Estimation of the Polarization Coupling Length in Standard Telecom Fibers from Measurements of Nonlinear Polarization Rotation

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Abstract:

An analytical solution for the influence and strength of nonlinear polarization rotation (NPR) in an optical fiber is presented. It agrees well with our measurements of NPR in a polarization maintaining fiber, made possible by removing the much larger, fluctuating linear birefringence with a Faraday mirror. The same technique is then employed to measure NPR in standard fibers, where its dependence on the polarization mode coupling length can be exploited to get a direct estimate for this important fiber parameter.

INTRODUCTION

The potential of NPR to build ultrafast devices has been recognized a long time ago and received considerable attention since then. It has been proposed to exploit it for optical switches, logic gates, multiplexers, intensity discriminators, nonlinear filters, or pulse shapers. An inherent problem to all this applications is the stability of the output state of polarization (SOP), generally subjected to fluctuations of the linear birefringence caused by temperature changes and drafts in the fiber environment. We recently proposed a method [1] for removing the overall linear birefringence, and therefore also its fluctuations, in a passive way by employing a Faraday mirror (FM) [2] and a double pass of the fiber under test. It was also demonstrated that the nonlinear birefringence, leading to NPR, remains 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 axes in a standard fiber reduce the NPR. This reduction depends on the polarization mode coupling length h, and can be intuitively understood by examining the extreme case of a fiber with a coupling length close to zero. All orientations of the SOP with respect to the local birefringence axes will be encountered with equal probability, and as the sense of rotation of the NPR depends on exactly this parameter [1], it averages out to zero. Consequently, it should be possible to derive information about the coupling length from the amount of NPR reduction.

The paper is organized as follows: First, the analytical model developed in [1], valid for PM fibers, is reviewed and generalized for standard fibers. We then present results for NPR measurements in a PM and 2 different standard fibers, and compare them with the simulations to obtain information about the coupling length h.

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. It is well known that in isotropic media, this self-induced birefringence leads to a rotation of the polarization ellipse while propagating in the medium. In an optical fiber however, the situation becomes more complicated as there is also the local intrinsic birefringence to be considered. Generally, the polarization ellipse changes are hard to predict in that case as the linear and nonlinear birefringence interact in a complicated manner. Starting from the nonlinear Schroedinger equation written in the form as given by Menyuk and assuming that the linear birefringence is much larger than the nonlinear one, it is possible to show that the evolution of the polarization vector ψ is given 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 amount of linear birefringence B is replaced by an effective birefringence B_{eff}, which includes the action of the nonlinear birefringence. The solution for Eq.1 is straightforward, $\psi_z = \exp(i\omega B_{eff} \sigma_\theta z)\psi_0$, and corresponds to a rotation of the input polarization vector around the linear birefringence axis $\sigma_{\theta,}$ with a rotation angle β given by

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

where $\alpha = n_2 P/(3cA_{eff})$, 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, the contribution of the nonlinear term is negligibly small compared to the linear one, and the slightest change in B will completely cover the NPR. A way out of this problem is to make a double pass of the fiber under test by means of a Faraday mirror. The linear birefringence accumulated during the forward path is thereby automatically removed on the return path. The nonlinear birefringence on the other hand does not cancel out but adds up [1]. This is because after reflection at the FM, which transforms the SOP to its orthogonal counterpart, the sense of rotation of the NPR remains the same as during the forward path.

As mentioned before, the situation is more complex in a standard fiber, and the NPR depends on the polarization mode coupling length h. To calculate the NPR for this case, we therefore resort to numerical simulations. The fiber is modeled as a concatenation of linearly birefringent trunks with length h and random birefringence axis orientation. For each of these trunks, Eq.1 still holds as for typical standard fibers (beatlength of less than 100 m), the linear birefringence is still much larger than the nonlinear one. The SOP can therefore be calculated piece by piece, with the projection m_θ being different for each new trunk. The final SOP will obviously depend on the choice of the (random) 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.

EXPERIMENT

The experimental setup 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. The polarization controller, PC1, allows to adjust the polarization of the light launched into the FUT, 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

First, a PM fiber with a length of 200 m was measured. The results are shown in Fig.2. One can see that for this fiber NPR starts to be important for launch powers above 1 W, and that 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) are then compared to the calculated values (solid curve) using Eq.1, where $m_\theta(0)$ was varied in order to give a minimum output power from the PBS channel like in the experiment. As Fig.2 shows, the agreement between measurement and model is good.

The same type of measurement was then performed for different standard fibers and compared to the corresponding simulations. The fiber lengths were typically 1 to 1.5 km, so that a large number of couplings is obtained, allowing for comparison with the mean simulation values. An example of the numerical results for a fiber length of 1.5 km is shown in Fig.3. One can see that the mean output power becomes indeed larger for smaller coupling lengths, indicating a reduced NPR.

Fig.4 shows the results for 2 standard fibers with large and small PMD. Note that for ease of comparison, 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 an NPR that is much lower than for a PM fiber (note that the results for the PM fiber had to be rescaled to account for its different length and n_2/A_{eff} parameters). However, the amount of NPR for the two standard fibers is also distinctively different. From comparison of the experimental results with the numerically obtained data (lines), the coupling lengths can be estimated to about 75 m for the small PMD and 625 m for the large PMD fiber. A value of $h<100$ m is quite reasonable for a good (i.e. low PMD) standard 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/$\sqrt{\text{km}}$ 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 [3] is in good qualitative agreement with the results presented here.

CONCLUSIONS

A model and measurements of NPR in optical fibers were presented. As the amount of NPR depends on the polarization mode coupling length, we were able to retrieve this important fiber parameter by comparing the measured and numerical data.

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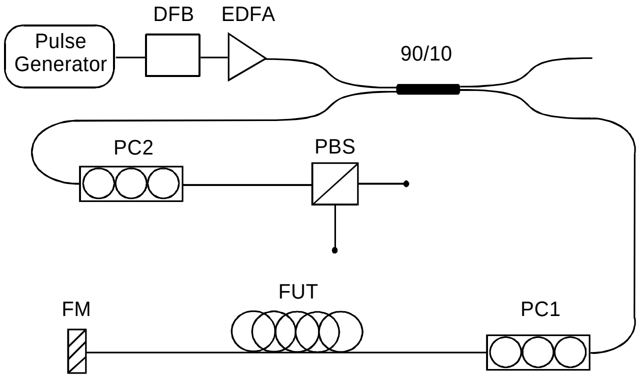

Figure 1: Experimental setup

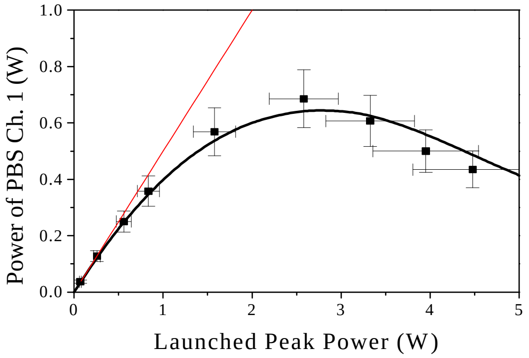

Figure 2: Minimum output power of PBS channel 1 for a 200 m long PM fiber

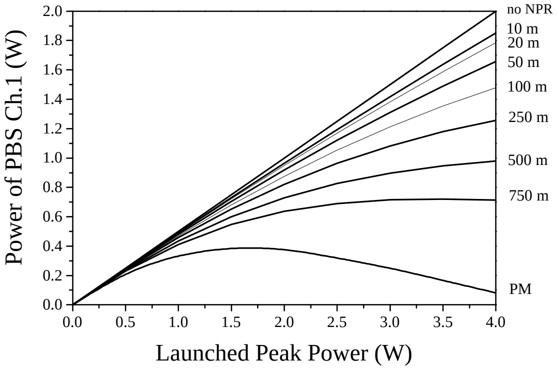

Figure 3: Numerical results for a fiber length of 1.5 km with different polarization mode coupling lengths h

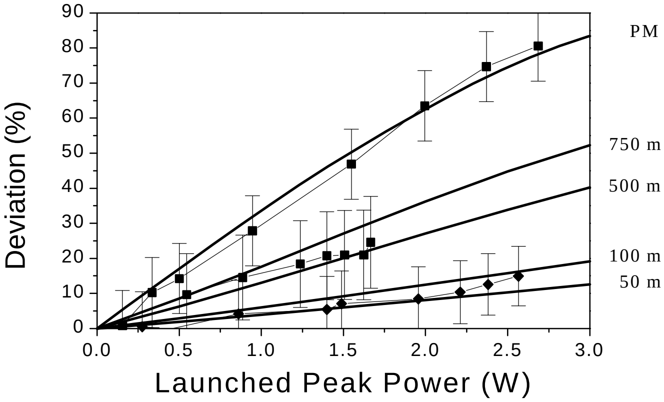

Figure 4: Experimental and numerical results of NPR strength in different fibers