_{10}[(1+\Gamma)/(1-\Gamma)]$. In order to derive the PDL distribution, the evolution equation of $\vec{\Gamma}$ obtained by Huttner (Huttner et al., 2000) is considered.

$$\frac{\partial \vec{\Gamma}}{\partial z} = \vec{\beta} \times \vec{\Gamma} + \vec{\alpha} - \vec{\Gamma}(\vec{\alpha} \cdot \vec{\Gamma}). \quad (5)$$

The vector $\vec{\beta}(\omega, z)$ is the local birefringence and $\alpha(z)$ is the local vector of polarization dependent loss. ω is the optical frequency and z is the position along the fibre link.

By considering the transmission system as consisting of a large number of elements that contribute to PDL in a statistically independent way, it can be assumed that PDL vectors of the individual elements are Gaussian vectors in Stokes space so that their orientation is uniformly distributed. Therefore, the first term on the right hand side of Eq. (5) can be omitted. It is arbitrary to assume that the local PDL vectors have Gaussian distributed components. However, it becomes irrelevant when the number of PDL elements in the system is large enough (Poole and Nagel, 1997). Now the PDL vector can be described as an individual element by $\eta d\vec{W}$, where $d\vec{W}$ is an increment of a standard three-dimensional Brownian motion (Gardiner, 1985) and its most relevant property is $d\vec{W} \cdot d\vec{W} = dz$. Therefore, the mean-square value of the local PDL element is $\eta^2 dz$ where η is a constant. To simplify the notation, the position parameter z can be normalized such that $\eta^2 = 1$. The normalized z should be interpreted as the accumulated sum of mean-square PDL values from the system input (where $z = 0$) to any given point along the link. With these assumptions, Eq. (5) can be rewritten in a stochastic differential form

$$d\vec{\Gamma} = d\vec{W} - \vec{\Gamma}(d\vec{W} \cdot \vec{\Gamma}) - \frac{1}{3}\vec{\Gamma}(2 - \Gamma^2)dz \qquad (6)$$

where the last term is the byproduct of translating a physical differential equation such as Eq. (5) into a stochastic differential equation. With the relation between $\vec{\Gamma}$ and ρ, the stochastic equation for ρ can be written as

$$d\rho = \frac{\gamma/3}{tanh(\rho/\gamma)}dz + \frac{\gamma}{\sqrt{3}}dW \qquad (7)$$

where $\rho \equiv 20/ln(10) \simeq 8.7$ and the scalar dW is an increment of a one-dimensional Brownian motion satisfying $dW^2 = dz$. A new vector process $\vec{\rho}(z)$ in Stokes space is introduced to obtain the distribution of ρ, such as

$$d\vec{\rho} = [\frac{\rho/\gamma}{tanh(\rho/\gamma)} - 1]\frac{\vec{\rho}}{3\rho^2}\gamma^2 dz + \gamma d\vec{W} \qquad (8)$$

and it has the relation $\rho = |\vec{\rho}|$. It shows the stochastic equation for $\sqrt{\vec{\rho}\cdot\vec{\rho}}$ is identical to Eq. (7). While $\vec{\rho}$ has no obvious physical interpretation, it is useful for deriving the distribution of ρ, because Eq. (8) can be approximated by performing a Taylor expansion of the first term on its right-hand side

$$d\vec{\rho} = [1 - \frac{1}{15\gamma^2}\rho^2 + \frac{2}{315\gamma^4}\rho^4 \cdots]\frac{1}{9}\vec{\rho}dz + \gamma d\vec{W} \qquad (9)$$

If the first term in the square brackets in Eq. (9) is considered, a linear equation is obtained , whose solution is a random vector with three independent Gaussian components of zero mean and variance $\sigma(z)^2 = 3\gamma^2/2(e^{2z/9} - 1)$. Therefore, the distribution of ρ is Maxwellian and it is given by

$$P_z(\rho) = \frac{4\rho^2}{\sqrt{\pi}[2\sigma^2(z)]^{3/2}}exp[-\frac{\rho^2}{2\sigma^2(z)}] \qquad (10)$$

The above approximation should be valid as long as the second term in the expansion is significantly smaller than one (i.e., $\rho^2 \ll 15\gamma^2$), a condition that is well satisfied for values of $\rho \ll 34$ dB. The mean-square value of the PDL is

$$\langle\rho^2\rangle = 3\sigma(z)^2 = \frac{9\gamma^2}{2}(e^{2z/9} - 1) \qquad (11)$$

and the mean PDL is given by $\langle\rho\rangle = \sqrt{8\langle\rho^2\rangle/(3\pi)}$, a relation that is defined by the Maxwellian distribution. Eq. (11) can be approximately written as $\langle\rho^2\rangle \simeq \gamma^2 z$ when $2z/9 \ll 1$, where z is the accumulated local mean-square PDL of the system.

Eq. (11) shows that the mean PDL exponentially increases along the fibre for long distance transmission but it can be seen as approximately linear when the distance is small enough.

2.3 Effect in Long Distance Transmission Systems

The PDL factor in modern built single mode fibre is about 0.02dB/km at the wavelength of 1550nm which is relatively small (standard attenuation in the same kind of single mode fibre is about 0.2dB/km) and its increase is approximately linear. However, the mean value of PDL increases exponentially with distance increasing in a ultralong-distance system, for example, hundreds or thousands of kilometres. This can be even worse in the old systems which were deployed decades ago.

PDL will affect ultralong-distance systems in another way. It can cause a significant degradation in the optical signal-to-noise ratio because it is randomly changing with time. In order to compensate PDL, polarization dependent amplifiers (fibre-based Raman amplifiers) are applied along the systems. In order to achieve a better performance, the polarization dependent amplifiers (PDA) are expected to have the Maxwellian distribution related to the distribution of PDL in the system. Therefore, it is significant to understand the relationship between polarization components and communication fibres, not only the working parameters, but also the optimum positions of polarization components.

When the PDL is significant, there is interaction between PMD and PDL and that caused some combined effects. In the presence of both PMD and PDL, the two states of polarization are not orthogonal, which leads to interferences producing anomalously large pulse spreading (Gisin and Huttner, 1997).

3 EMULATOR DESIGN

The PDL emulator described in this paper is designed with computer-drived polarization controllers connected with sections of single mode fibre. Polarization controllers can provide random states of polarization in time to simulate and enhance the PDL variation in the real situation, and they are connected with single mode fibre, which is used as the device under test (DUT).

A stable laser source is used to provide continuous lightwave at the wavelength of 1550 nm. A power splitter is deployed between the laser source and the system. 10% of the source power is sent to one channel of the multimeter as reference, and the other 90% goes into the emulator.

The sections of single mode fibre which are used to connect each polarization controllers are 15 metres long, as shown in Figure 1. All of the polarization controllers are changing their paddle positions rapidly and randomly to maximize the system randomization.

The system randomness is relative to the number of polarization controllers applied. By changing this it can be compared how PDL components in the transmission system affect the statistical results of the output PDL at the receiver. By changing the number of sections of optical fibre, it will give different results corresponding to the different transmission distance. Another variable in the emulator system is the positions of polarization controllers. By changing this, it can be helpful to find out the effect of PDL component position changing and the relationship of PDL component position and the transmission distance.

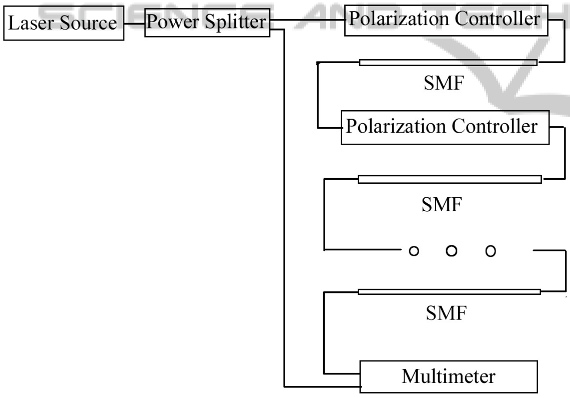

Figure 1: Emulator design.

By using the Stokes vector and Muller Matrix which are discussed in Section 2.2, the emulator can be described mathematically as

$$\vec{S_{out}} = F_n ... F_{p+2} F_{p+1} M_2 F_p ... F_2 F_1 M_1 \vec{S} \tag{12}$$

where M_1 and M_2 represent the polarization controllers and $F_1, F_2, ... F_n$ represent the sections of single mode fibre. M_1 and M_2 generate random states of polarization to optimum the measurement results. By assuming the states of polarization do not change within the relative short distance (15 metres), the Muller Matrix of fibre can be written as

$$F_1 = F_2 = ... F_n = \begin{pmatrix} exp(-\alpha L) & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{13}$$

where α is the loss parameter of the fibre and L is the length of fibre. By combining the Muller Matrices of coherent sections of fibres, Eq. (12) can be also written as

$$\vec{S_{out}} = F_{n-t} M_2 F_t M_1 \vec{S} \tag{14}$$

where

$$F_t = \begin{pmatrix} exp(-\alpha p L) & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$F_t = \begin{pmatrix} exp(-\alpha (n-p) L) & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

4 EXPERIMENTAL RESULTS

As described in the theoretical calculation, the statistical result of PDL obeys the Maxwellian distribution. In order to check whether the statistical distribution matches the theoretical calculation, the emulator runs for 24 hours continuously to generate a statistical result, which is shown in Fig. 2. The probability curve indicates that the result obeys Maxwellian distribution, which means the emulation results generated by this emulator is reliable to be used to study polarization dependent loss in a laboratory environment.

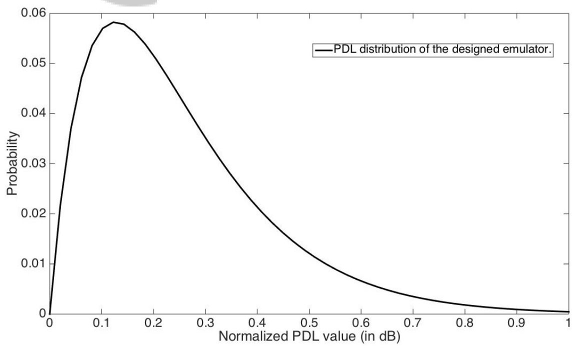

Figure 2: The statistical result of the designed emulator obeys Maxwellian distribution.

Based on Eq. (8), the mean-square value of the PDL ρ^2 exponentially increases as the communication length increases. However, even if the communication distance is fixed to a constant, the statistical results in the system varies. By assuming the communication fibre is in a constant of state of polarization, the main factor which varies the statistical results is the PDL components.

The PDL components statistically vary the results in two ways. Their random patterns change as their working environment changes in time. On the other hand, the positions where the PDL components were deployed in the systems can lead to different results as the combination of PDL component and the fibre length is changed. In order to study the relationship between the statistical results and the position of PDL components, the emulator is set in seven different cases (shown in Table 1). Polarization controller 1 is fixed between the laser source and the first section of fibre to provide an initial state of polarization and polarization controller 2 is deployed in different positions in different cases. Fibre length of each section is 15 metres.

Table 1: Case list of the different sets of emulator. PC1 and PC2 indicate polarization controller 1 and polarization controller 2 respectively, SMF indicates single mode fibre.

Case 1	PC 1⟶ PC 2⟶7 sections of SMF
Case 2	PC 1⟶ 1 section of SMF⟶PC 2⟶6 sections of SMF
Case 3	PC 1⟶ 2 sections of SMF⟶PC 2⟶5 sections of SMF
Case 4	PC 1⟶ 3 sections of SMF⟶PC 2⟶4 sections of SMF
Case 5	PC 1⟶ 4 sections of SMF⟶PC 2⟶3 sections of SMF
Case 6	PC 1⟶ 5 sections of SMF⟶PC 2⟶2 sections of SMF
Case 7	PC 1⟶ 6 sections of SMF⟶PC 2⟶1 section of SMF

The emulator runs continuously for 24 hours as one experimental period. Measurements were taken multiple times in each case to achieve a better statistical result. Figure 3, 4 and 5 show the distribution curve of PDL in all of the cases and Table 2 shows the mean value and variance of measured PDL in all of the cases.

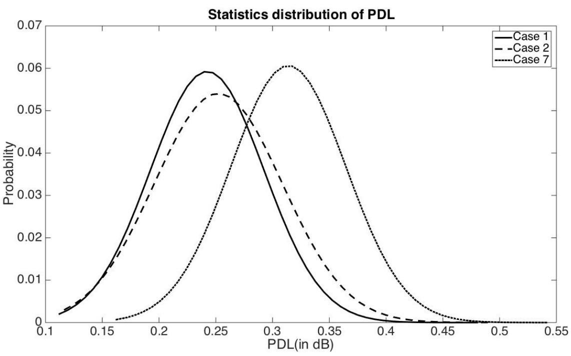

Figure 3: Statistical results of emulator(Case 1,2 and 7).

Table 2: Mean value and Variance of PDL in different cases.

Case No.	Mean value of PDL (in dB)	Variance of PDL
Case 1	0.2424	0.0025
Case 2	0.2522	0.0032
Case 3	0.5665	0.0031
Case 4	0.5831	0.0044
Case 5	0.5568	0.0033
Case 6	0.5639	0.0038
Case 7	0.3139	0.0026

As shown, when the fibre length is fixed, a continuous fibre link without any change of state of po-

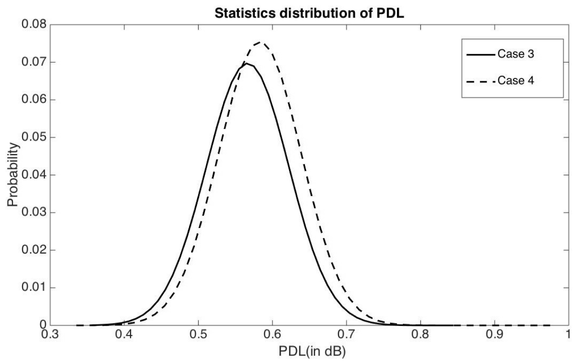

Figure 4: Statistical results of emulator(Case 3 and 4).

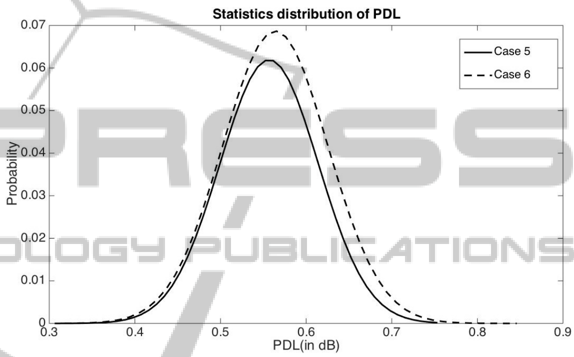

Figure 5: Statistical results of emulator(Case 5 and 6).

larization can generate a smaller mean value of PDL in statistics, such as Case 1,2 and 7. Inserting PDL components can significantly enlarge the mean value of PDL, even though the total length and total number of PDL components remain the same.

5 CONCLUSIONS AND FUTURE WORK

In this paper, a PDL emulator built with computer-driven polarization controllers and sections of single mode fibre is shown. Measurement results show that the PDL statistics obeys Maxwellian distribution. With this emulator, it is proved that the locations of PDL components (such as polarization dependent gain components) affect the statistics significantly even though the total fibre length and the total number of PDL components are fixed.

In order to develop the study of PDL emulator positioning, more polarization controllers will be involved in the future work. A mathematical model will be developed for calculating the optimum position where essential polarization components should be deployed to minimize the PDL in the system.

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