Polarization Mode Dispersion Measurements using Low-Coherence Interferometry

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***Resumo* – Foi testado um sistema interferométrico de medição de dispersão dos modos de polarização (PMD) em fibra óptica. Usando uma técnica de baixa coerência em um interferómetro de Michelson para determinar os valores da PMD em duas bobinas de fibra, partindo do valor do atraso de grupo diferencial (DGD). O valor mínimo mensurável do atraso de grupo está limitado pela fonte de baixa coerência a 0,13 *ps*, tendo sido medido um valor mínimo aproximado de 0,14 *ps*. Ao longo de intervalos de tempo diferentes para cada bobina foram obtidos os seguintes valores médios de PMD - 0,0405±0,0008 ps/km$^{1/2}$, e 0,0463±0,0004 ps/km$^{1/2}$. Foi observado um comportamento estocástico e aleatório da PMD.**

***Abstract* – An interferometric setup for measuring Polarization Mode Dispersion (PMD), was tested. It uses a low-coherence technique in a Michelson interferometer to determine the PMD values in two reels, measuring the Differential Group Delay (DGD). The low-coherence source bounds the minimum value of DGD detected to 0,13 *ps*, leading to a minimum value detected around 0,14 *ps*. The measured PMD mean value for one reel, in a period of several days was 0,0405±0,0008 ps/km$^{1/2}$, and for the other was 0,0463±0,0004 ps/km$^{1/2}$. Stochastic and random behavior of PMD was observed.**

I. INTRODUCTION

As the amount of traffic transmitted through optical networks all over the world increases, higher bit rates over long distances are required. Polarization Mode Dispersion (PMD) became more visible and its effects more significant for those long haul transmission systems with high bit rates (10Gbits, 40Gbits and higher).

PMD emerges as a direct outcome from the fact that the propagation of the optical power in a single-mode fiber occupies two orthogonal polarization modes with different velocities of propagation. The difference between the two modes is caused by optical birefringence. Any perturbation (imperfections in the fiber, mechanical stress, temperature fluctuations) that alters the circular symmetry of a homogeneous fiber will create two orthogonal polarization states, in a way that any wave, with an indiscriminate state of polarization (SOP), propagating through the fiber will have components on those states with two different velocities. The difference between the two propagating times leads the original pulse to spread. The difference between arrival times is described by the Differential Group Delay (DGD).

This leads to a variation of PMD value with time and fiber length in a random way.

1. Principle:

As mentioned, PMD has a random behavior over time and is dependent on the length of the optical fiber. So when determining PMD two cases are considered: small and long optical fiber sections.

In small sections of optical fiber, disturbances can be assumed as constant throughout the propagation length. The derivative of the birefringence, that is determined from the difference between propagation constants of the two orthogonal modes, in order of frequency, gives us the differential group velocity, $\Delta\tau$, per unit length[1]

$$\frac{\Delta\tau}{L} = \frac{d}{d\omega}\Delta\beta \quad (1)$$

The DGD is a temporal effect of PMD.

In long sections of optical fiber the disturbances cannot be considered as a constant over the whole length. It can be considered as a junction of small uniform ones, each with its random displacement of the polarization axes. So, as the signals in each mode (slow and fast) are projected from one smaller section to the next one, a coupling effect between the polarization modes occurs. This mode coupling, despite preventing DGD from accumulating linearly with the distance, also causes a variation of its value according to a Maxwell distribution over time. This implies that the mean value of DGD increases with the square root of the fiber length.

To distinguish between small and long fibers there is a parameter called *correlation length*, l_c, defined as the length of the fiber in which the mean power in a polarized orthogonal mode, drops to $1/e^2$ of the initial power[2].

For fiber smaller than l_c DGD varies linearly with distance, whereas for fiber longer than l_c the random variation of the SOP leads to a statistical Maxwell distribution of DGD. Then the PMD value is determined by[3]

$$PMD = \frac{\langle\Delta\tau\rangle}{\sqrt{L}} \quad (2)$$

where L is the propagation distance, and $<\Delta\tau>$ is the expected time differential delay.

Several techniques exist for measuring the PMD effect on optical fibers, in this work Low-Coherence Interferometry was selected.

2. Low-Coherence Interferometry:

This technique is a convenient and widely used technique for measuring PMD effects stemming from the DGD in the fiber[4-6]. It uses a low-coherence source to launch a beam through the Fiber Under Test, FUT, and into the Michelson interferometer. There, as the free arm moves, interference fringes are generated when the overall time-delay difference between the two arms and the delay generated by the FUT are lower than the source coherence time.

In the non-coupled case there are only two non-degenerate paths for which light can travel through the FUT, along the fast axis, or along the slow axis. So, the value of the difference between the propagation time of flight on the FUT will be 0 or $\pm\langle\Delta\tau\rangle$ (Fig.1). In the high mode-coupling case, the interference pattern has an indistinguishable number of peaks that are related with the number of mode-coupling sites on the fiber.

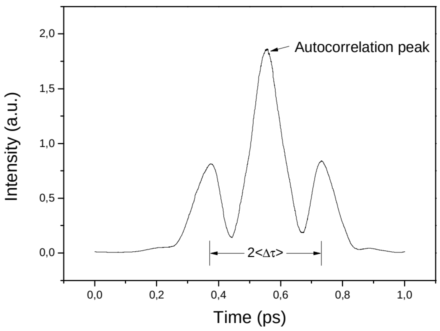

Fig.1 Interferogram envelope example for non-mode coupled devices.

The central peak, which is the autocorrelation peak of the source, stems from the interference between the fast or slow axis with themselves in the two interferometer arms. This peak corresponds to the coherence function of the source in the absence of interference or chromatic dispersion from the side lobes. The side lobes are generated when the polarization in the fast axis is delayed, in a way that it will coincide with the polarization mode in the slow axis. This implies that their distance from the central peak is equivalent to $\langle\Delta\tau\rangle$. The temporal resolution limit is determined by the source coherence time that is given by the width of the central peak. So when PMD has a very small value, the side lobes are added coherently with the central peak, making their identification difficult. Therefore, it must be a tradeoff between bandwidth and DGD resolution, which implies that narrow bandwidth sources allow better DGD detection but, at the expenses of having less DGD resolution. The finite width of the side lobes peaks is caused by two main mechanisms. On one hand, the source coherence time of the source broadens the peak. In the other, the parameter $\Delta\tau$ is not constant over the source spectrum, causing the broadening of the peak with the DGD variation with the wavelength.

II. PROPOSED SYSTEM

The Figure 2 presents the system used for measuring the Polarization Mode Dispersion using the Interferometer Method mentioned earlier. The used source was a Super Luminescent-Diode, SLD, with a nominal wavelength of 1550 *nm* with a measured central wavelength equal to 1552,9 *nm*, and having a estimated coherence length, L_c, of approximately 38,5 μm, which limits the DGD resolution to 0,13 *ps*. The Quarter Wave Plate (QWP) is used to control the polarization in the fixed arm of the interferometer, making possible the identification of the three envelopes used in the DGD determination. The components catalog include: a non-polarizing 50:50 beam-splitter, an amplified InGaAs photodiode with increase responsivity at 1550 *nm* and a data acquisition board. The system is fully controlled by LabView™. Even though the temperature was approximately constant in the laboratory over the acquisition time, the measurement setup was isolated to avoid external disturbances.

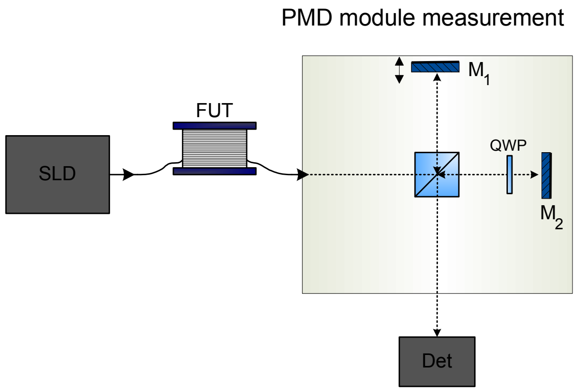

Fig.2 Experimental setup.

Two optical fiber reels with 50 *km* of the same manufacturer, factory rolled, were tested.

III. RESULTS AND DISCUSSION

After the implementation of the system, several acquisitions were taken in both reels. A typical interference pattern detected is shown in Fig. 3. To convert this pattern to one similar to Fig. 1, it is necessary to find out the absolute value in relation to the mean intensity, Fig. 4. Then the envelopes are adjusted to each pattern, allowing the determination of the instant DGD from the scanned distance, $2\Delta\tau=2l/c$.

Comparing these interference patterns with the one in Fig.1 it can be assumed that we were in the presence of a non-coupled case, because it clearly shows that the mode-coupling effect during the acquisitions did not reach levels high enough to be considered a high mode-coupling case. So it was used the non-mode coupling approach.

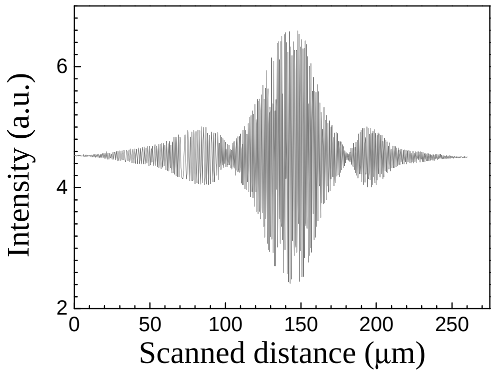

Fig.3 Typical Interference pattern.

As each interference pattern was slightly different from the previous one, to validate the statistical analysis [3] the acquisition of several sets of patterns to calculate the PMD measurements was needed.

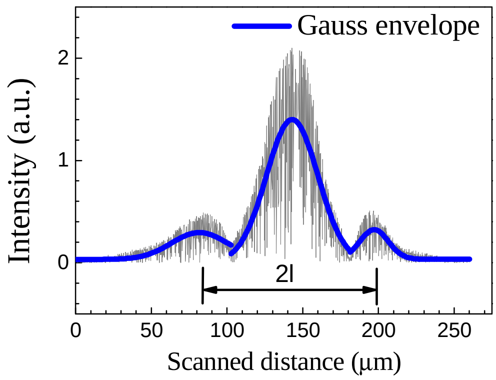

Fig. 4 Aproximation envelopes for the interference pattern, where l is the difference of paths travelled by the beam in the interferometer.

For each reel, the acquisitions taken show a characteristic curve that closely resembles a Maxwell distribution of the expected time differential delay $<\Delta\tau>$, Fig. 5. Using this value it is possible to determine the PMD value using equation (2).

For Reel 1, the acquisitions were made over a large time interval of 32 days. Whereas for Reel 2, the acquisitions were made over a much smaller time frame, of just 5 days, having however a greater number of measurements. In both cases the PMD value was determined using equation (2), with the expected DGD value obtained from the interference patterns. The mean PMD value for Reel 1 was $0{,}0405 \pm 0{,}0008\ ps/km$, while for Reel 2 the determined mean PMD value was $0{,}0463 \pm 0{,}0004\ ps/km$. The existence of extreme PMD values very distant from the mean PMD value, confirms that small variations of the initial parameters that affect birefringence cause unpredictable variations on PMD value. The difference between PMD mean values for the two reels, could be explained by the differences between their intrinsic properties in association with initial environmental conditions, temperature in particular, over a longer time frame for Reel 1when compared to the 5 days time frame for Reel 2.

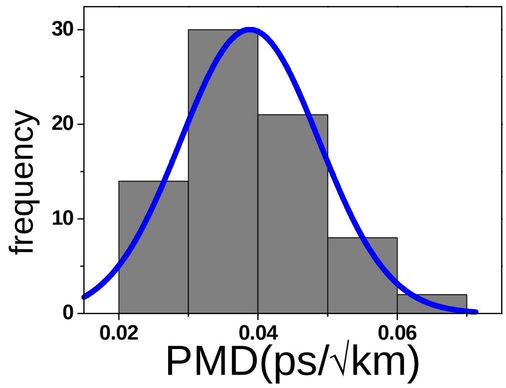

Fig. 5 Histogram of determined PMD values for Reel 1 in a 32 days time interval, with its normal representation.

The PMD values can be straightforward determined using this setup and starting from the interference patterns. In the case of well defined envelopes in the interference pattern (Fig. 3), it implies that the time delay between the two polarizations is greater than the coherence time of the source. When this condition is met, it is easy to determine the DGD from the interference pattern obtained with this setup.

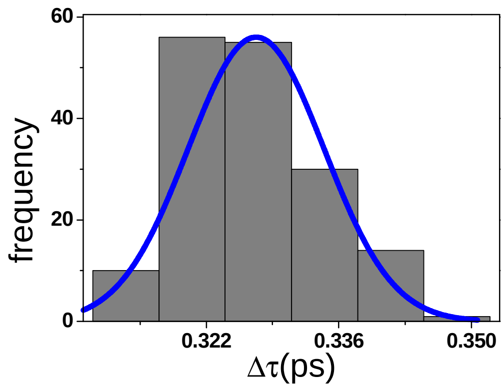

Fig. 6 Histogram of all DGD values for Reel 2.

One limitation to PMD measurement can become visible when, small and unpredictable variations of the states of polarization during the acquisition cause coupling between the fast and slow axis inside the reel, altering the interference pattern profile.

IV. CONCLUSIONS

The proposed Low-Coherence Interferometry based model for PMD measurement, is limited by the coherence time of the source to determinations of minimum DGD values of 0,13 *ps*. In this work, the minimum measured value was 0,14 *ps*.

As expected, probabilistic behavior of the first-order PMD was observed in the two 50 *km* optical fiber reels used. This reveals the influence that environmental factors have on PMD. One of these factors could be temperature, and its variation can cause serious changes in the output states of polarization of the fiber.

V. ACKNOWLEDGMENTS

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