

**Determination of the polarization coupling length in telecom fibers
exploiting the nonlinear polarization rotation**

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ABSTRACT

The polarization coupling length, an important parameter of the PMD probability distribution, is obtained from measurements and modeling of the nonlinear polarization rotation in optical fibers. Results for different types of fibers are presented.

IEEE INDEXING KEYWORDS

Optical Kerr effect, Optical fiber measurements, Nonlinear optics

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INTRODUCTION

It is well known that single-mode communication fibers are birefringent and that the orientation and the amount of birefringence is randomly distributed along the fibers. The corresponding polarization mode dispersion (PMD) becomes therefore a statistical quantity, and not only its mean value but also its probability distribution is important to assess the inferred system impairments. This distribution depends on two parameters: on the (mean) local birefringence B and on the coupling length h , which is the length over which the E field loses memory of its initial distribution between the local polarization eigenstates [1]. In fibers having a length L long compared to h , the probability distribution is Maxwellian with a mean PMD value of B , whereas for coupling lengths approaching the fiber lengths, the PMD statistics change considerably. In this paper we present a novel way to directly infer the polarization coupling length from measurements of the nonlinear polarization rotation (NPR) of the fiber.

We demonstrate too that NPR is present non only in polarization maintaining fibers [2] but even in standard single mode fibers. The resulting nonlinear change in the light's state of polarization (dependent on both the channel power and the coupling length) can affect, on long transmission links, the performances of polarization demultiplexing schemes and of first order PMD compensation.

PRINCIPLE OF OPERATION

In a dielectric medium, an intense elliptical input pulse induces birefringence – via the optical Kerr effect - due to the different amounts of intensity along the major and minor axis of the polarization ellipse. In an isotropic medium this self-induced birefringence leads to polarization ellipse self-rotation. In an optical fiber however, the situation is more complex due to the presence of the local intrinsic birefringence. The polarization changes are hard to predict in that case as the linear and nonlinear birefringences interact in a complicated manner. In general, the linear birefringence will however be much larger than the nonlinear one, and the evolution of the polarization vector ψ in a polarization maintaining fiber can then be approximated by [2]:

$$\partial_z \psi \approx i\omega B_{\text{eff}} \sigma_\theta \psi \quad (1)$$

where σ_θ accounts for the linear birefringence with axis θ . The linear birefringence B is replaced by an effective birefringence B_{eff} accounting for the nonlinear birefringence. The solution for Eq.1 is straightforward, and corresponds to a rotation of the input polarization vector around the linear birefringence axis σ_θ , with a rotation angle β given by

$$\beta = \omega B_{\text{eff}} z = \omega \left(B - \frac{\alpha}{2} m_\theta(0) \right) z \quad (2)$$

where $\alpha = n_2 P / (3cA_{\text{eff}})$, n_2 is the nonlinear Kerr coefficient, P the power, and A_{eff} the effective area. $m_\theta(z)$ is defined as the projection of the input SOP on the birefringent axis at the position z along the fiber. In principle the NPR can now be measured by varying the input power P and observing the corresponding change in the output SOP.

However, an inherent problem for this kind of measurements is the stability of the output SOP at the exit of the fiber, subjected to fluctuations of the much larger linear birefringence B due to temperature changes and drafts in the fiber environment. We have recently proposed a method for measuring the NPR [2] by removing the overall linear birefringence -and therefore also its fluctuations- in a purely passive way by employing a Faraday mirror (FM) [3] and a double pass of the fiber under test. Doing so, the nonlinear birefringence (leading to NPR) was shown to remain unaffected, i.e. the NPR of the forward and backward paths add up [2]. In this way we can measure NPR both in polarization maintaining (PM) fibers and in standard fibers. However, the random variations of the intrinsic local birefringence existent in a standard fiber reduce the NPR. The situation becomes more complex, and we therefore resort to numerical simulations. The fiber is modeled as a concatenation of linearly birefringent trunks with a physical length L_C kept constant. Concerning the birefringence, its strength is fixed and the orientation is allowed to vary driven by a white noise process $g_\theta(z)$ characterized by a dispersion σ_θ [1]. For each single trunk, Eq.2 is used to calculate the output SOP from the input one, with the input SOP calculated from the output SOP of the previous trunk. The SOP can therefore be calculated piece by piece, with the

projection m_θ being different for each new trunk. The final SOP will depend on the choice of the birefringence axis orientations, with variations being larger for large values of L_C . We therefore made 200 runs for each specific coupling length to get a mean value of the NPR.

EXPERIMENT

The experimental setup for the measurement of the NPR for the different test fibers is shown in Fig.1. The light source consists of a distributed feedback laser (DFB) operated in pulsed mode at a wavelength of 1559 nm. Typically, pulses with a duration of 30 ns, a repetition rate of 1 kHz, and a peak power of up to 6 W (after amplification by an EDFA) are used. The light is then launched into the fiber under test (FUT) via a 90/10 coupler and a polarization controller (PC1). The coupler is inserted for the detection of the backward traveling light after the double pass of the FUT, with its 90% output port connected to the source in order to maintain high launch powers into the FUT. The polarization controller, PC1, allows to adjust the polarization of the light launched into the FUT, i.e. m_θ which is important for the strength of the NPR as demonstrated by Eq.2. Note that for low launch powers (negligible NPR), the action of PC1 is removed by the Faraday mirror, and its setting is therefore of no importance in that case. The output SOP is examined by an analyzer consisting of a polarization controller

PC2 and a polarizing beam splitter (PBS). To achieve a good sensitivity of the analyzer, it is calibrated for equal power in the two PBS output arms for low power launch signals where no NPR occurs. The two PBS output channels were monitored by a fast photodiode (200 ps response time) and a sampling scope. The measurements were then performed in the following way: for a given launch power, the polarization launched into the FUT was adjusted (PC1) to give the smallest possible output power at the monitored PBS channel. Consequently, the difference between the two PBS output channels is maximized, corresponding to a maximum value of the NPR.

RESULTS AND DISCUSSION

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We first measured the NPR in a PM fiber with a length of 200 m. The results shown in [2] indicate that the effect of NPR is negligibly small up to about 0.5 W. For higher launch powers, NPR manifests itself with a reduction of the power in the monitored PBS channel. In fact, its action becomes so strong that for launch powers above about 2.5 W, the output power starts actually to decrease in spite of the linear increase that would be experienced in the absence of NPR. The measured data agree well with our model, in which $m_\theta(0)$ was varied in order to give a minimum output power from the PBS channel like in the experiment, and only one fiber trunk was used ($L_C = \text{fiber length } L$).

Numerical results for different values of L_C (keeping fixed the total fiber length) show that NPR is reduced for a larger number of couplings resulting in a more and more linear dependence of the output from the input power. This reduction is due to the increased probability that the NPR action in one trunk is compensated for by another. These theoretical predictions were then compared to measurements made on different standard fibers (see Tab.1). The fiber lengths were typically 1 km (simulations were adjusted accordingly to each fiber length and n_2/A_{eff} coefficient). Fig.2 shows the results for 3 standard fibers with large (fiber B) and small PMD (fiber A,C), respectively. The three standard fibers clearly exhibit a different amount of NPR. The fitting of the experimental data is made with two free different parameters; the length of each single trunk of fiber L_C and the dispersion σ_θ . Different combinations of their values can fit the same experimental data but in accordance with the definition of coupling length if the model is consistent the product $\sigma_\theta^2 L/L_C$ has to remain constant. This is shown to be the case for our data as shown in the inset of Fig. 2. Here L_C is varying between 5 and 200 m and σ_θ between 10 and 70 degrees.

The coupling length h defined as the length at which the fiber autocorrelation function $\langle \cos[\theta(z) - \theta(0)] \rangle$ is equal to $1/e$, can be shown to be equal to $2/\sigma_\theta^2$. For the case in which each piece of fiber has a fixed length L_C , it's easy to show that $h = 2L_C/\sigma_\theta^2$. The simulations show that for the three different fibers the coupling length can be estimated to be about 160 m for the fiber A and 350 m for the large PMD fiber (fiber B). The coupling length of $h \sim 1000$ m for the third 'standard' fiber

(fiber C) is quite large, indicating that there might be well defined birefringent axes in that fiber.

The large values we found for the coupling lengths appear to be remarkably high, so we have successively made a different estimation for the coupling length of the same fibers, from PMD and beat length measurements using an Optical Frequency Domain Reflectometer (OFDR) [4]. The values we found in this way are of the order of tens of meters (see Tab.1) except for fiber C that even with this method presents a coupling length of the order of the entire fiber length.

This difference in the estimated coupling length between the two methods is quite surprising so we tested the validity of our model in two ways. One, as mentioned before, consisted in fitting the experimental data using different combinations of the single trunk of fiber L_C and the dispersion σ_θ (keeping the product $\sigma_\theta^2 L/L_C$ constant). The inset of Fig.2 shows the consistency of the model.

The other test consisted in demonstrating that the NPR will add even in the presence of a discontinuity in the linear birefringence (i.e. the fiber is a concatenation of two PM fibers spliced together, with a coupling angle different from zero) as is the case of our model. To prove this we considered two PM fibers connected together with a varying coupling angle θ . Depending on the value of θ , the amount of rotation will change (maximum when $\theta = 0$, i.e. fiber aligned). The experimental data are in good agreement with the theoretical ones [5].

From these tests it is not clear at this moment why the values of h we obtained with the nonlinear method are much higher compared with the ones calculated using the OFDR. We clearly showed that the h does play a major role in determining the strength of the NLR, although maybe it is not the only one.

CONCLUSION

Measurements and a model of NPR in optical fibers were presented, allowing for direct determination of the polarization mode coupling length. Coupling length values of several 100 m were obtained for large PMD fibers, whereas it was as low as 160 m in state-of-the-art low PMD fibers. Despite the demonstrated consistency of the model, a high discrepancy is present between the h values measured with the OFDR method and the nonlinear one.

One SMF fiber (fiber C) presented an unusually extremely high coupling length in accordance with both the measurements methods.

The presence of significant NPR in SMF fibers, even in the ones with short coupling lengths as measured from the OFDR method, can constitute a serious problem in particular for first order PMD compensation or polarization demultiplexing schemes.

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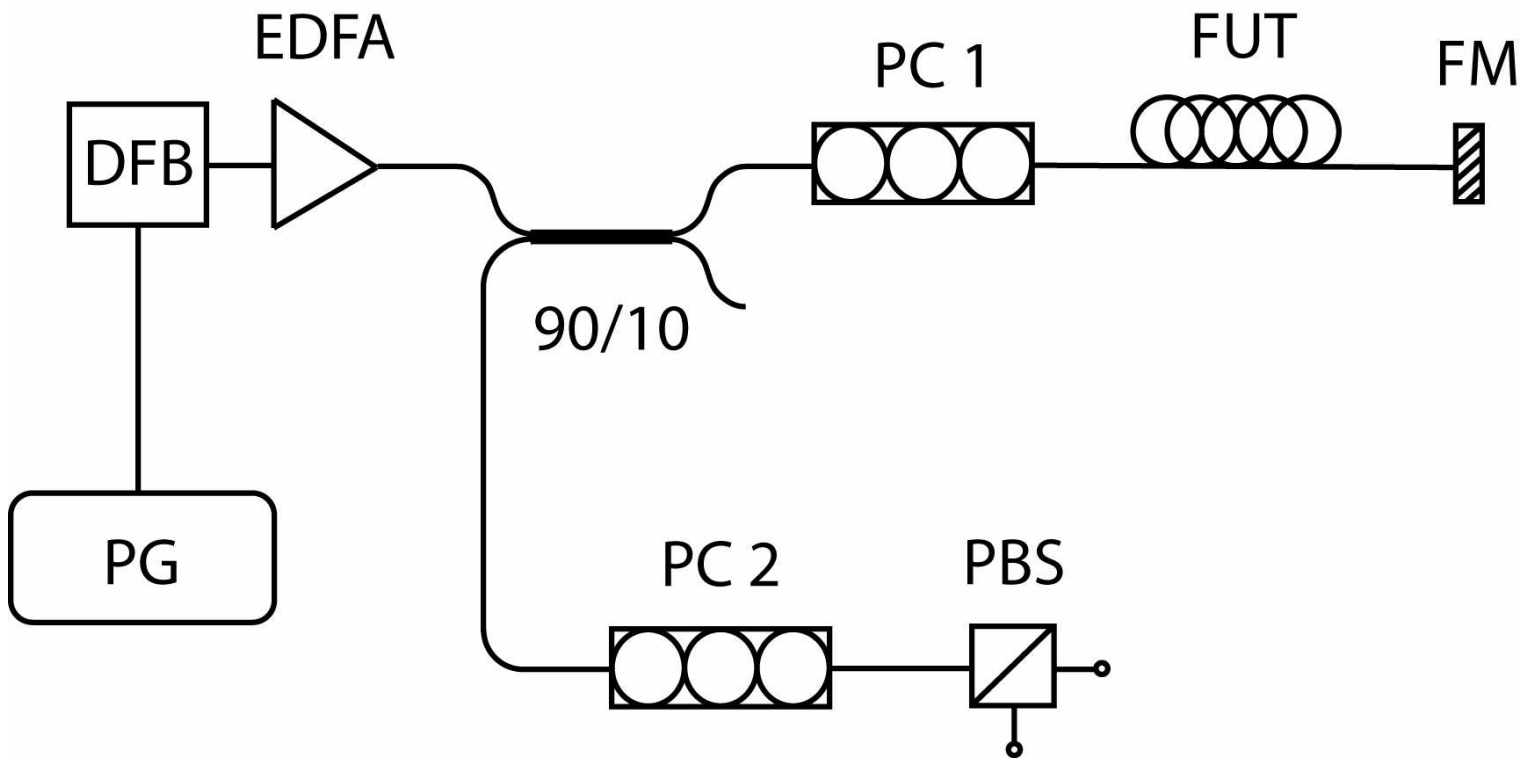
CAPTIONS

Fig. 1 Experimental setup of the NPR measurements. PG pulse generator, DFB distributed feedback laser, EDFA Erbium doped fiber amplifier, PC polarization controller, FUT fiber under test, FM Faraday mirror, PBS polarizing beam splitter

Fig. 2 Minimum output power of PBS channel 1 as a function of the launched power for fibers A (open circles), B (full circles), and C (full squares). Symbols: measured data. Solid curve: prediction from our model. Dashed bold line: prediction in the absence of any NPR. Bold curve: PM fiber. The inset shows the values of the calculated h for different $\square\square$ and LC combinations giving curves that fit the experimental data for fibers A and B.

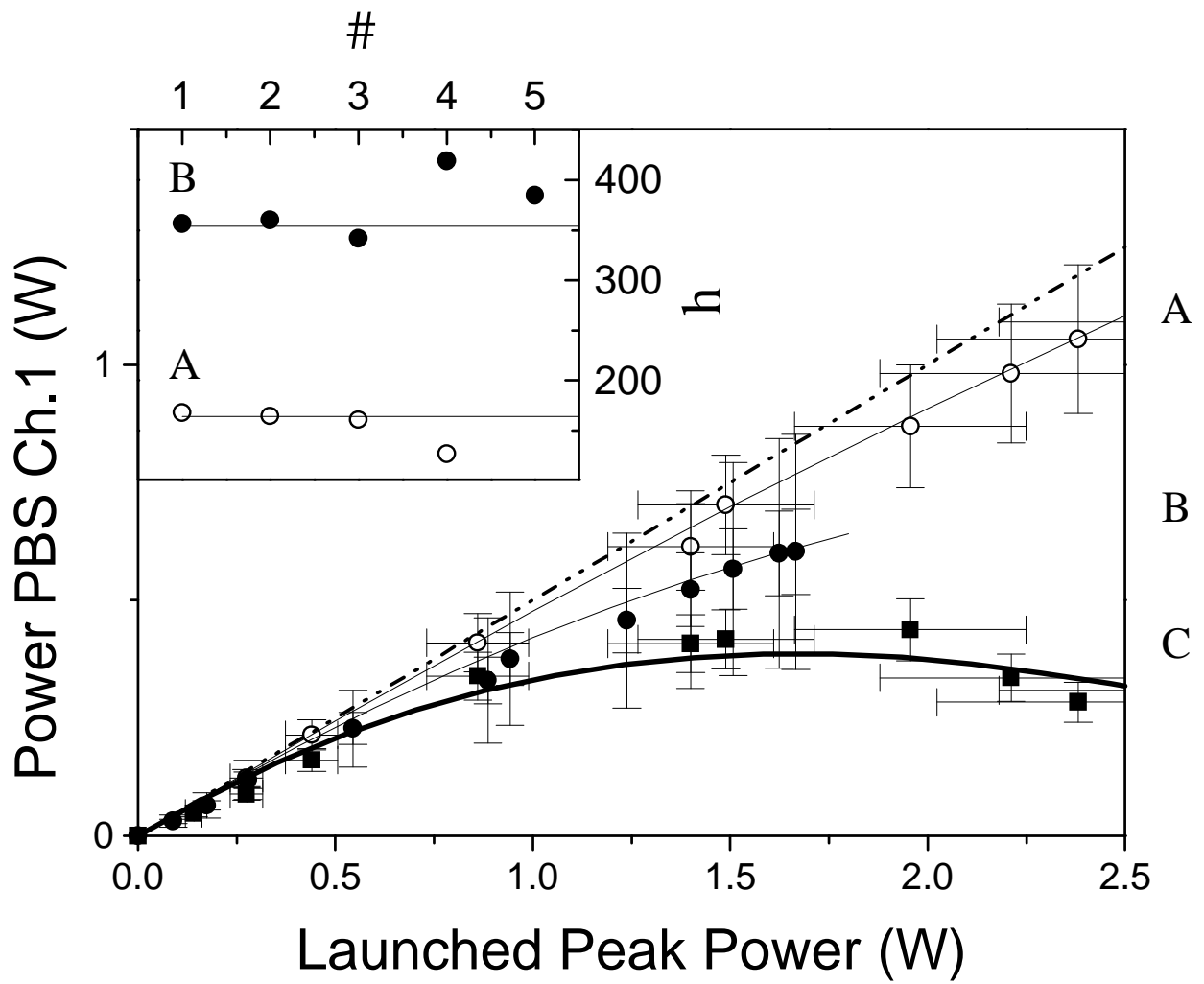
Tab. 1 Parameters for the different fibers: total length, PMD, and beat length L_b . In the last two columns is reported the coupling length as derived from the measured beat length L_b and PMD, and the one estimated through the nonlinear polarization rotation.

FIGURE 1



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FIGURE 2



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TABLE 1

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Fiber	Length (km)	PMD (ps/$\sqrt{\text{km}}$)	L_b (m)	h [OFDR] (m)	h [nonlinear] (m)
A	1.5	0.05	12	15	160
B	1.0	1.9	.5	47	350
B*	1.0	0.05	20	43	350
C	1.0	0.14	30	Fiber length	Fiber length