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PMD SOURCE: A PROPOSAL FOR A REFERENCE STANDARD DEVELOPMENT

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Abstract − This paper presents the development of a controllable PMD (Polarization Mode Dispersion) source based on piezoelectric actuators as the element responsible for the birefringence variation. This device will be able to reproduce the PMD quantity in a controlled way in order to use it as a reliable metrological reference.

Keywords: Polarization mode dispersion, optical fiber metrology, measurement standards, PMD source

1. INTRODUCTION

The study of the PMD phenomenon and its influence in optical communication began in the late 80' [1, 2]. Many aspects are already well established as its stochastic characteristics and measurements problems [3-8]. PMD is defined as a vector quantity with a magnitude, DGD (Differential Group Delay), and a direction, PSP (Principal State of Polarization). In many cases, PMD is also referred to as the averaged value obtained from a set of DGD measurements. Unlike other fiber optic impairments, such as chromatic dispersion, PMD dynamically varies with time, wavelength, temperature, pressure and any external influence on the fiber. Even with nowadays high performance fibers, PMD effects become critical when long haul optical communication links are operated at high-speed rates (40 Gb/s and beyond).

The demand for a reliable and controllable PMD reference that could be used to validate evaluations performed by the system operators, manufacturers of optic fiber and components and research laboratories motivated the development of PMD emulators. The first ones attempted to mimic this PMD random behavior [9, 10] but they do not determine in what PMD states the system performance is degraded or fails. In order to overcome this difficulty, considerable effort has been done to generate PMD in a controlled way using a cascade of high-birefringent crystals or concatenated pieces of optic fiber with high-birefringence [11-14].

We propose here a compact and robust device capable of generating PMD values at some wavelength spans with reproducibility and repeatability. A Hi-Bi fiber and a set of piezo-electric actuators controlled individually compose this device. Several DGD x wavelength characteristic curves can be obtained according to the previously determined configuration of the pressure imposed (input voltage) to individual actuators and the distances between them. By controlling the environmental influences and other sources of uncertainty, this device can be used as a reference to compare the performance of two or more different PMD measurement systems.

2. PMD THEORY

2.1. Basic Concepts

The PMD is a fundamental property of single mode fibers and components where the energy of the optical signal propagates in two orthogonal polarization modes with different propagation velocities that are called fast and slow propagation modes. The difference of arrival times of these modes is called differential group delay. The cause of this phenomenon is the residual birefringence in the optical fiber. As this birefringence varies along the fiber, one way to represent it is by a concatenation of small pieces of optical fibers with different lengths. To the process of the electric field emerging from one-piece end projected to the next piece front we call mode coupling.

There are two PMD definitions [3, 6]. The first one is closely related to the definition of the modal dispersion on multimode fibers. In fact singlemode fibers support only one mode but in the presence of random mode coupling the fiber behaves as a multimode fiber. This can be expressed as the mean square deviation of the time of flight of the various polarizations mode generated as in (1).

$$PMD_1 = 2\left(\frac{\int I(t)t^2 dt}{\int I(t)dt} - \left(\frac{\int I(t)tdt}{\int I(t)dt} \right)^2 \right)^{\frac{1}{2}} \tag{1}$$

Where *I(t)* is the light pulse intensity (when the initial condition is a delta impulse).

Considering that the coherence time of the light source is larger than the polarization mode delay and that these modes interfere, this produces two outcoming pulses with a differential group delay, the DGD. The mean DGD over a wavelength range is the second definition.

$$PMD_2 = \langle DGD(\omega) \rangle_\omega = \frac{\int_{\omega_1}^{\omega_2} DGD(\omega) d\omega}{\omega_2 - \omega_1} \tag{2}$$

There is a relation between these two definitions for high polarization mode coupling (Maxwellian DGD shape):

$$PMD_2 = \frac{PMD_1}{\sqrt{3\pi/8}} = \frac{PMD_1}{1.085} \quad (3)$$

The differential group delay is frequency independent. This effect alone is sufficient to cause systems outage, but more complex effects, like second- and higher-order PMD, play an important role. The first-order PMD is the well-known differential group delay (DGD), which is the time difference between two orthogonal polarization components. Second-order PMD (SOPMD) introduces frequency dependences to the impact PMD has on a transmission system.

The PMD can be represented in the Poincaré sphere by the polarization dispersion vector, $\vec{\Omega}$, (4) whose module is the DGD ($\delta\tau$) and its direction characterize the fast component of the Principal State of Polarization (PSP) in the Poincaré sphere ($\vec{r}$).

$$\vec{\Omega} = |\Omega| \cdot \hat{\Omega} = \delta\tau \cdot \vec{r} \quad (4)$$

The vector variation in the sphere, $\vec{\Omega}$, occurs both in its module as well in its orientation. In this way both DGD and the relative orientation between the signal orientation and the PSP's vary in time and in optical frequency, ω. This phenomenon gives rise to a supplementary distortion called second order PMD (SOPMD), which can be mathematically represented by the relative derivation of $\vec{\Omega}$ in relation to ω (5), the calculation is applied both in magnitude and in direction (6).

$$\vec{\Omega}_\omega = \frac{\partial \vec{\Omega}}{\partial \omega} \quad (5)$$

$$\vec{\Omega}_\omega = \partial_\omega(\delta\tau \cdot \vec{r}) = \delta\tau \frac{\partial \vec{r}}{\partial \omega} + \frac{\partial \tau}{\partial \omega}\vec{r} \quad (6)$$

The derivative produces two terms: the first is related to the DGD variation with frequency also called depolarization that represents the frequency dependence of the PSP rotation. Under this effect one signal will always be affected by depolarization. The second term refers to the unit vector derivative $\vec{r}$, also called polarization dependent chromatic dispersion (PCD).

The PCD acts similarly as the chromatic dispersion, where the signal depends on which PSP is coupled and is the SOPMD component parallel to the PMD vector. Its magnitude represents the DGD change with the frequency that causes pulses compresses or broadening. Both SOPMD component are frequently treated apart and considered as the parallel and perpendicular component of the SOPMD.

2.2. Measurement techniques

Several different techniques for measuring the PMD are widely used. Three of them became international standards (ANSI/TIA): wavelength scanning, Jones Matrix Eigenanalyis (JME) and Interferometric.

The wavelength scanning technique relies on the spectral transmission measurement of the light when it passed through a polarizer, the fiber and another polarizer. The result is analyzed either by *extrema counting* or by application of Fourier analysis. The interferometric technique relies on measuring the mutual coherence between different polarizations at the fiber output; in the Jones matrix technique the polarization response to three input polarizations is measured as a function of wavelength to allow calculation of the wavelength-dependent polarization dispersion vector. Ideally, all techniques would be rigorously linked by theory, which in turn would be confirmed by measurement.

3. EXPERIMENTAL SET-UP

3.1. Proposed PMD Source

The source proposed here is based on an entire piece of a Hi-Bi fiber and a set of piezoelectric actuators disposed along the fiber at different distance among each other, Fig.1. Each piezoelectric is controlled by a computer interface. The aim is to obtain a device capable of generate a PMD value establishing DGD x λ shapes with long-term stability and repetitively.

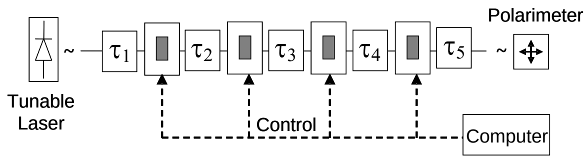

Fig. 1: A schematic diagram of the proposed PMD source.

The experimental set up used for the construction and characterization of the PMD source was built by a PC, A/D controller and HiBi fiber pieces, piezoelectric actuators and a polarimeter. The PC user data acquisition software that controls the A/D board and allows an automatic adjust of the pressures imposed on the piezos.

Firstly several simulation were done to identify a specific set of construction parameters which are the distance between piezoelectrics and the applied voltage to each piezoelectric that is necessary to generate the desired local birefringence. The fiber optic pieces lengths, h_i, and the coupling angles, α_i, determine the final results. Considering a device with fix total length, L, many structures were tested changing the number of pieces, length and angles distribution. The simplified draw of this structure is represented in Fig. 2. The simulation software generates randomly many $\{h_i,\alpha_i\}$ sets in the following situation: fixed $\{h_i\}$ value with random generation of $\{\alpha_i\}$ and fixed $\{h_i\}$ with generation of a Gaussian distribution of $\{\alpha_i\}$. After the structure parameters definition the performance of the device was obtained using mathematics modelling where the Jones matrix $T(\omega,t)$ is expressed in (7) [5]. N is the number of pieces, b is the birefringence and ω is the optical frequency.

$$T(\omega,t)=\prod_{i=1}^{N}\begin{bmatrix} e^{j(b_i(t)\omega h_i)/2} & 0 \\ 0 & e^{j(b_i(t)\omega h_i)/2}\end{bmatrix}\begin{bmatrix}\cos\alpha_i & \sin\alpha_i \\ -\sin\alpha_i & \cos\alpha_i\end{bmatrix} \quad (7)$$

The randomicity in the DGD generation is done by the use of the expression (8) where *δ(t)* is the random number.

$$b_i(t)=b_i(0)+\delta_i\cdot t \quad (8)$$

The DGD can be calculated from the determinant of *T´(ω)* (matrix calculated deriving (4) in relation to *ω* as shown in (9).

$$DGD=\mathrm{Re}\left(2\sqrt{\det(T')}\right) \quad (9)$$

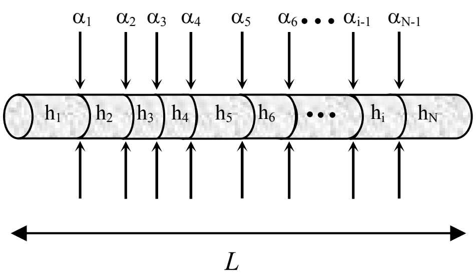

Fig. 2: Representation of the N pieces fiber optic concatenation.

3.2 Measurement method

The measurement system is composed by a synthesized laser source, a polarimeter, a polarizer, a PC and the device under test (DUT), which is the PMD source. The polarizer is responsible for generating the three input linear state of polarization. The laser source should have a sufficiently narrow-bandwidth in order not to generate depolarization in the DUT input signal. The polarimeter used applies the JME method (Jones-Matriz-Eingenanalysis) and performs the Stokes vector conversion into the Jones. The PMD/DGD, SOPMD (PCD + Depol) e os PSPs values, among other information are provided by the polarimeter system. The polarimeter has coupled to its system a polarization controller responsible for generating random mode couplings (different input polarization states).

The measurements swept the wavelength range from 1530 nm to 1595 nm with wavelength steps of 0,4 nm. This step was chosen in order to provide the best measurement accuracy since it is directly responsible for it. It is well known that large steps could provide better accuracy due to the reduction in the time measurement. By the other side, they could interfere in the DGD variation reproduction fidelity over the wavelength range chosen if the polarization variation occurred during one step change do not cause a rotation in the SOP, in relation to the principal axis, higher than 180º.

The equipments that are controlled by the PC provide the Stokes parameters PSP vectors by which it can be calculated the DGD and both SOPMD components. The polarimeter measures the DUT output SOP when the input states are changed.

4. MEASUREMENTS ANALYSIS

4.1. Measurement Results

The experiment was performed inside an environmental chamber in order to obtain a good temperature control and stability. It can be observed in Fig. 3, that the DGD x λ curve have a behavior, related to temperature changes, very similar to that one obtained by P. A. Williams [11].

It can be observed a mean DGD difference between both curves of, approximately, 0,05 ps and a maximum difference of 0,12 ps. The temperature variation of 7 ºC can be observed in many laboratories where the temperature is not suitable controlled as well as in field measurements. But this is not the Inmetro case which environmental control of the metrological laboratories is kept unchanged in 23 ºC ± 1 ºC. Fig. 3 also shows the necessity of developing a temperature control system of the PMD source in order to maintain the measurement uncertainties as low as possible.

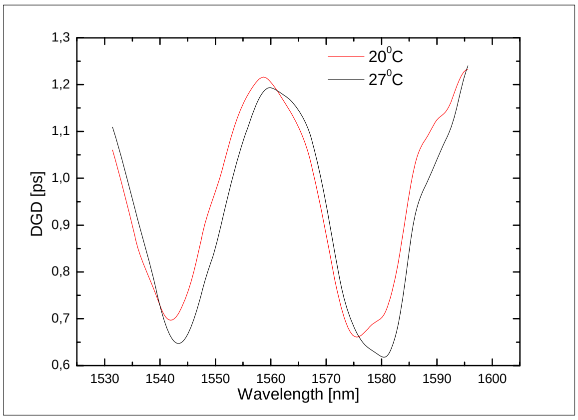

Fig. 3: DGD measurement response of the PMD source prototype under controlled temperature variation.

After the preliminary analysis and considering that the temperature was stabilized some measurements were performed when the actuators input pressures were changed. Although it was used a set of four actuators, in the Fig. 4, it was not applied voltage in all of them in the same time. In curves DGD 1 and DGD 2 only one piezoelectric was charged. The difference in curves shapes was obtained because different piezoelectric was chose each time. It can be considered that although the other three piezos were not activated them have a residual pressure that can be represented as a new polarization coupling. In the DGD 2 curve it was applied the maximum voltage and in the DGD 1 curve a value about 30% lower.

Those two curves represented in Fig.4 are in fact a mean of 20 DGD measurements taken over a short time period (30 minutes). The measures were taken over a wavelength span that produces 180 wavelengths.

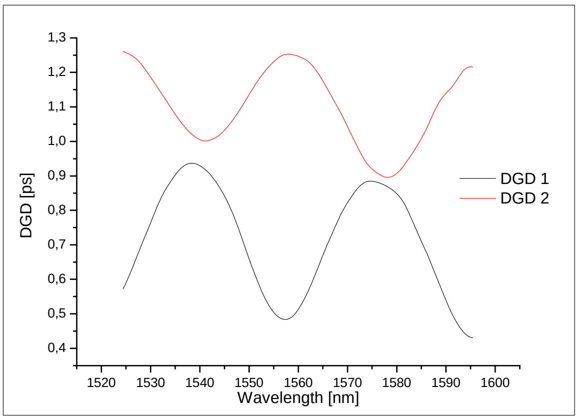

Fig. 4: PMD source measurements with different actuator conditions.

In Table 1 is shown the mean PMD, SOPMD with both components, Depolarization and PCD. One can observe that for the two pressure configuration chosen produces a mean PMD change of about 10% in relation to the expected value (about 0,8 ps) and 0,38 ps between each other (equivalent to almost 40%). The SOPMD did not change this much.

Table 1: Data information for the two measured DGD x wavelength curves.

	DGD 1	DGD 2
PMD [ps]:	0,72	1,10
SOPMD [ps^2]:	0,29	0,30
Depol [ps^2]:	0,003	0,0006
PCD [ps^2]:	0,29	0,30

It was demonstrated that if it is applied voltage in two actuators the curve shape can be changed to a non sinusoidal one, this can be seen in curve 5 in Fig. 5. The curves sown in Fig. 5 represent a mean of 20 curves taken in 20 different time instants and curve 3 were taken when one actuator was feed with maximum voltage and curve 4 with 80% of maximum voltage.

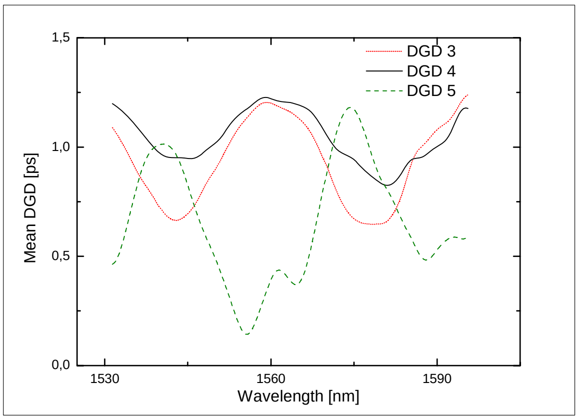

Fig 5: Mean DGD values measured on PMD source with different actuator conditions.

Although in the present work only the DGD behavior is studied it was decided to analyze the SOPMD behavior. In Fig 6. is shown the SOPMD, PCD and Depolarization of the PMD source when the same configuration used in Fig. 5. We consider this evaluation extremely important for the PMD source as a differential of the scientific work. As a preliminary analysis it can be seen that although a considerable DGD mean variation was observed when the voltage applied was changed (curve 3 and 4) the SOPMD curves did not change considerably and their mean values was quite the same (see Table 2). But the same did not happen when one more actuator was energized, see the results for curve 5. The major contribution for the SOPMD came from the depolarization component.

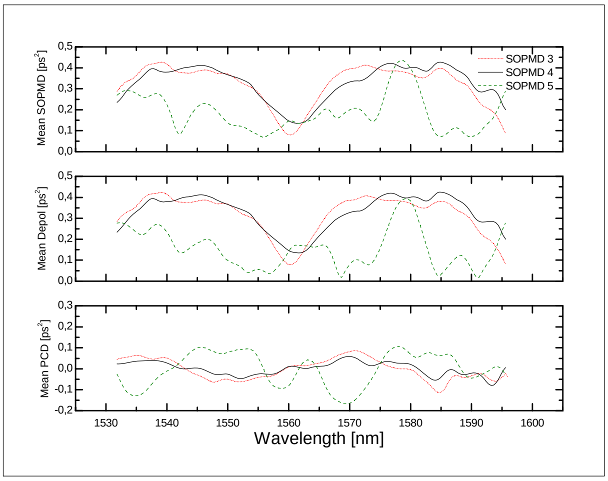

Fig. 6: SOPMD, PCD and Depolarization curves of the PMD source with different actuator conditions.

Table 2: Data information for the two measured DGD x wavelength curves.

	PMD [ps]	SOPMD [ps^2]
curve 3	0,927	0,321
curve 4	1,042	0,329
curve 5	0,658	0,185

4.2. Simulations Results

Basic simulations scheme are displayed in Fig. 1. Eq. (7), (8) and (9) were used in order to obtain final DGD values. The control of each PZT is independent and we can move all or only one of them.

Results for a particular case where one PZT has it values changed and the other three PZT are kept with a specific fixed residual pressure are showed in Fig. 7. Each curve has a different shape and represents a different piezo movement. These curves can be compared to experimental results showed in Fig. 4. Both experimental and simulation results show a similar sinusoidal behavior that can be explained by a few number of actuators.

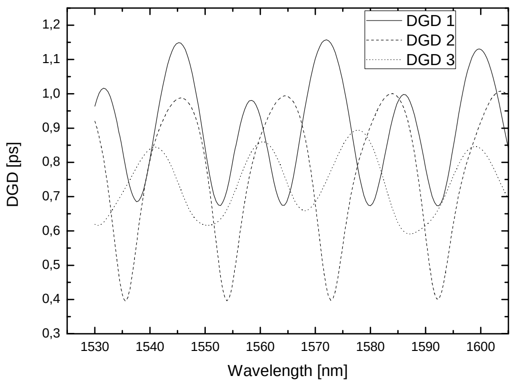

Fig 7- PMD source simulations with different actuator conditions. One active piezo and three piezos with a specific fixed residual pressure.

Fig. 8 illustrates a condition where two piezos has a active function and two piezos are kept with a specific fixed residual pressure. Insertion of an extra active piezo makes sinusoidal behavior less significant. This conclusion agrees with the known fact that using few actuators the necessary DGD statistic generation couldn't be achieved.

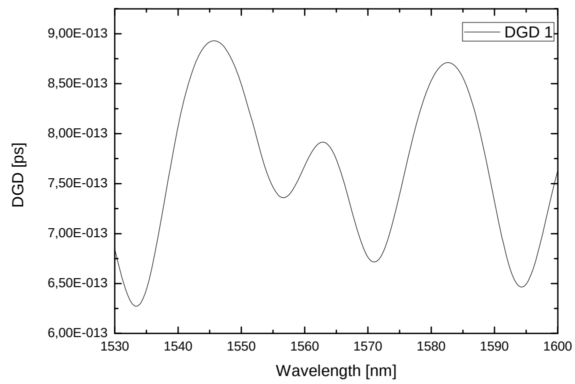

Fig 8 – PMD source simulation with different actuator conditions. Two active piezos and two piezos with a specific fixed residual pressure.

Fig. 9 displays results obtained from a scheme using different number of piezos. The basis is similar to that one showed in Fig. 1, but now a variable number of piezos is used. We tried to find the minimum number of piezos that could guarantee a good performance.

Instead of four piezos, simulations were performed for number of piezos equal to 5, 7, 8 and 10. All of them were controlled. At each temporal step, a random, positive or negative, change in each PZT is performed. This change occurs increasing or decreasing the actuating angle of the piezo.

Increasing number of piezos also increases system complexity, so it's desirable that we can be able to develop a PMD source with best configuration of the number of actuators. We can conclude that using seven PZT's is possible to achieve a good compromise between number of controlled piezos and efficiency. Although we can find in the literature that eight pieces of HiBi should not be sufficient to construct an efficient PMD emulator, in this PMD source there will be seven active piezos instead of seven fixed coupling angle between HiBi segments as usually happens in emulators.

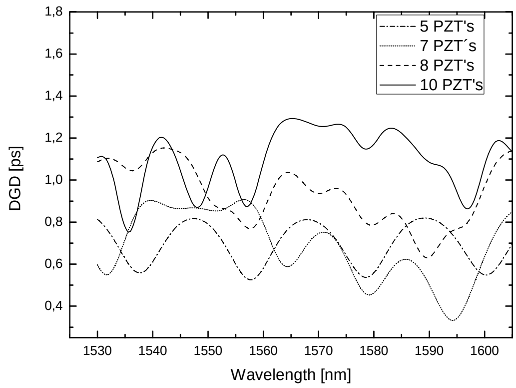

Fig. 10 - PMD source simulation with different number of piezos.

We also simulated a system with equal τ_n, that means, equal length to each HiBi element. According to the literature, a sinusoidal behavior is strongly achieved.

5. CONCLUSIONS

The spectral curves variation demonstrated that it is critical to develop an internal temperature control system. Also it will be necessary to complete the study of the behavior of the second order PMD components. We will continue to verify the necessity to enlarge the number of piezoelectric actuator in order to see the best configuration of HiBi optic fiber pieces.

After the complete characterization of the PMD source that includes several measurements, definition of the temperature dependence, statistical analysis of the results including the uncertainty budget we will propose an international comparison to verify the PMD source efficiency. The comparison of the PMD value against another NMI (National Metrology Institute) will give us the necessary robustness as a national measurement reference laboratory.

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