PMD MEASUREMENTS BASED ON LOW-COHERENCE INTERFEROMETRY USING A MICHELSON INTERFEROMETER

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ABSTRACT: *A low-coherence technique in a Michelson interferometer for measuring polarization mode dispersion (PMD) was tested. 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 reel, it was 0.0463 ± 0.0004 ps/km$^{1/2}$. Stochastic and random PMD behavior was observed.*
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Key words: *differential group delay; polarization mode dispersion; Michelson interferometer; low-coherence interferometry*

1. INTRODUCTION

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

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.

1.1. Principle

As mentioned before, PMD has a random behavior over time and depends 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 constants throughout the propagation length. The derivative of the birefringence, 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. However, 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. Other than preventing DGD from accumulating linearly with the distance, this mode coupling 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 fibers smaller than l_c, DGD varies linearly with distance, whereas for fibers 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]

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

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

There are several techniques to measure the PMD effect on optical fibers. In this work, low-coherence interferometry was selected.

1.2. Low-Coherence Interferometry

This technique is a convenient and widely used technique to measure 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 a noncoupled case, there are only two nondegenerate paths for which light can travel through the FUT, along the fast axis

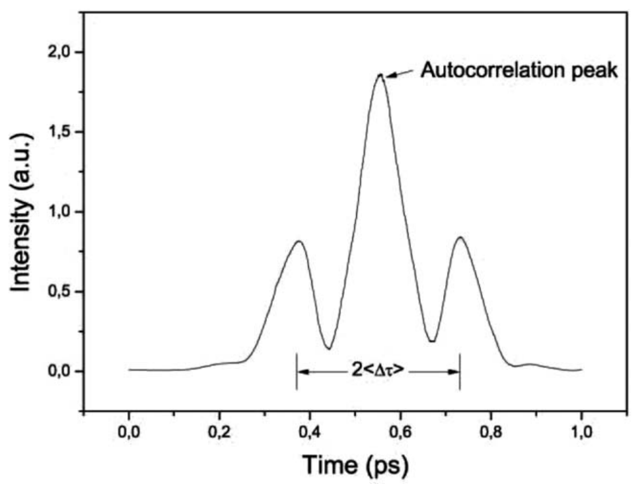

Figure 1 Interferogram envelope example for nonmode-coupled devices

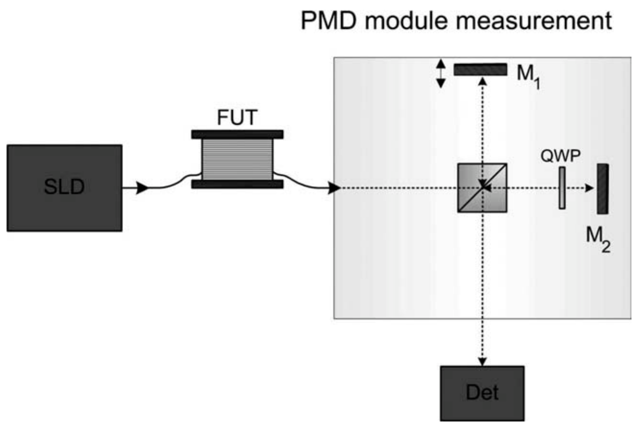

Figure 2 Experimental setup

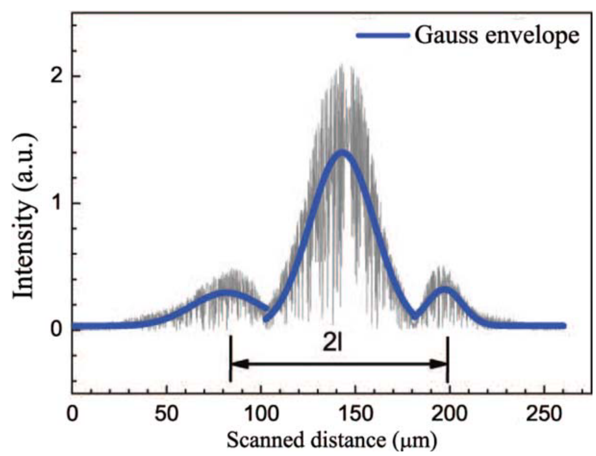

Figure 4 Approximation envelopes for the interference pattern where l is the difference of paths traveled by the beam in the interferometer. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

or along the slow axis. So, the difference value between the propagation time of flight on the FUT will be 0 or $\pm\langle\Delta\tau\rangle$ (see Fig. 1). In the high mode-coupling case, the interference pattern has an indistinguishable number of peaks that are related to the number of mode-coupling sites on the fiber.

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 overlaps 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 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. On the other, the parameter $\Delta\tau$ is not constant over the source spectrum causing the peak with the DGD variation to broaden with the wavelength.

2. PROPOSED SYSTEM

Figure 2 presents the system used to measure the PMD using the interferometer method mentioned earlier. The source used was a superluminescent diode with a nominal wavelength of 1550 nm and a measured central wavelength equal to 1552,9 nm, also having an estimated coherence length, L_c, of $\sim$38.5 μm limiting the DGD resolution to 0.13 ps. the quarter-wave plate is used to control the polarization in the fixed arm of the interferometer, making it possible to identify the three envelopes used in the DGD determination. The components catalog include: a nonpolarizing 50:50 beam splitter, an amplified InGaAs photodiode with increase responsivity at 1550 nm, and a data acquisition board. Even though the temperature was approximately constant in the laboratory over the acquisition time, the measurement setup was isolated to avoid external disturbances. The system is fully controlled by LabView^{TM}.

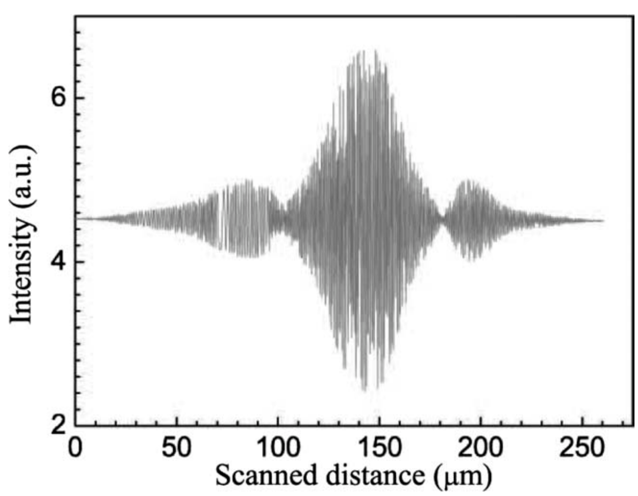

Figure 3 Typical interference pattern

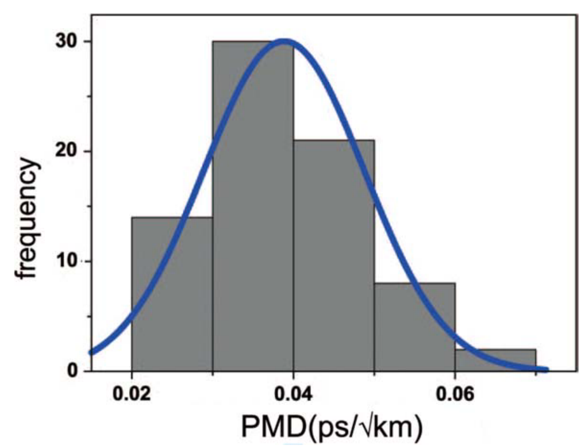

Figure 5 Histogram of determined PMD values for Reel 1 in a 32-days time interval with its normal representation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

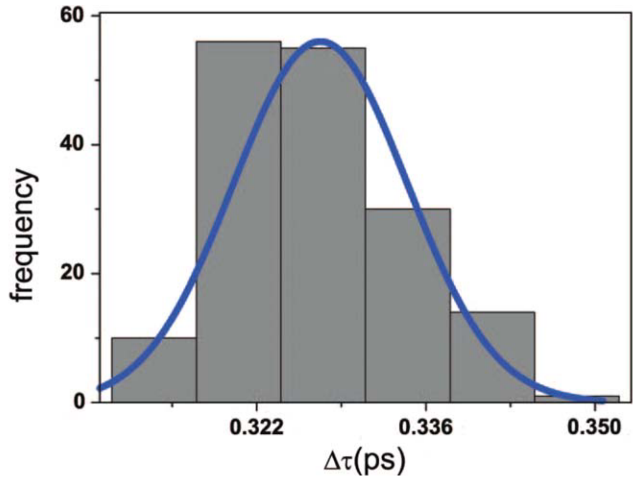

Figure 6 Histogram of all DGD values for Reel 2. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

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

3. RESULTS AND DISCUSSION

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

Comparing the interference patterns with the one in Figure 1, it can be assumed that we are in the presence of a noncoupled case because it clearly shows that the mode-coupling effect during the acquisitions did not reach levels high enough for this to be considered a high mode-coupling case. Then, nonmode-coupling approach is used.

As each interference pattern differs slightly from the previous one, to validate the statistical analysis [3], it was necessary to acquire several sets of patterns to calculate the PMD measurements.

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

For Reel 1, the acquisitions were made over a time interval of 32 days. Whereas for Reel 2 (Figure 6), the acquisitions were made over a much smaller time frame—5 days—registering however, a greater number of measurements. In both cases, the PMD value was determined using Eq. (2) with the expected DGD value obtained from the interference patterns. The mean PMD value for Reel 1 was 0.0405 ± 0.0008 ps/km, while for Reel 2, the determined mean PMD value was 0.0463 ± 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 the 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 1 when compared with the 5-days time frame for Reel 2.

The PMD values can be determined straightforward using this setup and starting from the interference patterns. In the case of well-defined envelopes in the interference pattern (see Fig. 3), it is implied that the time delay between the two polarizations is greater than the coherence time of the source. When this condition is met, the DGD is easily determined from the interference pattern obtained with this setup. One limitation to PMD measurement can become visible when small and unpredictable variations of the states of polarization during the acquisition cause the fast and slow axis inside the reel to couple, thus altering the interference pattern profile.

4. CONCLUSIONS

The proposed low-coherence interferometry–based model proved to be a good method for PMD measurement, being only 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 that were 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.

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WIRELESS PASSIVE PHOTO DETECTOR FOR INSECT TRACKING

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ABSTRACT: *This letter presents a passive wireless photo detector for precise localization of insects in biological studies. The detector is based on a photo diode matched to an antenna, and it produces*