Polarization Mode Dispersion Mapping in Optical Fibers With a Polarization-OTDR

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***Abstract*—We describe a technique for the measurement of the polarization mode dispersion distribution along an optical fiber link based on a polarization optical time-domain reflectometer technique setup. This technique does not require the complete measurement of the polarization state of the backscattered signal. We report results performed on different types of fibers: standard step index, dispersion shifted, and dispersion compensating fibers.**

***Index Terms*—Beat length, coupling length, distributed measurement, polarization mode dispersion (PMD), polarization optical time-domain reflectometer based technique (POTDR).**

I. INTRODUCTION

POLARIZATION mode dispersion (PMD) has now become the most serious limiting factor in high-speed optical communication systems. The PMD of a fiber depends on two parameters: the beat length (L_B) and the coupling length (L_C) [1]. The beat length depends on the mean birefringence of the fiber and the coupling length is related to the phenomena of polarization mode coupling. Measuring the spatial distribution of PMD therefore consists of measuring the distribution of both beat and coupling lengths.

There exist several measurement techniques of PMD, but they only allow for measuring the global value and do not give information about the distribution of PMD along the fiber length. Measuring the spatial distribution of PMD is, however, important; such a measurement would indeed allow to locate the bad trunks in an optical link, causing high PMD value. Moreover, it can be essential in the frame of a network upgrade.

Some polarization optical time-domain reflectometer based technique (POTDR) have been developed for PMD characterization. Most of them [2], [3] allow for measuring the distribution of the beat length along an optical link and, therefore, do not allow for a determination of the distributed PMD. However, Sunnerud *et al.* presented a POTDR-based setup enabling the measurement of the accumulation of PMD along the fiber [4]. A technique based on the measurement of the degree of polarization has also been presented in [6]. This technique does not allow quantification of the PMD, but enables detection of the fibers' trunks with high PMD. More recently, Galtarossa *et al.* described another technique for the PMD measurement for which the coupling length is determined from the correlation of the birefringence vector [5] that requires the measurement of the polarization states of the backscattered signal. In this letter, we present a new POTDR technique which allows a mapping of the PMD along an optical fiber link by quantifying the PMD on each fiber of the link. The main advantage of the technique we have developed is that it does not require the complete measurement of the backscattered polarization state evolution and only uses a linear polarizer at the fiber input, which is quite simple to implement. The determination of the PMD is based on the analysis of the statistical properties of the POTDR trace.

II. FIBER MODELING

In general, an optical fiber with axially varying birefringence can be represented by a series of concatenated homogeneous elements, each characterized by a Jones matrix [3]. Moreover, we suppose that the fiber only exhibits linear birefringence as it is usually accepted in telecommunications [2]. The Jones matrix of the ith element depends on δ_i, the local birefringence, defined as the phase delay between the two local eigenmodes, and on q_i, the angle between the fast axis and the arbitrary Ox axis.

The birefringence δ_i is characterized by a Rayleigh statistical distribution [2], [3] along the fiber length, and we assume that the rate of change of the birefringence angle q_i is described by a Gaussian distribution as in [7], with zero mean and standard deviation (σ), depending on the polarization mode coupling strength.

III. PRINCIPLE OF MEASUREMENT

A. Measurement of the Beat Length L_B

The beat length of the fiber is related to the birefringence by $L_B = 2\pi/\langle\delta_i\rangle$, where $\langle\delta_i\rangle$ is the mean value of the birefringence along the fiber length. Our calculation of the beat length is based on the measurement of the number N of maximums of the POTDR trace. Fig. 1 presents the number n of maximums by unit of length ($n = N/L$, where L is the fiber length) in function of the beat length for different values of σ. This figure shows that n varies not only with L_B but also with the strength of the polarization mode coupling. In order to estimate L_B from n, the curve corresponding to $\sigma = 10$ (the dashed curve in Fig. 1) is used, which minimizes the maximum possible error if we assume that σ is smaller than 15°/m (which corresponds to a coupling length bigger than 14.6 m; see Relation 3). This leads to the following relationship between the estimated L_B and N:

$$L_B = \frac{1}{c_1}\left(\frac{2L}{N} - c_2\right) \tag{1}$$

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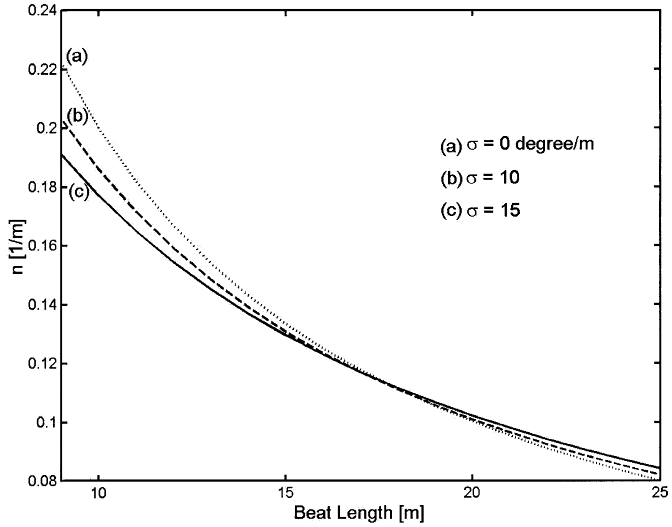

Fig. 1. Number n of maximums of the POTDR trace by unit of length versus L_B for different values of σ.

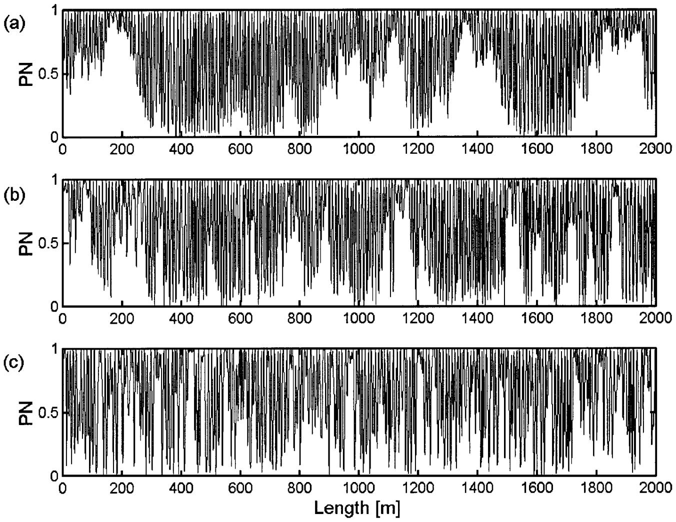

Fig. 2. Simulated POTDR traces with σ = (a) 2, (b) 4, and (c) 8 degrees/m. It appears that the lower envelope of the curves varies in a smoother way when σ decreases.

where c_1 and c_2 have been found to be equal to 0.91 and 1.65, respectively.

B. Measurement of the Coupling Length L_C

L_C characterizes the rate of change of the polarization eigenmodes along the fiber length and is defined by [6]

$$\frac{1}{L}\int_0^L \boldsymbol{\beta}(z)\boldsymbol{\beta}(z+v)\,dz = \langle\delta_i\rangle^2 e^{-2(|v|/L_C)} \tag{2}$$

where $\boldsymbol{\beta}$ is the birefringence vector. From (2), a relationship between L_C and σ can be derived similarly to that of [7]

$$L_C = \frac{1}{\sigma^2}. \tag{3}$$

A statistical approach, explained hereafter, has been used for determining the coupling length from the POTDR trace. Fig. 2(a)–(c) shows different simulated normalized POTDR (PN) traces, obtained for a beat length of 25 m and for different values of σ: 2, 4, and 8°/m, respectively. One can observe that the lower envelop of the curves varies in a smoother way when σ decreases and, therefore, when L_C increases.

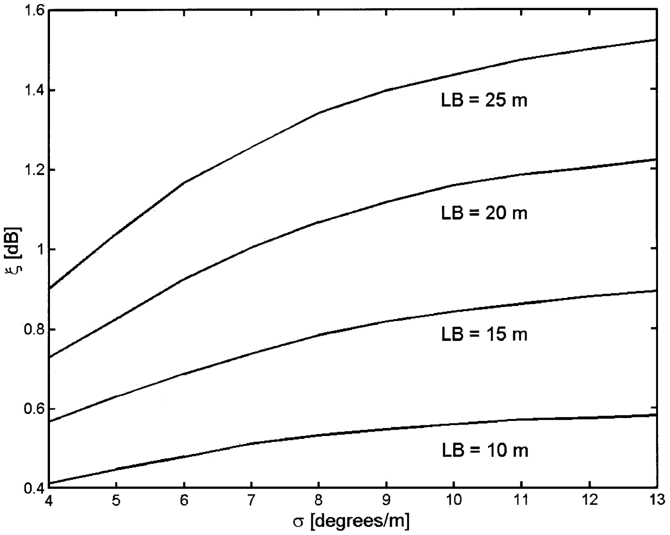

Fig. 3. ξ versus σ for different values of the beat length L_B. It clearly appears that ξ increases with σ and, therefore, when the coupling length L_C decreases.

Let us define ΔP_i as the absolute value of the difference in ordinate between two successive minimums of the POTDR trace P

$$\Delta P_i = |P(z_i) - P(z_{i+1})| \tag{4}$$

where z_i and z_{i+1} correspond to the distances of the ith and the $i+1$th minimums, respectively.

Let us now define a new parameter ξ calculated as

$$\xi = \langle \Delta P_i \rangle_i \tag{5}$$

where $\langle \bullet \rangle_i$ is the mean value for i varying from 1 to the number of minimums of the POTDR trace. ξ is a measure of the speed variation of the lower envelope of the backscattered signal along the fiber length. With regards to the observation made for Fig. 2, one can expect that ξ will increase with σ. Fig. 4 shows the evolution of ξ according to σ for different values of the beat length L_B, and it indeed appears that ξ increases with σ as expected. This figure has been obtained by simulations taking into account the characteristics of the measurement setup, i.e., the finite extinction ratios of the modulators (see Fig. 4) and the time jitter introduced by the electronic equipment. These curves were found to be independent on the angle of the input polarizer of the POTDR.

The value of ξ in the case of a Hi–Bi fiber (δ is a constant and $\sigma = 0$) can be easily calculated. The normalized backscattered power becomes

$$PN(z) = \tfrac{1}{2}\left(2 - k\sin^2 \delta z\right) \tag{6}$$

where k is a constant depending on the birefringence angle and the direction of the input polarizer (see setup in Fig. 4). Hence, the value of $PN(z)$ at its minimums z_m is a constant along the fiber length $PN(z_m) = (1/2)(2-k)$ and ξ is, therefore, equal to zero.

Then, the procedure for the determination of L_C is the following. From the POTDR trace, the number N of maximums and each ΔPi are measured. The beat length is then computed

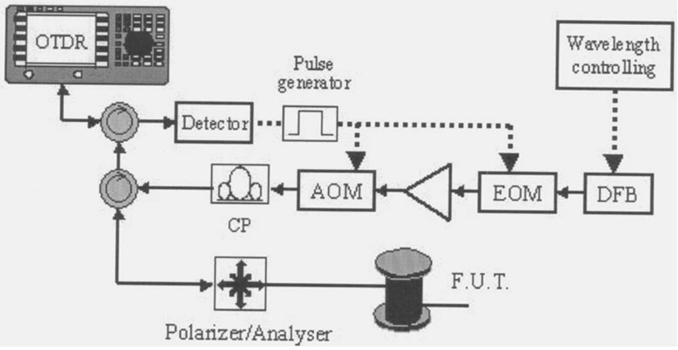

Fig. 4. Experimental setup. The coherence noise due to the high coherence of the source is reduced by varying the wavelength on a range of 1 nm.

by means of relation (1) and ξ is calculated using (5). Finally, σ can be deduced from ξ by using the curve of Fig. 3 corresponding to the beat length and L_C is calculated by means of relation (3).

C. Calculation of the PMD

From the measurement of the beat length and the coupling length explained in the previous sections, it is easy to determine the PMD value by [1]

$$PMD^2 = \frac{1}{2}\left(\frac{\lambda}{cL_B}\right)^2 L_C^2 \left(\frac{2L}{L_C} - 1 + e^{-(2L/L_C)}\right) \quad (7)$$

where c is the light velocity in a vacuum and λ the measurement wavelength.

IV. EXPERIMENTAL SETUP AND RESULTS

The measurement setup is shown in Fig. 4. The OTDR pulses (10 ns) externally modulate a 1553-nm distributed-feedback laser via a pulse generator and an electrooptic modulator (EOM). The coherence noise due to the high coherence of the source is reduced by varying the wavelength on a range of 1 nm during the measurement of a POTDR trace; the measured curve is therefore a mean of the POTDR traces on the wavelength range. After amplification, the pulses are launched into the fiber through an acoustooptic modulator (AOM), which suppresses the amplified spontaneous emission noise of the erbium-doped fiber amplifier between two successive pulses. The linear polarizer is placed at the fiber input and a polarization controller is used to obtain the maximum power after the polarizer.

The technique described in the previous sections has been applied to two concatenations of two fibers, as well as to a concatenation of three fibers. We used different fiber types: step index, dispersion-shifted, and dispersion compensating fibers. All of them were spooled on drums which had a diameter of 200 mm. After a POTDR measurement, the contributions on the POTDR trace corresponding to the different fibers of the optical link are processed independently. For each fibers of the concatenation, the beat length, the coupling length, and then the PMD are derived by analyzing the maximums and minimums distributions of the backscattered signal as explained previously.

TABLE I
RESULTS AND COMPARAISON WITH THE INTERFEROMETRIC TECHNIQUE

Link	**Fiber**	**L_B (m)**	**L_C (m)**	**L (m)**	**PMD_c (ps)**	**PMD_m (ps)**
1	DSF	24.6	137.8	6074	0.191	0.196
	DSF	15.9	62.1	2611	0.131	0.158
2	SI	24.3	39.9	2470	0.067	0.067
	DCF	8.3	86.8	7305	0.495	0.464
3	SI	22.5	45.8	2245	0.074	0.064
	DSF	16.5	40.5	2246	0.093	0.125
	SI	14.6	40.7	2676	0.117	0.125

The results are presented in Table I. PMD_c is the calculated PMD obtained from the measurement of L_B and L_C, and by means of relation (7). PMD_m is the value obtained by a previous measurement using the interferometric technique. One can notice that a good agreement is observed between both PMD values. Several measurements have also been done on the same fiber after moving it between the measurements and with different angles of the input polarizer. We noticed a good reproducibility of the calculated PMD.

V. CONCLUSION

In this letter, we described a new POTDR trace analysis which enables the computation of the PMD mapping along an optical fiber link. The main advantage of this technique is that it does not require the complete measurement of the backscattered polarization states, and only uses a linear polarizer which is quite easy to implement. The results obtained on concatenations of different types of fibers show a good agreement between the PMD values obtained by our technique and the PMD values measured by the interferometric technique.

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