Measurement of the Polarization Coupling Length in Telecom Fibers using 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.

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1. 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 giving the distance after which a considerable amount of power has coupled into the other polarization mode. In fibers having a length L long compared to h, the probability distribution is Maxwellian with a mean PMD value of $B\sqrt{hL}$, whereas for coupling lengths approaching the fiber lengths, the PMD statistics can 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.

2. Theory

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 [1]:

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

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

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

where $\alpha = n_2P/(3cA_{eff})$, n_2 is the nonlinear Kerr coefficient, P the power, and A_{eff} the effective area. $m_\theta(0)$ is the projection of the input SOP on the birefringent axis. 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 NPR [1] by removing the overall linear birefringence -and therefore also its fluctuations- in a purely passive way by employing a Faraday mirror (FM) 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 path add up.

This allows to measure NPR both in polarization maintaining (PM) fibers and in standard fibers. However, the random variations of the intrinsic local birefringence axis 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 h kept constant and a random birefringence axis orientation. For each of these trunks, 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 coupling lengths h. We therefore made 100 runs for each specific coupling length to get a mean value of the NPR.

3. Experiment

The experimental setup for the measurement of NPR for 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. $m_\theta(0)$, 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.

4. Results

We first measured the NPR in a PM fiber with a length of 200 m. The results are shown in Fig.2. As can be seen, NPR starts to be important for launch powers above 1 W. In spite of the linear increase that would be experienced in the absence of NPR (straight line), the output power actually starts to decrease for input powers above 2.5 W. The measured data (squares) agree well with our model (solid curve), 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 (coupling length h = fiber length L).

In Fig.3, numerical results for different coupling lengths (indicated on the right) for a fiber length of 1.5 km are given. 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 because of the increased probability that the NPR action in one trunk is compensated for by another. As the figure demonstrates, the results for the different coupling lengths can be clearly distinguished.

These theoretical predictions were then compared to measurements of different standard fibers. The fiber lengths were typically 1 to 1.5 km (of course the simulations were adjusted accordingly). Fig.4 shows the results for 2 standard fibers with large and small PMD, respectively. Note that for a clearer distinction of the curves, the figure gives the strength of NPR, i.e. the reduction of the output power from the value without NPR. As expected, the two standard fibers exhibit a NPR that is much lower than for a PM fiber. But the amount of NPR for the two standard fibers is distinctively different as well. From comparison of the experimental results with the simulations, the coupling lengths can be estimated to about 75 m for the small PMD and 625 m for the large PMD fiber, respectively. A value of $h<100$ m is quite reasonable for a state-of-the-art, low PMD fiber. The coupling length of $h\sim600$ m for the high PMD 'standard' fiber is large, but its high PMD value of 1.9 ps/√km could indeed indicate that there might be well defined birefringent axes in that fiber. Moreover, a different estimation for the coupling length of these fibers from PMD and beat length measurements using Optical Frequency Domain Reflectometry [2] is in good qualitative agreement with the results presented here.

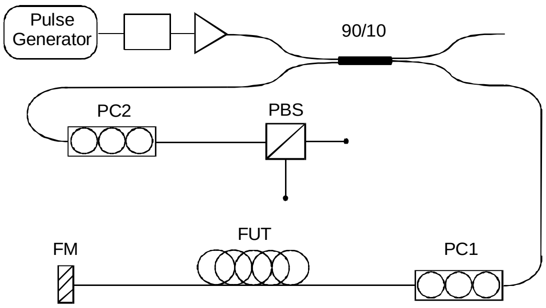
5. Conclusions

Measurements and a model of NPR in an optical fiber 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 75 m in state-of-the-art low PMD fibers.

5. References

[1] C. Vinegoni, M. Wegmuller, B. Huttner, and N. Gisin “Measurement of nonlinear polarization rotation in a highly birefringent optical fiber using a Faraday mirror”, J. Opt. A **2**, 314-318 (2000).

[2] M. Wegmuller, J.P. von der Weid , P. Oberson, and N. Gisin “High resolution fiber distributed measurements with Coherent OFDR”, ECOC 2000, paper 11.3.4



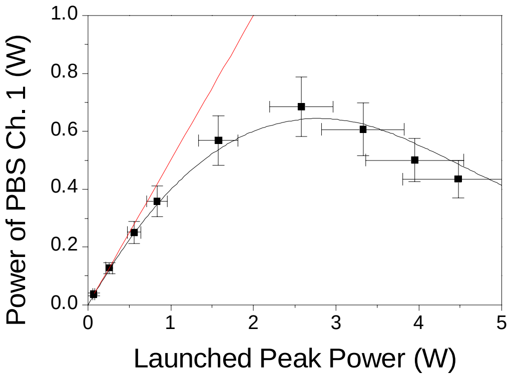
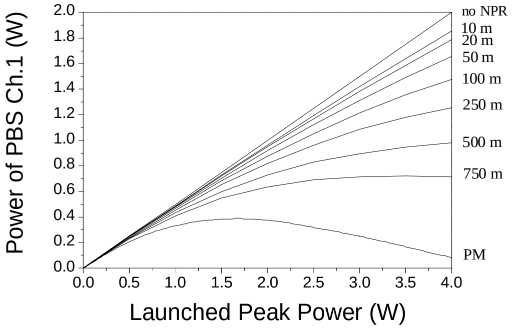


Fig. 1. Experimental setup.
Fig. 2. Minimum output power of PBS channel 1 for a 200 m long PM fiber



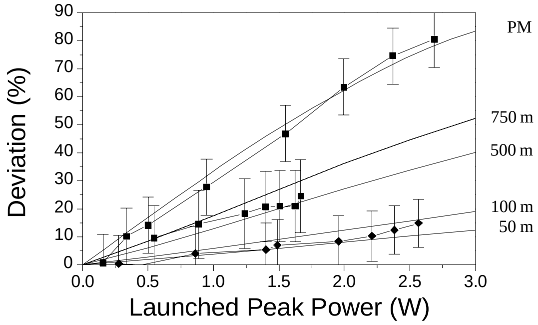


Fig. 3. Numerical results for a fiber length of 1.5 km with different polarization mode coupling lengths h.
Fig. 4. Experimental and numerical results of NPR strength in different fibers.