Measurements of beat length and perturbation length in long single-mode fibers

Andrea Galtarossa and Luca Palmieri
Dipartimento di Elettronica ed Informatica, Università di Padova, Via Gradenigo 6/A, 35131 Padua, Italy

Marco Schiano and Tiziana Tambosso
Centro Studi e Laboratori Telecomunicazioni, Via Reiss Romoli 274, 10148 Turin, Italy

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Experimental results of measurement of the beat length and the differential group delay of several types of long single-mode fiber are presented. The proposed measurement technique is based on a polarization-sensitive analysis of the backscattered signal and allows one to calculate the correlation length of the random birefringence affecting the fiber. © 2000 Optical Society of America

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Polarization mode dispersion (PMD) has been the object of several studies over the past 15 years. Initially PMD played a minor role in optical system design compared with the severe impairment owing to chromatic dispersion. Recently, with the introduction of chromatic-dispersion compensators, PMD has become the ultimate limit for high-capacity optical systems.

The main parameter used to describe PMD is the well-known differential group delay (DGD), that is, the macroscopic effect of PMD. Although DGD is a very important parameter in optical system design, it does not give any information on the origin of PMD, since DGD does not describe the properties of the random birefringence affecting the fiber. Rather, such a characterization is strictly related to the two parameters that determine the DGD: the beat length, $L_B$, and the correlation length of the perturbation affecting the fiber, $L_F$ (i.e., perturbation length, also called $h_{fib}$ in Ref. 2).

It is well known to researchers involved in PMD measurement that DGD evolves as a function of time and depends on cabling conditions. Consequently, knowledge of the values of $L_B$ and $L_F$ may be important, because it can help in predicting the behavior of a fiber in terms of PMD before it is cable or even installed. Nevertheless, up to now $L_B$ has been only roughly estimated with a local analysis of the geometrical properties of the fiber cross section an analysis that cannot be applied to installed cables; in addition, to our knowledge $L_F$ has never been measured.

In this Letter we present what are, to the best of our knowledge, the first measurements of the beat lengths of various kinds of long single-mode fibers. The measurement technique is based on polarization optical time-domain reflectometry; hence it is applicable to installed cables, requires the use of only one fiber end, and allows a spatially distributed analysis. Moreover, by measuring the DGD of the fibers, one can easily calculate their perturbation lengths. Consequently, an experimental characterization of the random birefringence causing PMD in long single-mode fibers will be provided.

The theory supporting $L_B$ measurements was recently published. The main idea of such measurements is to perform a kind of fixed polarizer analysis of the optical time-domain reflectometer trace in the z domain; i.e., we want to analyze the power detected after the backscattered field is passed through a polarizer. Let $T(z)$ represent this detected normalized power. In Ref. 1 it was shown that $T(z)$ can be expressed as follows:

$$T(z) = \frac{1}{2} [1 + \hat{s}_b(z) \cdot \hat{p}]$$

$$= \frac{1}{2} [1 + \{R(z)M\hat{p} \cdot [MR(z)\hat{s}_0]\},$$

where $R(z)$ is the M"uller matrix of the fiber; $M = \text{diag}(1, 1, -1)$; and $\hat{s}_b(z)$, $\hat{s}_0$, and $\hat{p}$ are, respectively, the Stokes unit vectors representing the state of polarization (SOP) of the backscattered field, the input SOP, and the fixed polarizer. The subsequent step is to assume that $\hat{p} = \hat{s}_0$, so Eq. (1) simplifies to

$$T(z) = \frac{1}{2} [1 + \hat{s}_f(z) \cdot [M\hat{s}_f(z)]]$$

where $\hat{s}_f(z) = R(z)\hat{s}_0$ is the Stokes unit vector of the SOP of the forward-propagating field. The statistical properties of $\hat{s}_f(z)$ are well known, and hence we were able to calculate the statistical properties of $T(z)$. In particular, we found results that allowed us to determine $L_B$ by means of level crossing rate (LCR) and (or) power spectral density analyses. In Ref. 1 it was shown that

$$L_B = \frac{4\sqrt{v}}{\ln(n)} = \frac{1}{\sigma \sqrt{\frac{12}{\pi}}}$$

where $v$ represents a generic level of 0 to 1, $n(v)$ is the mean number of times $T(z)$ crosses the level $v$ per unit length, and $\sigma^2$ is the variance of the PSD of the signal $T(z)$.

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The condition \( \hat{s}_0 = \hat{p} \) can be simply achieved by placement of a linear bidirectional polarizer just before the fiber input. In spite of its simplicity, such a solution suffers from two drawbacks: The measured backscattered power fluctuates not only because of SOP variations but also because of fiber local losses and fading noise owing to pulse coherence. It is not possible to separate or compensate for these contributions, and hence a more complicated experimental setup is needed.

As shown in Fig. 1, the solution that we have adopted is to measure the complete SOP of the backscattered power, but this requires further theoretical consideration. Actually, we have to take into account the optical splitter (which can be a circulator as well as a coupler) that separates the forward path from the backward one and that is unavoidably present in any polarization optical time-domain reflectometry setup. So, let \( \mathbf{R}_{12} \) be the matrix representing the optical path from the input of the splitter (point \( \odot \)) to the point at which the forward and backward paths separate themselves (point \( \odot \)). Similarly, let \( \mathbf{R}_{23} \) be the matrix of the path from point \( \odot \) to the input of the polarization analyzer (point \( \odot \)).

The SOP measured by the analyzer is not the quantity \( \hat{s}_b(z) \); rather, it is the SOP of the field after it has propagated through to the input jumper of the splitter, the fiber (in both directions), and the output jumper. This SOP can be expressed as

\[
\hat{s}_b(z) = \mathbf{R}_{23}\mathbf{R}_b(z)\mathbf{R}_{12}\hat{s}_m,
\]

where \( \mathbf{R}_b(z) \) is the matrix representing the round-trip propagation in the fiber, and \( \hat{s}_m \) is the input SOP. Note that there is no control on the launched SOP, since, as we will show, knowledge of \( \hat{s}_m \) is not necessary.

It is well known that the backscattered signal retains a "memory" of the initial SOP, and as a matter of fact \( \langle \mathbf{R}_b(z) \rangle = (1/3)\mathbf{M} \), where \( \langle \cdot \rangle \) represents the ensemble average.\(^3\) If we assume that \( \mathbf{R}_b(z) \) is ergodic (as can be easily numerically verified), then the ergodic average is equal to the ensemble one, so we can write

\[
\langle \hat{s}_b(z) \rangle = \frac{1}{\Delta} \int_\Delta \hat{s}_b(z)dz = \langle \mathbf{R}_{23}\mathbf{R}_b(z)\mathbf{R}_{12}\hat{s}_m \rangle = \mathbf{R}_{23}\mathbf{MR}_{12}\hat{s}_m,
\]

where \( \langle \cdot \rangle \) represents the ergodic average. We now show that the signal \( T(z) \) can be calculated from \( \hat{s}_b(z) \) only. Note that \( \mathbf{R}_{12}\hat{s}_m \) is the SOP of the field at the fiber input (i.e., point \( \odot \)), so \( \mathbf{R}_{12}\hat{s}_m = \hat{s}_0 \). Moreover, letting \( \mathbf{R}_b(z) = \mathbf{MR}^T(z)\mathbf{MR} \), where the superscript \( T \) is the transpose, and recalling that \( \mathbf{R}_{23}^T\mathbf{R}_{23} \) is the identity matrix (as it is for any Muller matrix), we obtain the result that

\[
3\langle \hat{s}_b(z) \rangle = \begin{pmatrix} \mathbf{R}_{23}\mathbf{MR}_{12}\hat{s}_m \end{pmatrix} \cdot \begin{pmatrix} \mathbf{R}_{23}\mathbf{R}_b(z)\mathbf{R}_{12}\hat{s}_m \end{pmatrix} = \begin{pmatrix} \mathbf{R}_{23}\mathbf{M}\hat{s}_0 \end{pmatrix}^T\mathbf{R}_{23}(\mathbf{MR}^T\mathbf{MR})\hat{s}_0 = \hat{s}_f(z) \cdot [\mathbf{M}\hat{s}_f(z)].
\]

Now we can state that the signal \( T(z) \) can be calculated as follows (\( z \) dependence is omitted):

\[
T(z) = \frac{1}{2} (1 + 3\langle \hat{s}_b(z) \rangle \cdot \hat{s}_b(z) = \frac{1}{2} [1 + \hat{s}_f \cdot (\mathbf{M}\hat{s}_f)],
\]

which coincides with Eq. (2), so that all the results still hold. We now have a simple but effective recipe for measuring the beat length: (1) Measure the SOP of the backscattered field, \( \hat{s}_b(z) \), (2) calculate \( T(z) \) according to Eq. (4), and (3) apply the LCR and PSD analyses.

Finally, recall that the mean DGD, \( \langle \Delta \tau \rangle \), \( L_B \), and \( L_F \) are strictly related. This relationship is expressed by Eq. (26) of Ref. 2, which can be rearranged as follows:

\[
\langle \Delta \tau \rangle^2 = \frac{1}{3} \left( \frac{8\lambda L_F}{\pi c L_B} \right)^2 \left[ \exp(-L/L_F) + \frac{L}{L_F} - 1 \right],
\]

where \( L \) is the fiber length, \( \lambda \) is the wavelength, and \( c \) is the speed of light in vacuum. So, by measurement of the DGD and \( L_B \) it also possible to calculate \( L_F \).

We performed laboratory tests on different types of fiber (step-index G.652, dispersion-shifted G.653, and nonzero-dispersion G.655), tightly wound on drums (with a 15-cm diameter) and as long as 25 km. DGD measurements were performed by Jones matrix eigenanalysis of the backreflection from the far end of the fiber, as described in Ref. 5, and averaging over the 100-nm band.

\( L_B \) was measured with the experimental setup shown in Fig. 1. A high-resolution commercial optical time-domain reflectometer was used to trigger a pulse generator and to record the backscattered power. We set the pulse width to 5 ns to achieve good spatial resolution of \( \sim 0.5 \) m. Measurements of \( \hat{s}_b(z) \) were performed at a fixed wavelength of 1532 nm.

Typical evolution of the LCR as a function of level is shown in Fig. 2; the theoretical prediction of Eq. (3) fits the experimental data very well. A 13-km-long G.652 fiber was measured; \( L_B \) was 24 m and was calculated by application of LCR analysis to the entire length of the fiber.

However, it is also possible to perform a local analysis by selection of a subsection of the signal \( T(z) \). An example is shown in Fig. 3, in which the evolution of \( L_B \) along a cascade of two G.653 fibers (3 and 4 from Table 1), that are spliced together is presented.
Fig. 2. Evolution of LCR as a function of level. The solid curve refers to Eq. (3), and the filled circles are the experimental data.

Fig. 3. Evolution of $L_B$ along a cascade of two G.653 fibers (3 and 4 from Table 1). The shaded area indicates a window of 900 m centered on the fiber splice.

Table 1. Measurements of $L_B$, $L_F$, and $\delta \tau$

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Type</th>
<th>LCR</th>
<th>PSD</th>
<th>$L_F$ (m)</th>
<th>$\delta \tau (\text{ps}/\sqrt{\text{km}})$</th>
</tr>
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<tr>
<td>1</td>
<td>G.652</td>
<td>22.5</td>
<td>21.3</td>
<td>23</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>G.652</td>
<td>24.3</td>
<td>24.3</td>
<td>13</td>
<td>0.04</td>
</tr>
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<td>3</td>
<td>G.653</td>
<td>15.7</td>
<td>14.6</td>
<td>14</td>
<td>0.06</td>
</tr>
<tr>
<td>4</td>
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<td>12.0</td>
<td>10.3</td>
<td>10</td>
<td>0.06</td>
</tr>
<tr>
<td>5</td>
<td>G.652</td>
<td>11.7</td>
<td>11</td>
<td>5</td>
<td>0.03</td>
</tr>
<tr>
<td>6</td>
<td>G.652</td>
<td>7.2</td>
<td>6.2</td>
<td>17</td>
<td>0.14</td>
</tr>
<tr>
<td>7</td>
<td>G.655</td>
<td>20.9</td>
<td>18.9</td>
<td>19</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Each point on the curve $[z_c, L_B(z_c)]$ was obtained by application of LCR analysis to a 900-m-long spatial sliding window centered at $z_c$. The result shown in Fig. 3 refers to a cascade of the two G.653 fibers. The difference in the values of $L_B$ of the two fibers is evident. Also, note that the average values of the two subsections (dashed lines in Fig. 3) coincide with those measured for the individual fibers before they were spliced. The residual oscillations are due both to local variation of $L_B$ and to statistical error. Actually, we can reduce this error by increasing the window width, i.e., by decreasing the spatial resolution.

The whole set of measurements is summarized in Table 1. Note that there is fairly good agreement between the values of $L_B$ calculated with the LCR and the PSD analyses, even if the PSD technique sometimes underestimates the beat length. It can be shown that this underestimation occurs because the PSD analysis is more sensitive to the noise affecting the measure, which can cause an overestimation of the average birefringence and, consequently, a reduction in the calculated $L_B$.

The G.652 fibers (1 and 2 from Table 1) show longer $L_B$ than the G.653 fibers. This result may be due to the fact that the latter fibers have a larger index difference between core and cladding, which may increase internal stresses. The situation changes completely when G.652 fibers are included in a four-fiber ribbon (along with fibers 5 and 6, which are the outermost and innermost fibers, respectively). In fact, the common external coating superimposes a large birefringence, whose amplitude varies with fiber position inside the ribbon. This behavior agrees with other published results.6

Finally, G.655 nonzero-dispersion fibers (7 from Table 1) present characteristics that are very similar to those of G.652 fibers, in terms of both $L_B$ and DGD.

Interesting issues regarding perturbation length remain. Even if this quantity was not directly measured, its values were inferred from the knowledge of $L_B$ and $\langle \Delta \tau \rangle$, according to Eq. (5). For all fibers that were tested, $L_F$ was of the same order of magnitude as $L_B$. This result is reasonable, since the fibers were tightly wound on drums ~15 cm in diameter. The value of $L_F$ is expected to increase for installed fiber cables; indeed, further investigations of this topic are needed.

A. Galtarossa’s e-mail address is andrea.galtarossa@dei.unipd.it.

References