Low polarization mode dispersion measurements in ad hoc drawn spun fibers

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Abstract

Polarization mode dispersion causes significant impairment in high bit-rate optical telecommunications systems. It is well accepted that polarization mode dispersion can be strongly reduced by spinning the fiber while drawing, even if a comparison between theoretical predictions and experimental evidence has never been reported. In this paper we focus on the polarization mode dispersion measurement of ad hoc drawn periodically spun fibers, providing a first although preliminary experimental analysis of the spin induced differential group delay reduction. When measuring very low differential group delays as in the case of spun fibers, standard techniques are affected by rather high uncertainties. This problem is usually solved repeating several times the measurements while randomly perturbing the fiber. We support experimentally this method by means of polarization sensitive reflectometric measurements.

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1. Introduction

In recent years a great effort has been devoted to the mitigation of polarization mode dispersion (PMD) [1] by developing low PMD fibers. The most effective way to produce low-PMD fibers consists in spinning the fiber while it is drawn, so to rotate the birefringence axes [2]. The spin process is described by a spin function that represents, as a function of distance, the angle by which the fiber is rotated. Different kinds of spin functions have been studied, such as, unidirectional, modulated, and periodic ones [3,4]. Several papers dealt with modeling and design aspects: in particular it has been theoretically shown, and numerically confirmed [3], that by properly tuning the amplitude and the period of a periodic spin profile, the PMD coefficient can be reduced by even two orders of magnitude.

Actually, the practical implementation of these theoretical results is conditioned by two fundamental points: on one side, it depends on the capability of implementing such optimal spin profiles, and on the other side, it depends on the experimental verification of the theoretical predictions. Concerning the former, in [5,6] two different methods for the measurement of the spin period have been proposed. Concerning the latter, PMD measurements on unidirectionally spun fibers have been reported in [7], whereas an experimental validation of theoretically predicted optimal periodic spin parameters is still lacking.

The spin effectiveness in reducing the PMD can be conveniently measured in terms of the spin induced reduction factor (SIRF), defined as the ratio between the mean differential group delay (DGD) of a spun fiber \( \langle \Delta \tau (z) \rangle \), and the mean DGD the same fiber would have if it were not spun \( \langle \Delta \tau_{\text{un}} (z) \rangle \),

\[
\text{SIRF} = \frac{\langle \Delta \tau (z) \rangle}{\langle \Delta \tau_{\text{un}} (z) \rangle}.
\]

Since \( 0 \leq \text{SIRF} \leq 1 \), the smaller the SIRF, the higher the spin effectiveness in the DGD reduction.

In this paper we report some measurements of the SIRF of periodically spun fibers and compare them with the expected theoretical values.
2. Measurement procedures

It is important to note that in the case of fibers with very low PMD, DGD measurements and SIRF calculation are critical for two reasons. First, since the SIRF is the ratio between two measured quantities, its relative error is the sum of the relative errors of $\langle \Delta \tau_{\text{inst}}(z) \rangle$ and of $\langle \Delta \tau(z) \rangle$. Second, we recall that the DGD is a statistical quantity, thus all DGD measurements involve an averaging over a finite sample set. Typically, this averaging is performed over a set of wavelengths, but in the case of very low DGD values it is difficult to obtain in this way accurate estimates of the mean DGD [8,9]. Thus it is important to carry out an experimental procedure that allows to explore the statistical ensemble of DGD values.

In the literature, this problem is solved by populating the PMD statistical ensemble upon measuring the fiber DGD under different perturbation conditions [9–11].

Actually, birefringence and, consequently, DGD properties depend strongly on the fiber deployment. IEC standard [9] prescribes also that the fiber under evaluation has to be kept at a minimal tension either by deploying the fiber in loops on a flat smooth surface (“floor test”), or by loosely wrapping the fiber onto a spool (“low-tension bobbin”) [10,12]. In fact, it is known, that when a fiber is tightly wound on a standard shipping bobbin, the birefringence induced by the winding process is usually larger than the intrinsic one [13].

In our experiments we adopted the “floor test” because of its simplicity. Fiber samples were loosely deployed on the floor with a bending radius larger than 0.5 m to avoid any detectable bending birefringence [9,12].

In order to populate the PMD statistical ensemble, we used a procedure similar to the one described in [11], consisting in gently stirring the fiber before each DGD measurement, so to change its perturbation conditions. Although this approach seems reasonable and has been already used [9–11], its correctness has never been proved so far.

Indeed, the measured DGD values should belong to an homogeneous statistical ensemble, but there is no a priori guarantee that under different perturbation conditions the fiber has the same PMD statistical properties. Regarding this point, it is convenient to recall that PMD is a consequence of fiber random birefringence. In its turn, the birefringence is characterized by:

\begin{itemize}
  \item the beat length, $L_B$, that is inversely proportional to the root mean square of the birefringence strength;
  \item the birefringence correlation length, $L_F$, that describes how fast the random birefringence evolves along the fiber; the shorter $L_F$, the faster the birefringence evolution;
  \item the spin profile, $\alpha(z)$, that describes in which way the fiber is eventually spun.
\end{itemize}

Once $L_B$, $L_F$, and $\alpha(z)$ are fixed, the statistical properties of the DGD are completely defined. By changing the perturbation conditions we cannot change the spin profile, but we might change $L_B$ and $L_F$, and when this happens the PMD statistical properties are modified. This means that DGD values obtained by changing the perturbation conditions, belong to the same statistical ensemble only if the birefringence parameters $L_B$ and $L_F$ do not change.

In order to verify that the stirring does not modify $L_B$ and $L_F$, we measured the birefringence properties of the fiber by means of the polarization-optical time domain reflectometry (P-OTDR) technique. A tutorial explanation of the P-OTDR technique and of its applications can be found in [13]; here it is sufficient to recall that it can be effectively used to perform spatially-resolved polarization-sensitive measurements. In particular, it is possible to measure the birefringence parameters $L_B$ and $L_F$.

We performed a set of measurements on an unspun fiber, 1600 m long, deployed on the floor in a circular path of about 1 m diameter. The measurements were carried out using the following scheme:

1. $L_{B1}$, $L_{F1}$ and $\Delta \tau_1(\lambda)$ are measured;
2. the fiber is left as it is;
3. $L_{B2}$, $L_{F2}$ and $\Delta \tau_2(\lambda)$ are measured;
4. the fiber is stirred;
5. $L_{B3}$, $L_{F3}$ and $\Delta \tau_3(\lambda)$ are measured;
6. the fiber is left as it is;
7. $L_{B4}$, $L_{F4}$ and $\Delta \tau_4(\lambda)$ are measured.

Figure 1 reports the evolution over the test band of $\Delta \tau_1(\lambda)$, $\Delta \tau_2(\lambda)$, $\Delta \tau_3(\lambda)$, and $\Delta \tau_4(\lambda)$, shown with solid line, dashed line, solid line with circles and solid line with crosses, respectively. It can be noted that if the fiber under test is not stirred, also the DGD behavior as a function of wavelength does not change. In fact $\Delta \tau_1(\lambda)$ and $\Delta \tau_2(\lambda)$ are superimposed, and also $\Delta \tau_3(\lambda)$ and $\Delta \tau_4(\lambda)$ are almost superimposed again. Conversely, after stirring the fiber the resulting $\Delta \tau_3(\lambda)$ has a completely different behavior with respect to $\Delta \tau_2(\lambda)$.

In contrast, it is remarkable that the stirring procedure does not affect the birefringence properties. Indeed, as it can be observed from Table 1 the variations of $L_B$ and $L_F$ induced by the stirring are negligible, whereas the DGD values, $\langle \Delta \tau \rangle_{\omega}$, obtained by averaging over the 130 nm bandwidth are substantially different.

These results give a clear validation to the use of the fiber stirring procedure for collecting DGD values in the same statis-
In general, the measured SIRF values are a little bit larger than the expected ones. This difference has a random nature and might be due to some nonuniformities of the spinning process, to unexpected spin induced variations of the birefringence parameters, or to extrinsic birefringence induced accidentally during the fiber deployment. Furthermore, considering the uncertainties in spin process, it has been shown [18] that the spin amplitude transferred to the fiber can be up to 50% smaller than the nominal value depending on the ratio between the spin period and the length of fiber in viscous state during drawing.

Nevertheless, we see that the experimental results follow the general trend of the theoretical prediction. Indeed, the SIRF values get smaller as the spin period is reduced, confirming that the short period assumption is crucial in attaining high DGD reduction. Furthermore, note that, as predicted by the theory, the analysis technique [9,16], and varying the wavelength between 1490 and 1620 nm with a step of 5 nm. The measurements were repeated 25 times for each fiber, each time slightly perturbing the fiber deployment.

The unspun fiber sample was the same used to validate the stirring procedure in Section 2, and it was used as a reference to calculate the SIRF, according to Eq. (1). The measured PMD coefficient of the unspun fiber is $0.04 \, ps/km^{1/2}$, while the measured beat length and birefringence correlation length are $L_B \approx 9 \, m$ and $L_F \approx 1.8 \, m$, respectively.

Since all the fibers were drawn from the same preform, it is reasonable to assume that they have statistically the same birefringence properties and consequently the same $L_B$ and $L_F$. Given that $L_B \approx 9 \, m$ and $L_F \approx 1.8 \, m$, we can observe in Table 2 that only the samples of set 3 satisfy the short period assumption ($p^2 \ll L_B^2$); moreover, for all the three sets the spin period is longer than $L_F$.

We numerically estimated the nominal SIRF corresponding to the given $L_B$, $L_F$ and spin parameters by modeling the fiber birefringence according to the so called “random modulus model” (RMM), defined in [17] and described in detail in [14]. We simulated an ensemble of 100,000 fibers and calculated the corresponding SIRF that is reported in Figs. 3–5 (solid curves) as a function of the spin amplitude $a_0$ for the values of $p$ and $e$ of sets 1–3, respectively.

The measured 9 values of the SIRF are also reported in Figs. 3–5 with dots; vertical bars indicate the measurement uncertainty.

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### Table 2

<table>
<thead>
<tr>
<th>Set</th>
<th>$p$ (m)</th>
<th>$e$ (m)</th>
<th>$a_0$ (turns/m)</th>
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<td>6</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
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<td>0.8</td>
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Table 1

<table>
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<tr>
<th>$I$</th>
<th>$L_B$ (m)</th>
<th>$L_F$ (m)</th>
<th>$\langle \Delta \tau \rangle_{\omega}$ (ps)</th>
</tr>
</thead>
<tbody>
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<td>1.9</td>
<td>0.066</td>
</tr>
<tr>
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<tr>
<td>4</td>
<td>9.1</td>
<td>1.7</td>
<td>0.037</td>
</tr>
</tbody>
</table>

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![Fig. 2. Trapezoidal spin-rate function.](image)

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3. PMD measurements on spun fibers

It has been theoretically and numerically shown [3,4,14], that when a fiber is spun according to a periodic spin function, the rule for minimizing the spun fiber DGD is not to spin as fast as possible, but rather to select optimal spin parameters.

In general, the spin parameters that allow to minimize the fiber DGD depend both on $L$ and on $F$, but in the ideal case of deterministic birefringence ($L \to +\infty$), if the spin period $p$ is such that $p^2 \ll L_B^2$, it is possible to find optimized spin parameters that make the SIRF close to zero and that are independent of the fiber birefringence. Such spin parameters correspond to minima in the SIRF also in the case of fibers with random birefringence if $p < L_F$ [15].

To our knowledge, up to now these results have been proven only numerically and analytically. In the following we provide a first partial experimental validation.

We drew 1 unspun and 9 spun fibers, each a few kilometers long, using the same preform. The latter 9 fibers were spun according to a trapezoidal spin-rate, characterized by a spin period $p$, a maximum spin-rate $\omega_0$, and a swivel length $e$ as shown in Fig. 2. The spun fibers were divided in three sets as indicated in Table 2. Samples belonging to the same set are characterized by the same nominal spin period and swivel length, whereas the three samples within each set have different maximum spin-rates. For each set two values of $\omega_0$ correspond to a local minimum of the SIRF, while the other corresponds to a relative maximum of the SIRF.

We performed PMD measurements according to the stirring procedure explained in Section 2, using the Jones Matrix Eigen-
fibers spun with $\alpha_0 = 0.6$ turns/m (set 2) and $\alpha_0 = 0.8$ turns/m (set 3) provide a lower SIRF than the fibers with $\alpha_0 = 1.1$ and 1.0 turns/m, respectively, despite the latters were spun at higher spin-rate. This is indeed a preliminary experimental evidence of the existence of optimal spin parameters.

4. Conclusions

We have presented preliminary experimental results about the SIRF induced by trapezoidal spin-rate. The influence of period and maximum spin-rate have been analyzed and a fair qualitative agreement with theoretical predictions has been found.

In order to overcome the problems related to the measurement of very low PMD values, we have validated a method to collect statistically independent DGD values based on gently stirring a loosely deployed fiber. This method has been thoroughly tested by means of DGD and birefringence measurements.

Acknowledgments

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