

Measurement of Local Beat Length and Differential Group Delay in Installed Single-Mode Fibers

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Abstract—We present beat length and polarization mode dispersion (PMD) measurements performed on installed fibers. Results regard three different kinds of fibers: standard step-index, dispersion shifted and nonzero dispersion (NZD). After a historical comparison with standard differential group delay measurement collected four years ago on the same fibers, we perform a spatial-resolved measurement of the beat length by analyzing the state of polarization of the backscattered field. We compare PMD properties of different fibers and calculate the statistical distribution of the beat length. The differential group delay (DGD) and the beat length statistics depend strongly on fiber type and on fiber position along the link. The influence of the beat length on the DGD is also discussed.

Index Terms—Beat length, birefringence, differential group delay (DGD), polarization mode dispersion (PMD).

I. INTRODUCTION

SEVERAL authors [1]–[4] have shown that polarization mode dispersion (PMD) is the ultimate limit in high bit rate optical system with chromatic dispersion compensation, because it causes a difference in the group delay (DGD) between orthogonally polarized modes. Consequently, PMD has been widely investigated theoretically, numerically and experimentally for the last 15 years.

While the statistical description of this phenomenon and of its impact on system penalties can be found in literature, the knowledge of physical aspects concerning fiber local properties, like birefringence, is not satisfactory. Such a lack of information may have displeasing consequences: for example, it is hard to estimate the PMD variation induced on fibers by the cabling process. Furthermore, standard PMD measurement techniques permit to calculate only the total DGD of the link, while information on the link subsections is not available. Moreover, all standard methods need both fiber ends, one for transmission and one for detection, and this may cause severe problems in field tests on installed cables.

These are the main reasons fostering the recently proposed reflectometric technique for PMD measurement [5]. This technique uses a polarization optical time domain reflectometer (POTDR), which is based on the analysis of the state of polarization of the backscattered field. By means of a POTDR

the local properties of fiber birefringence can be characterized; preliminary results of laboratory tests performed on fibers tightly wound on drums can be found in [6]. In particular, it has been shown that dispersion shifted (DS) fibers usually show shorter beat length (10 m–20 m) compared with that of step-index (SI) fibers (15 m–25 m). However, all results are restricted to laboratory tests on bare fibers, while data on installed cables are not yet available.

The aim of this work is to apply the POTDR measurement technique to installed fibers. The optical cable we tested was installed in late 1995 between the ISCTI laboratory (Istituto Superiore delle Comunicazioni e delle Tecnologie dell'Informazione) located in Rome and a shelter located in Pomezia. Few months later it was characterized in terms of DGD. Recently, we have repeated the DGD measurements and compared the results so to obtain information on DGD evolution on a long time-scale. Most important, we have also measured the beat length evolution along several fibers of the cable. Hence, we have estimated the statistical distribution of the beat length and compared the behavior of different fiber types.

II. STANDARD DGD MEASUREMENT

The link we have tested is 23.6 km long, and it is composed of ten sections of different length, spliced as shown in Fig. 1. The cable contains 80 single-mode fibers of three different kinds: 30 (numbered from 1 to 30) are ITU-T G.652 standard step-index (SI), 30 (from 31 to 60) are ITU-T G.653 dispersion shifted (DS) and 20 (from 61 to 80) are ITU-T G.655 nonzero dispersion (NZD). Fibers are grouped in eight tubes, ten fibers per tube.

Fibers were characterized in terms of DGD four years ago, a few months after the cable installation. This work was carried out in the framework of the ACTS-ESTHER project (Exploitation of Soliton Transmission Highways in the European Ring): a field test of soliton transmission at 10 and 40 Gb/s. In that occasion, two standard PMD measurement techniques (Jones Matrix Eigenanalysis [7] and Wavelength Scanning [8]) were used. We looped couples of fibers at the Pomezia side, so that measurements were performed on 47.2 km long links, and both source and receiver were placed in Rome, into the ISCTI laboratory.

The DGD was averaged over a wavelength window of 100 nm around 1550 nm. The main result was that the mean DGD per square root of length (i.e., the PMD-coefficient) of the SI, DS, and NZD fibers was 0.032, 0.228, and 0.043 ps/ $\sqrt{\text{km}}$, respectively. As a general comment, we can state that DS fibers showed a DGD about six-times larger than that of SI and NZD fibers.

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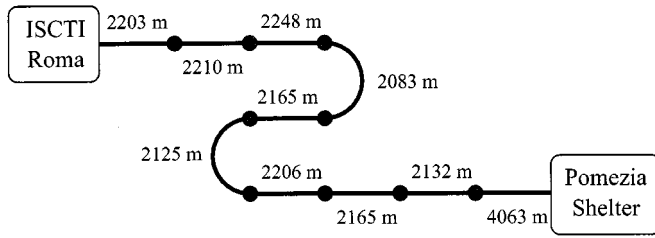


Fig. 1. Cable layout.

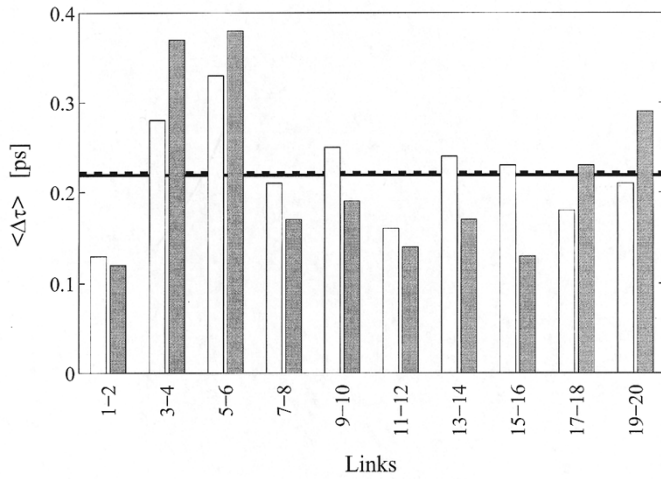


Fig. 2. Wavelength-average DGD of the SI fibers: empty bins refer to the four-years old measurements, shaded bins to the recent measurements. Dashed and continuous lines (almost overlapped) represent the average of the old and new data, respectively.

Recently, we have performed the same measurements on the same couples of fibers, to investigate the long-term time-evolution of DGD. This time, the PMD-coefficient of SI, DS, and NZD fibers was 0.032, 0.231, and 0.061 ps/ $\sqrt{\text{km}}$, respectively. It can be observed that the average properties of SI and DS fibers have undergone small changes, whereas NZD fibers have increased their average PMD-coefficient by roughly 40%.

A more detailed comparison is shown in Fig. 2, which refers to SI fibers: empty bins represent the DGD measurements obtained four years ago, and shaded bins refer to the new DGD values. Dashed line shows the old DGD average value, while the continuous one refers to the new DGD average value. Figs. 3 and 4 (which refer to DS and NZD fibers, respectively), have the same meaning.

As a comment, it can be noted that polarization dispersion properties are (and were four years ago) comparable inside each set of fibers (SI, DS and NZD). However, a few exceptions are represented by fibers 71–72 and, mainly, 39–40, which present a larger DGD compared with the others of the same kind. It should also be noted that some links (those involving fibers no. 21–30, 75, and 76) were not measured, since they were carrying telecommunication traffic.

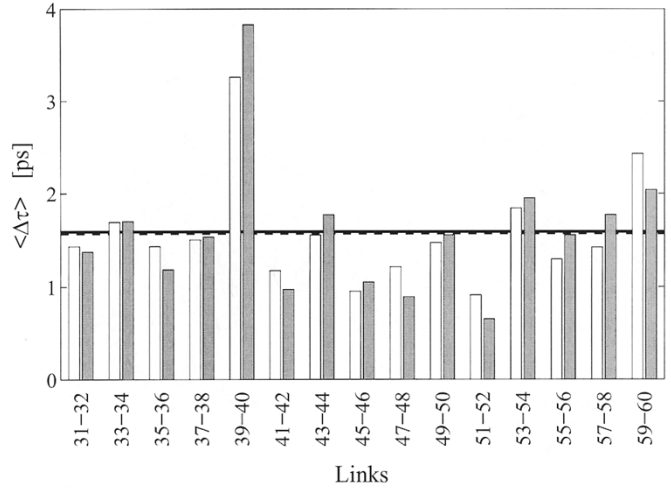


Fig. 3. Wavelength-average DGD of the DS fibers: empty bins refer to the four-years old measurements, shaded bins to the recent measurements. Dashed and continuous lines (almost overlapped) represent the average of the old and new data, respectively.

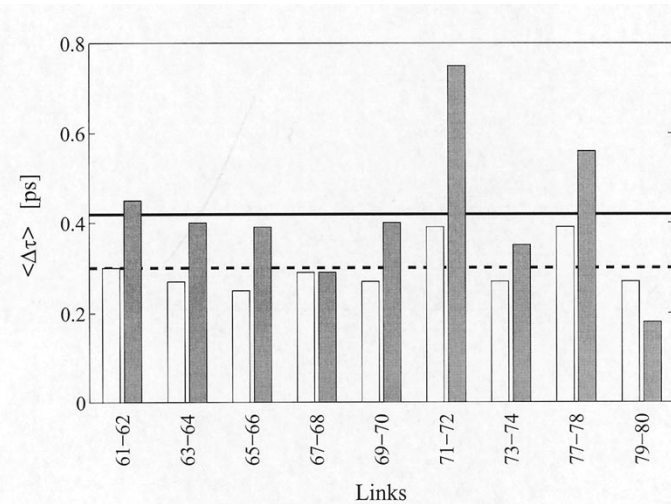


Fig. 4. Wavelength-average DGD of the NZD fibers: empty bins refer to the four-years old measurements, shaded bins to the recent measurements. Dashed and continuous lines represent the average of the old and new data, respectively.

In order to compare the results in a quantitative way, the following parameter can be defined:

$$\delta_j = \frac{\langle \Delta\tau \rangle_j - \langle \Delta\tau \rangle_{j,\text{old}}}{\langle \Delta\tau \rangle_{j,\text{old}}} \quad (1)$$

where

j indicates the link;

$\langle \Delta\tau \rangle_j$ measured average DGD of the j th link;

$\langle \Delta\tau \rangle_{j,\text{old}}$ DGD measured on the same link four years ago.

Some properties of these quantities are shown in Table I, where the first and the second rows are the maximum and the mean value assumed by the modulus of δ_j , respectively, while the third row is the average of δ_j .

In general, all fibers show large absolute variations in their average DGDs, although DS fibers seem more stable. A pos-

TABLE I
VARIATION OF THE DGD FOR DIFFERENT KINDS OF FIBER

Fiber type	SI	DS	NZD
$\max\{ \delta_j \}$	44.6 %	28.8 %	95.8 %
$\langle \delta_j \rangle$	25.1 %	11.7 %	44.7 %
$\langle\delta_j\rangle$	-2.0 %	1.0 %	42.3 %

sible explanation for this behavior is that DGD is influenced at the same time by the intrinsic fiber birefringence as well as by external perturbation. When the intrinsic birefringence is high, fiber should be less sensitive to external actions. This tentative explanation will be confirmed in the following sections.

Additionally, if we consider the mean value of δ_j , we may argue that SI and DS fiber-links present, on average, practically the same values as four years ago. On the contrary, the average DGD increases more than 40% in NZD fibers. It should be noted that by averaging the values of δ_j we have sensibly reduced the measurement uncertainty. Hence, the 40% DGD increase in NZD fibers should not be attributed to measurement error, but rather it should represent a real change of NZD fibers properties.

In summary, DS fibers are statistically the most predictable in terms of average DGD; in other words, it seems that DS fibers are more robust against environmental changes. The DGD of SI fibers seem predictable in terms of ensemble average while a large fluctuation may occur in the average DGD for a single fiber. Finally, NZD fibers show a large relative increase of the average DGD, although the absolute values are still very low. However, this increase cannot be considered a definitive result, and it could be interesting to monitor these kind of fibers, in order to check if such a behavior is a general trend.

III. BEAT LENGTH MEASUREMENT

The theoretical backgrounds of beat length measurement can be found in [9] and [10]. Here we briefly recall that this kind of measurement is based on the analysis of the following signal:

$$T(z) = \frac{1}{2}(1 + \hat{s}_B(z) \cdot \hat{s}_0) \quad (2)$$

where \hat{s}_0 is the Stokes vector representing the input state of polarization (SOP), and $\hat{s}_B(z)$ is the Stokes vector representing the SOP of the backscattered field. Two kinds of analysis can be performed, which are based on the level crossing rate (LCR) or on the power spectral density (PSD) of $T(z)$.

According to the LCR analysis, the beat length L_B is related to the mean number of times $T(z)$ crosses a given level v , in

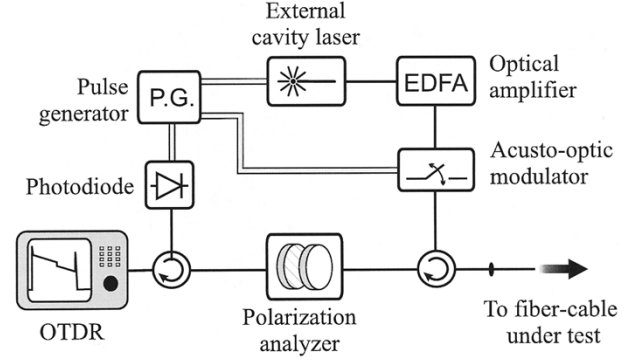


Fig. 5. Basic scheme of the experimental setup.

a unitary length. If we call this average number $n(v)$, then we have [9]

$$L_B = \frac{4\sqrt{v}}{n(v)}. \quad (3)$$

In order to reduce the measurement uncertainty, we can evaluate $n(v)$ for $N > 1$ different levels v_k , and calculate L_B according to the least square error criteria, i.e., by means of the following formula:

$$L_B = \frac{4 \sum_{k=1}^N v_k}{\sum_{k=1}^N n(v_k) \sqrt{v_k}}. \quad (4)$$

The beat length can be deduced also from the PSD analysis. If $W(f)$ is the power spectral density of the signal $T(z)$, and if we define the width of $W(f)$ as

$$\sigma_W = \left(\frac{\int_{\mathbb{R}} f^2 W(f) df}{\int_{\mathbb{R}} W(f) df} \right)^{\frac{1}{2}}$$

then, it can be shown that the following simple relationship holds [9]:

$$L_B = \frac{1}{\sigma_W} \sqrt{\frac{12}{\pi}}. \quad (5)$$

The SOP of the backscattered field was measured by means of the POTDR. The setup, schematically shown in Fig. 5, is based on an high-resolution commercial OTDR, which was used to record and process the evolution of the backscattered power. Since the OTDR has a relatively wide-band source, its pulses are not suitable for a PMD measurement, hence they were used to drive an external cavity laser followed by an erbium-doped fiber amplifier. The pulse width was set to 5 ns, in order to achieve a fairly good spatial resolution of about 0.5 m. Measurements were performed at the wavelength of 1532 nm. An acousto-optic modulator was placed after the EDFA in order to eliminate its spontaneous emission disturbing the OTDR receiver. By means of an optical circulator, the backscattered field was passed through a polarization analyzer, before being detected by the OTDR.

Once $\hat{s}_B(z)$ is measured, $T(z)$ and hence L_B can be calculated. We did not apply the LCR and the PSD analysis to the whole optical link, since it is composed of inhomogeneous

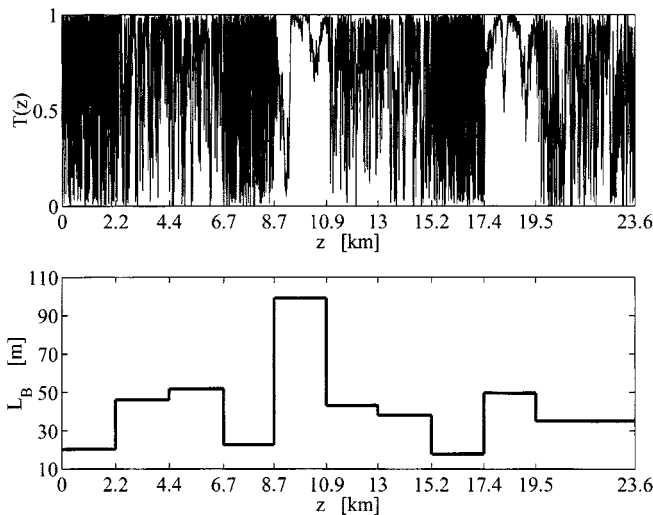


Fig. 6. Upper graph: evolution of $T(z)$ (defined by (2) as measured on fiber no. 1. Lower graph: stepwise evolution of L_B averaged over each section of fiber no. 1.

fibers; rather, we have applied those analysis separately to each of the ten sections composing the link. As already pointed out in [10], the two techniques are in good agreement, and this behavior is confirmed by the present measurements. Hence, for the sake of brevity, we will not report the results of both techniques, but only those of the LCR analysis.

First of all, let us consider Fig. 6, which shows a sample evolution of $T(z)$ (upper graph), together with the related evolution of the average beat length (lower graph, where L_B is averaged over each section). Results refer to the SI fiber no. 1. It can be observed that $T(z)$ tends to accumulate toward its upper limit 1, as predicted by the theory [9]. Moreover, a glimpse to the evolution of $T(z)$ may give qualitative information on the beat length, but this information should be carefully used, since it may be occasionally wrong. For example, let us compare Sections 5 and 9: they show a similar evolution of $T(z)$, yet they exhibit a different L_B . Analogously, Sections 7 and 9 show similar beat length values, but different $T(z)$ evolutions. Hence, deeper and more rigorous analyzes (as the LCR and PSD ones) are recommended.

We measured the beat length on the ten sections of seven SI fibers, seven DS fibers, and four NZD fibers. So we collected an ensemble of 70 L_B values for the SI fibers and for the DS fibers, and of 40 values for the NZD fibers. Based on these results, we have performed a statistical analysis on the beat length of the three different kinds of fiber. Fig. 7 shows the histogram of the measured L_B for SI fibers: it can be seen that the beat length ranges between 10 m and 120 m, around an average value of 42 m, with a standard deviation of 26 m. Results of a similar analysis performed on DS and NZD fibers are shown in Figs. 8 and 9, respectively. DS fibers have an average L_B of 20 m, and a standard deviation of 13 m, while NZD fibers exhibit a mean beat length of 18 m, with a standard deviation of about 5 m. It is evident that, compared with SI fibers, both DS and NZD present a remarkably lower beat length and a lower standard deviation.

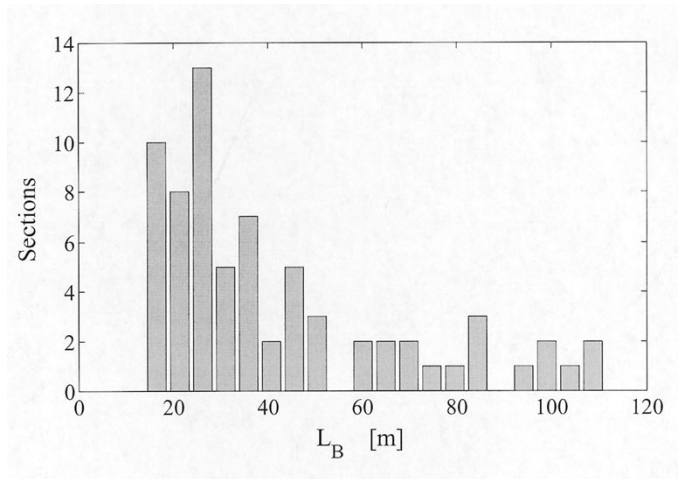


Fig. 7. Histogram of the values of L_B measured on the 70 sections of SI fibers. The mean value is 42 m, with a standard deviation of 26 m.

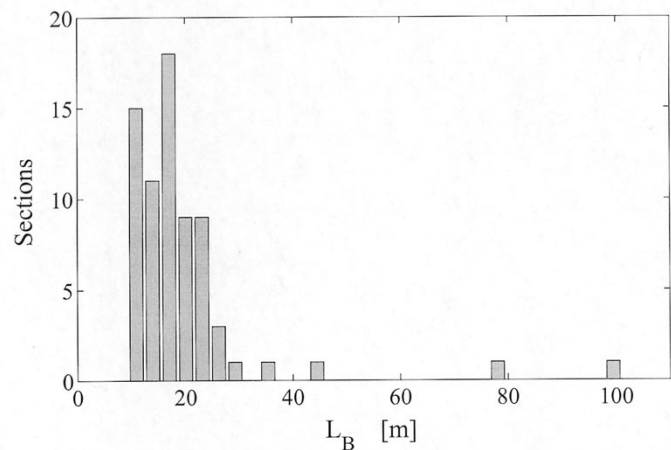


Fig. 8. Histogram of the values of L_B measured on the 70 sections of DS fibers. The mean value is 20 m, with a standard deviation of 13 m.

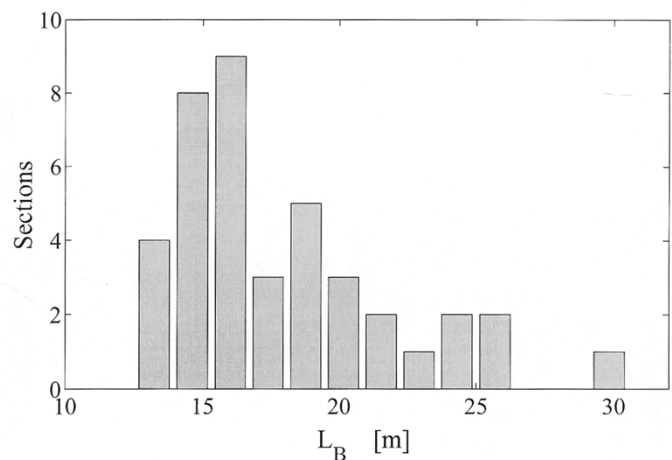


Fig. 9. Histogram of the values of L_B measured on the 40 sections of NZD fibers. The mean value is 18 m, with a standard deviation of 5 m.

Other interesting results can be obtained by analyzing the local evolution of L_B . Fig. 10 shows such evolution for SI fibers

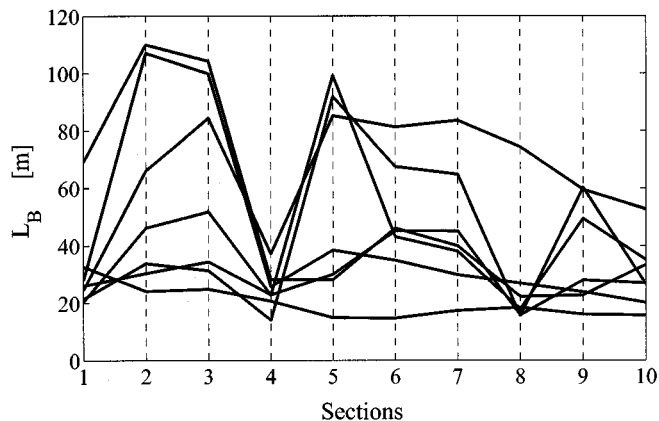


Fig. 10. Evolution of L_B for SI fibers. Each line refers to one fiber. The beat length was averaged over the length of each section.

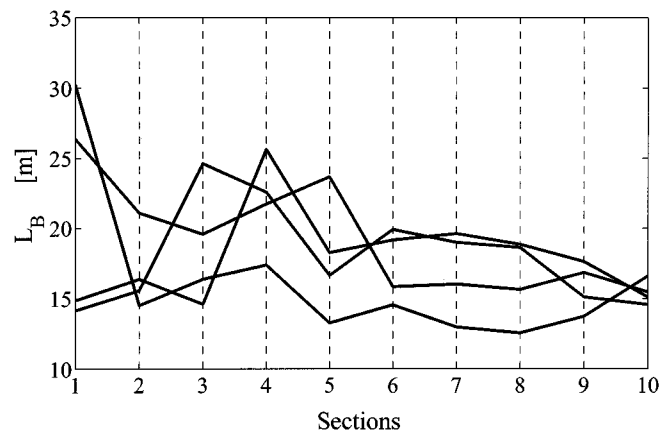


Fig. 12. Evolution of L_B for NZD fibers. Each line refers to one fiber. The beat length was averaged over the length of each section.

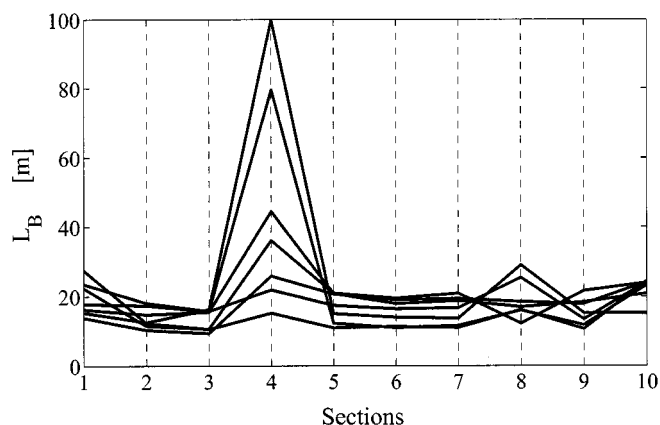


Fig. 11. Evolution of L_B for DS fibers. Each line refers to one fiber. The beat length was averaged over the length of each section.

(now we do not use a stepwise representation for the sake of clearness). It can be seen that fibers in Section 4 present less spread L_B values, which is unusual compared with the other sections. Something similar happens for DS fibers (see Fig. 11). Section 4 shows again a different behavior; however, in this case L_B assumes more spread (rather than less spread) values compared with the rest of the link. It should also be noticed that, excluding Section 4, the beat length of DS fibers has a mean value of roughly 17 m, with a standard deviation of only 4 m; this shows that the high values of L_B appearing in Fig. 8 are due only to Section 4. Finally, a similar graph has been plotted for NZD fibers (see Fig. 12), but in this case, we do not observe different behaviors among the sections.

We do not have a definitive explanation for the strange behavior of the Section 4. By looking at the SI fibers, one may think that this section is exposed to stronger external perturbations; but it is hard to believe that the same perturbations may reduce the beat length of DS fibers. Moreover, NZD fibers seem to be unaffected by those perturbations. In our opinion, Section 4 of the cable behaves in a different way simply because its fibers may come from different production batches; however, at the moment we don't have information supporting our hypothesis.

IV. CONCLUSION

We have characterized the birefringence of several fibers of three different kinds: standard SI, DS, and NZD, and we have analyzed their DGD variation on a four-year-long timescale.

Concerning the beat length, standard SI fibers exhibit longer values (hence a lower birefringence) compared with DS fibers. Moreover, the L_B values of SI fibers have a larger standard deviation, compared with that of DS and NZD fibers. This cannot be considered a real surprise, since the total birefringence is usually a superimposition of several contributions (internal stresses, elliptical core section, external stresses, etc.). In NZD fibers and DS fibers, it is reasonable that the major effect on birefringence should be caused by internal stresses due to higher dopant concentration. Hence, those fibers result less sensitive to external stresses induced by cabling and by the environment, and consequently the fluctuation of beat length is limited compared with SI fiber case. This behavior is also confirmed by laboratory tests on the same kinds of fibers published elsewhere [10].

Other supports to our conclusions arise from the DGD properties of the two family of fibers: in fact, the DGD of DS fibers is on average greater than that of the SI ones, which agrees with the larger measured birefringence of the former.

On the contrary, NZD fibers have shown a peculiar behavior: first of all, their average DGD is grown of roughly 40% in the last four year, whereas the average DGD of SI and DS fibers is practically unchanged. Furthermore, NZD fibers have almost the same beat length as the DS, yet they have a lower average DGD, comparable to that of the SI. This may suggest that they are affected by a large polarization coupling.

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