Single-End Reflectometric Measure of Differential Group Delay in Single Mode Fiber Links

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Abstract - We present a theoretical analysis showing how polarization sensitive optical time domain reflectometry is able to to measure the differential group delay of an arbitrary subsection of a link by using two different methods. Analytical predictions are validated and supported by experimental results.

I. Introduction

Reflectometric techniques are very popular since they are able to easily measure the local properties of optical fibers. In particular, polarization-sensitive optical time domain reflectometry (P-OTDR) has been introduced about thirty years ago to measure polarization properties of fibers and fiber links [1]. Recently, P-OTDR was introduced to measure the mean differential group delay (DGD) [2–4] to show up bad fiber sections within installed links.

It is commonly reported in literature that reflectometric techniques cannot measure the instantaneous (i.e.: not averaged) DGD, because they apparently miss information about the third component of the polarization mode dispersion (PMD) vector.

However, Dong et al. [5], did show that reflectometric techniques can correctly measure the instantaneous DGD under reasonable assumptions. The solution proposed, however, has two drawbacks: it measures only the total DGD cumulated along the link and not the DGD of isolated subsections and, more important, it requires the calculation of second order derivatives, which may be quite critical on experimental data due to their noisiness.

In this work we present theoretical background and experimental results on two techniques for the measurement of DGD.

The first technique is able to calculate the instantaneous DGD of arbitrary subsections of the link under test, by analyzing in a novel way the data gathered with a P-OTDR. The technique holds when there is no polarization dependent loss and under some other assumptions discussed in detail below. Finally, we show also that P-OTDR can theoretically measure the instantaneous DGD under a rather wide range of conditions. On the other hand, the second technique is able to calculate the root mean square DGD of a fiber link (or of an arbitrary subsection) by simply estimating the autocorrelation function (ACF) of the measured round-trip birefringence.

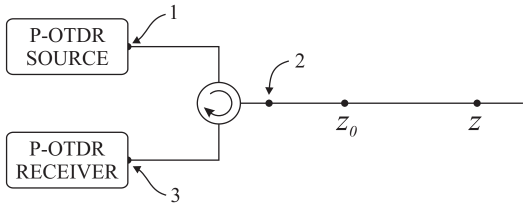

Figure 1. Schematic optical path of a P-OTDR. Point 2 marks the beginning ($z = 0$) of the fiber link under test.

II. Theoretical Background

The P-OTDR setup is schematically shown in fig. 1. Let $\boldsymbol{F}(z_0)$ be the Mueller matrix representing the forward propagation from the P-OTDR source (point 1) to an arbitrary point z_0 within the fiber link under test. Let also $\boldsymbol{B}(z_0)$ and $\boldsymbol{W}(z;\, z_0)$ represent the backward propagation from z_0 to the P-OTDR receiver (point 3) and the forward propagation within the fiber from z_0 to z, respectively.

The round-trip propagation from point 1 to z and back to point 3 is then represented by the matrix $\boldsymbol{R}(z) = \boldsymbol{B}(z_0)\boldsymbol{M}\boldsymbol{W}^T(z;\, z_0)\boldsymbol{M}\boldsymbol{W}(z;\, z_0)\boldsymbol{F}(z_0)$, where $\boldsymbol{M} = \mathrm{diag}(1,\, 1,\, -1)$ is a diagonal matrix [1]. All the above matrices, except $\boldsymbol{M}$, are in general functions of the angular frequency ω, even if this is not explicitly written for simplicity.

The z-dependence of $\boldsymbol{W}$ is governed by the equation $\partial\boldsymbol{W}/\partial z = \boldsymbol{\beta} \times \boldsymbol{W}$, where $\boldsymbol{\beta}(z, \omega)$ is the birefringence vector [6]. On the other hand, the ω-dependence of $\boldsymbol{W}$ reads $\partial\boldsymbol{W}/\partial\omega = \boldsymbol{\Omega} \times \boldsymbol{W}$, $\boldsymbol{\Omega}(z, \omega)$ being the PMD vector.

The same formalism holds for equations describing the dependence on z and ω of the round-trip matrix, $\boldsymbol{R}$; namely: $\partial\boldsymbol{R}/\partial z = \boldsymbol{\beta}_R \times \boldsymbol{R}$ and $\partial\boldsymbol{R}/\partial\omega = \boldsymbol{\Omega}_R \times \boldsymbol{R}$. The round-trip birefringence vector reads

$$\boldsymbol{\beta}_R(z) = 2\boldsymbol{B}(z_0)\boldsymbol{M}\boldsymbol{W}^T(z;\, z_0)\boldsymbol{\beta}_L(z)\,, \qquad (1)$$

where $\boldsymbol{\beta}_L = (\beta_1,\, \beta_2,\, 0)^T$ is the linear component of the birefringence vector $\boldsymbol{\beta}$, while the analogous expression for the round-trip PMD vector, $\boldsymbol{\Omega}_R(z)$, is somewhat more cumbersome as it includes also the PMD contributions of $\boldsymbol{F}$ and $\boldsymbol{B}$ [1].

Assuming that $\boldsymbol{\beta}$ is linear and parallel to its ω-derivative, $\partial\boldsymbol{\beta}/\partial\omega$, Dong et al. [5] have shown that the instantaneous DGD of a fiber can be calculated from $\boldsymbol{\beta}_R$, $\boldsymbol{\Omega}_R$, $\partial\boldsymbol{\beta}_R/\partial\omega$ and $\partial\boldsymbol{\Omega}_R/\partial z$. Theoretically, the P-OTDR

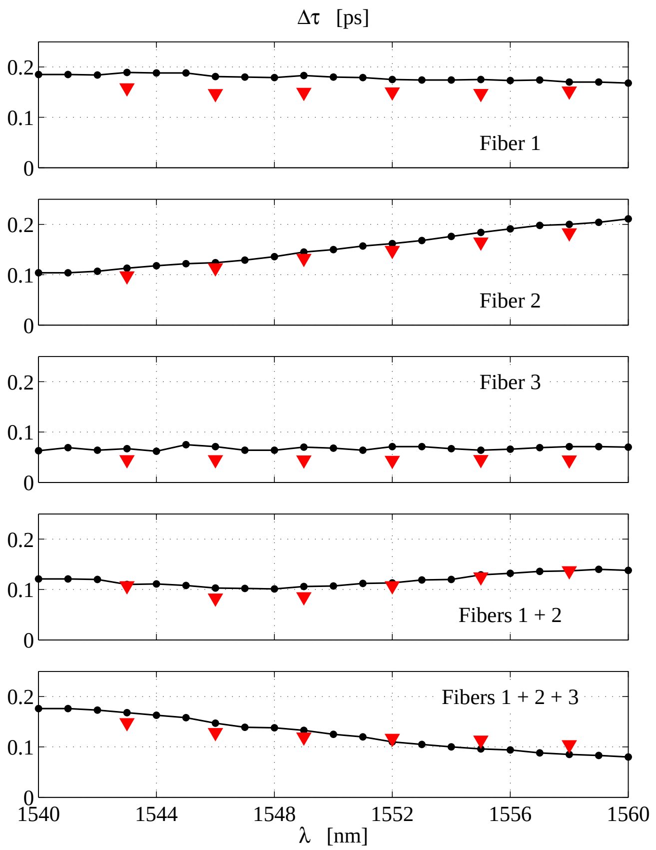

Figure 2. Instantaneous DGD as a function of wavelength for different link configurations. Continuous curves and triangles represent JME and P-OTDR measurements (method No.1, respectively.

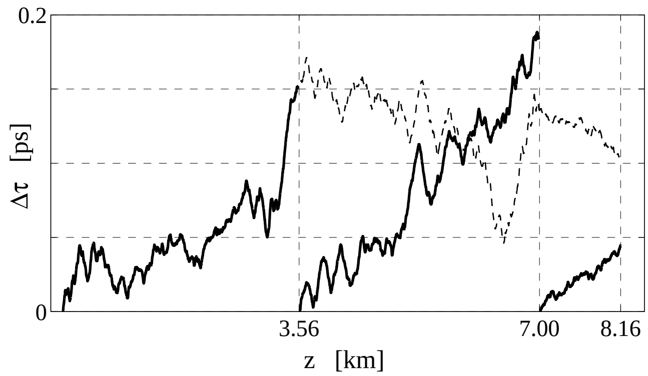

Figure 3. DGD as a function of distance. Thick continuous curves are the DGD of each fiber sample; the thin dashed curve is the DGD cumulated along the cascade of the three fiber samples.

can measure all these quantities and consequently the DGD can be calculated as a function of z. From a practical point of view, however, the calculation of $\partial\boldsymbol{\beta}_R/\partial\omega$ or $\partial\boldsymbol{\Omega}_R/\partial z$ is based on a second-order derivative on experimental data. Since P-OTDR measurements are quite noisy and the signal amplitude is very limited, this task is hardly practicable. In fact this technique has been tested in [5] only on the Fresnel reflection from the fiber far end face that is orders of magnitude larger than Rayleigh scattering. Since the solution proposed is based on the Fresnel reflection of fiber far end, [5] provides only the overall DGD, and bad sub-sections may not be located.

III. Method No. 1: instantaneous DGD measure

An alternative approach to the distributed measurement of the PMD may start by considering the PMD vector, $\bar{\Lambda}(z)$, of the propagation from z to the P-OTDR receiver (point 3 in fig. 1). This path is described by the matrix $\boldsymbol{Q}(z) = \boldsymbol{B}(z_0)\boldsymbol{M}\boldsymbol{W}^T(z;\, z_0)\boldsymbol{M}$ and the corresponding PMD vector yields ($z \geqslant z_0$)

$$\bar{\Lambda}(z) = \bar{\Lambda}(z_0) + \boldsymbol{B}(z_0)\boldsymbol{M}\boldsymbol{W}^T(z;\, z_0)\boldsymbol{\Omega}(z;\, z_0)\,. \qquad (2)$$

Note that $\boldsymbol{\Omega}(z;\, z_0)$ is the PMD vector of the forward propagation from z_0 to z. Using the well known PMD dynamical equation [6], we may find out the dependence on z of $\bar{\Lambda}(z)$ as follows

$$\frac{\partial\bar{\Lambda}}{\partial z} = \boldsymbol{B}(z_0)\boldsymbol{M}\frac{\partial\boldsymbol{\Omega}_{\rm in}}{\partial z} = \boldsymbol{B}(z_0)\boldsymbol{M}\boldsymbol{W}^T(z;\, z_0)\frac{\partial\boldsymbol{\beta}}{\partial\omega}\,, \qquad (3)$$

where we defined $\boldsymbol{\Omega}_{\rm in}(z;\, z_0) = \boldsymbol{W}^T(z;\, z_0)\boldsymbol{\Omega}(z;\, z_0)$ as the input PMD vector of the fiber section between z_0 and z.

Let us consider a typical condition of fiber with linear birefringence ($\boldsymbol{\beta} = \boldsymbol{\beta}_L$); this is not too restrictive, as non-negligible circular birefringence may be induced only by strongly twisting the fiber [7]. Furthermore, let us assume also $\partial\boldsymbol{\beta}_L/\partial\omega = \boldsymbol{\beta}_L/\omega$, [6,8]. Then, owing to (1) and (3), $\partial\boldsymbol{\Omega}_{\rm in}/\partial z$ reads

$$\frac{\partial\boldsymbol{\Omega}_{\rm in}}{\partial z} = \frac{1}{2\omega}\boldsymbol{M}\boldsymbol{B}^T(z_0)\boldsymbol{\beta}_R(z)\,. \qquad (4)$$

That expression can be readily integrated and since the instantaneous DGD, $\Delta\tau(z;\, z_0)$, of the link section between z_0 and z is equal to the modulus of $\boldsymbol{\Omega}_{\rm in}(z; z_0)$, we find the following result:

$$\Delta\tau(z_0,\, z) = \frac{1}{2\omega}\left|\int_{z_0}^{z}\boldsymbol{\beta}_R(t)\,{\rm d}t\right|\,. \qquad (5)$$

This means the the DGD of an arbitrary section of the link can be calculated basically by integrating the round-trip birefringence vector measured by the P-OTDR.

Experimental validation of (5) has been performed by measuring the DGD of a cascade of three fibers. The round-trip birefringence vector has been measured at six equally spaced wavelengths between 1543 nm and 1558 nm, using the set-up and procedures described in [9] (pulse-width 5 ns, spatial resolution 0.5 m).

The total DGD values of each fiber and of the cascades of those fibers have been measured also with the standard Jones matrix eigenanalysis (JME) [10], taking care in not moving the patch-cords connecting the fibers when in cascaded configuration.

Results are shown in fig. 2 for different configurations as indicated in the graphs. Black, continuous curves refer to the reference JME measurements, while triangles are the DGD values obtained by means of (5); the agreement is fairly good.

Note that the JME measurements were performed on each link separately as indicated on the corresponding graph, whereas the P-OTDR DGD measurements have been obtained immediately by a single measure performed on the cascade; the DGD of each fiber section has been obtained by integrating $\boldsymbol{\beta}_R(z)$ over the corresponding interval. This is the main demonstration of the

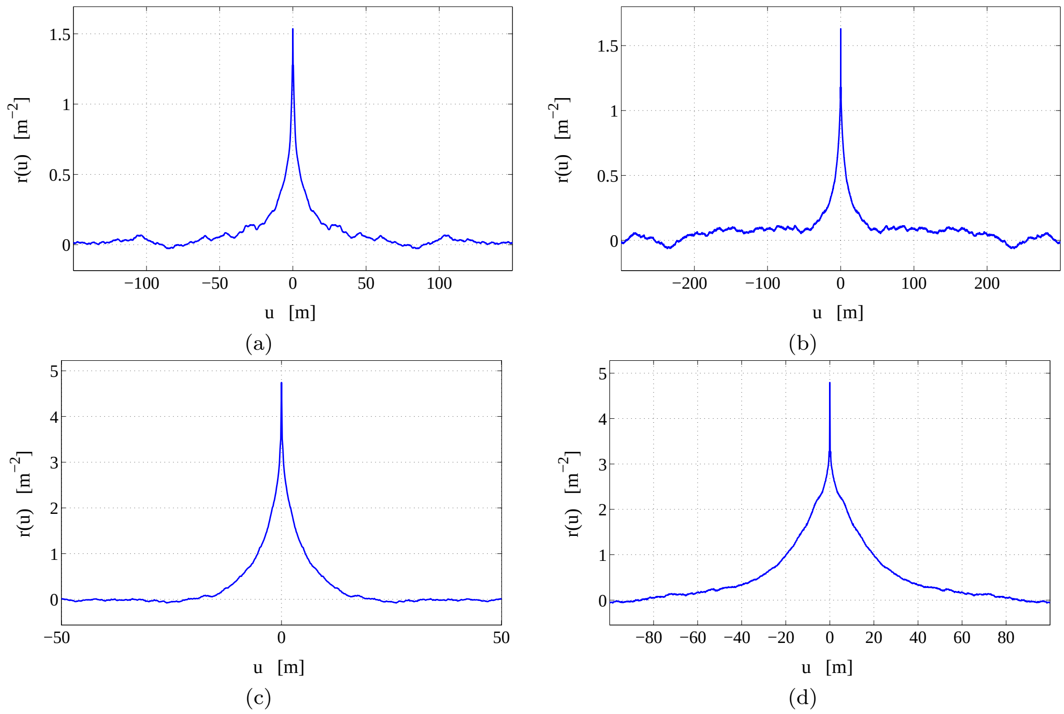

Figure 4. Ergodic estimate of ACF of the round-trip birefringence, measured on four G.652 fibers.

effectiveness of the Method No. 1 in isolating the PMD contribution of any arbitrary subsection.

Fig. 3 shows the DGD as a function of z, measured with the P-OTDR at 1558 nm. Thick continuous curves are obtained by applying (5) to subsections comprising each fiber separately; the thin dashed curve is obtained by applying (5) to the whole link (the first part of this curve is overlapped with the DGD curve of the first fiber). The figure clearly shows the ability of the method in measuring the local DGD.

IV. Method No. 2: r.m.s. DGD measure

In previous section, (5) has been calculated under two assumptions. First, the circular birefringence possibly affecting the fiber should be negligible; this assumption is well verified when the fiber is not strongly twisted, which is quite reasonable. Second, the frequency dependence of the linear birefringence should be $\partial\boldsymbol{\beta}_L/\partial\omega = \boldsymbol{\beta}_L/\omega$; indeed, this relation holds for anisotropic media and is generally considered a good approximation also for randomly birefringent fibers [8, 11].

Starting from (5), the mean square DGD can be expressed as

$$\langle \Delta\tau^2(z_0,\, z)\rangle = \frac{1}{4\omega^2}\int_{z_0}^{z}\int_{z_0}^{z}\langle \boldsymbol{\beta}_R^T(t)\boldsymbol{\beta}_R(s)\rangle\, dt\, ds\,. \qquad (6)$$

Note that the round-trip birefringence vector is uncorrelated and asymptotically stationary; furthermore, the asymptotic regime is reached on a length scale corresponding to some correlation lengths, i.e. in a few meters [12]. Consequently, $\boldsymbol{\beta}_R(z)$ can be assumed practically to be stationary, hence its auto-correlation function (ACF), $r(s-t) = \langle \boldsymbol{\beta}_R^T(t)\boldsymbol{\beta}_R(s)\rangle$, depends only on the difference $s-t$.

Exploiting this symmetry, setting $u = s - t$ and after proper integral manipulations, eq. (6) yields result for Method No. 2:

$$\langle \Delta\tau^2(\Delta z)\rangle = \frac{1}{2\omega^2}\left\{\Delta z\int_0^{\Delta z} r(u)\, du - \int_0^{\Delta z} u\, r(u)\, du\right\}\,, \qquad (7)$$

where $\Delta z = z - z_0$. According to (7) the mean square DGD of any fiber section depends only on the length of the section itself and not on its position along the fiber. This is strictly related to the stationarity of the round-trip birefringence vector, that is, in its turn, a consequence of the longitudinal uniformity of the fiber.

As the length of the fiber section increases, both integrals in (7) asymptotically tend to finite value. For this reason, the second integral tends to be negligible compared to the first term, which increases linearly with the fiber length.

Therefore, for long fiber section, i.e. large Δz, (7) can be further simplified as

$$\langle \Delta\tau^2\rangle \simeq \left\{\frac{1}{2\omega^2}\int_0^{\infty} r(u)\, du\right\}\Delta z\,. \qquad (8)$$

Finally, it is worthwhile remarking that the ACF $r(u)$ can be estimated from a single measurement of $\boldsymbol{\beta}_R(z)$, by substituting the ensemble averaging $\langle\cdot\rangle$ with the ergodic averaging in z. [12]

Validation of (7) and (8) has been performed by measuring the DGD of some fibers with a P-OTDR and comparing the results with those obtained with the standard Jones matrix eigenanalysis (JME) [10].

In this case, the round-trip birefringence vector has been measured on four G.652 fibers (each about 3.3 km long), labeled (a-d), by means of a standard P-OTDR [9]. The measurement has been performed at 1534 nm, using a 5-ns probe pulse with a peak-power of 23 dBm.

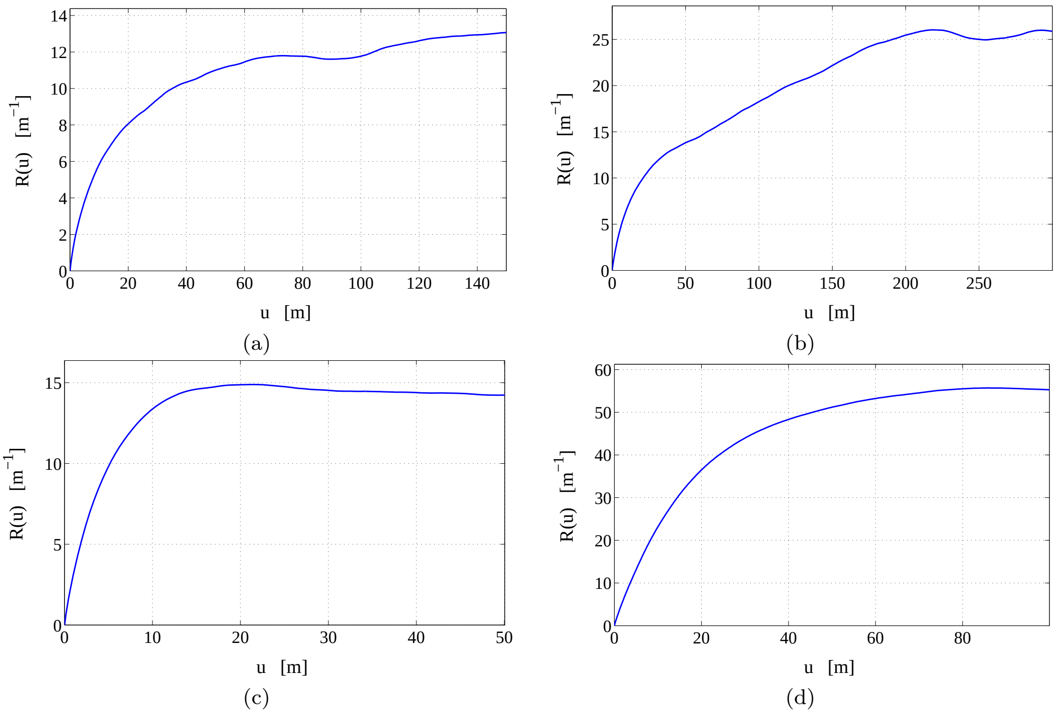

Figure 5. Plots of $R(u) = \int_0^u r(s)\,ds$ as a function of u for each of the corresponding ACF of fig. 4.

Fig. 4 shows the ACFs, $r(u)$, estimated in each fiber; note how these ACFs go to zero rather rapidly (although with different speeds related to the correlation lengths) confirming that the round-trip birefringence is asymptotically not correlated. For the same reason, the integral $R(u) = \int_0^u r(t)\,dt$, shown in fig. 5 for each fiber, approaches a constant value for large Δz. This finite asymptotic value can be used in eq. (8) to calculate the mean square DGD, once Δz is substituted with the exact fiber length. The outcome of this procedure is summarized in Tab. 1.

The same table also shows the root mean square (r.m.s.) DGD measured by standard JME technique. In this case, firstly the instantaneous DGD has been measured in the range 1490–1600 nm, in steps of 1 nm; then, the r.m.s. DGD has been calculated averaging the square of the instantaneous values.

The last column of Tab. 1 shows the uncertainty of JME measurements, according to the expression [13]

$$\sigma \simeq 0.9\sqrt{\frac{\langle\Delta\tau\rangle}{\Delta\omega}}\,, \tag{9}$$

where $\Delta\omega$ is the frequency range over which the instantaneous DGD has been averaged.

Comparison of results summarized in Tab. 1 also confirms that Method No. 2 is fairly accurate and provides values in agreement with the JME.

Fiber	r.m.s. DGD [ps]		σ [ps]
	P-OTDR	JME	
(a)	0.12	0.12	0.03
(b)	0.17	0.19	0.04
(c)	0.13	0.16	0.04
(d)	0.25	0.31	0.06

Table 1. r.m.s. DGD values measured by means of P-OTDR exploiting (8) and by means of JME; σ is the uncertainty of JME measurements according to (9).

V. Conclusions

In this paper two reflectometric methods, based on P-OTDR scheme, for the measurement of the instantaneous DGD and the root mean square DGD have been proposed and analyzed. Their main advantage is the possibility of characterizing a specific subsection of a fiber or of a fiber link by performing a single-end measurements and exploiting a fixed-wavelength (or a few wavelengths) optical source. Furthermore, the mean square DGD estimation is based on an ergodic average, which may be potentially more robust and accurate than the wavelength average, commonly performed, especially for very limited DGD values. [14]

The technique is based on the assumption that the fiber is longitudinally uniform. Indeed, for long fiber links that can be considered a cascade of homogeneous fiber sections, the two methods can be successfully applied on each of the homogeneous subsection of the link, allowing an easy determination of the worst ones.

The theoretical analysis has been supported by preliminary experimental results, which seems to confirm the viability of the technique.

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