International Journal of Scientific Research in Science and Technology
Available online at : www.ijsrst.com
Print ISSN: 2395-6011 | Online ISSN: 2395-602X
doi : https://doi.org/10.32628/IJSRST52411187

Study of Non-Linear Polarization Rotation and Optical Switching in Optical Fibers

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ARTICLEINFO

Article History:
Accepted: 15 Jan 2024
Published: 30 Jan 2024

Publication Issue :
Volume 11, Issue 1
January-February-2024

Page Number :
395-403

ABSTRACT

In this paper, we present both a theoretical and experimental analysis of the nonlinear polarization rotation in an optical fiber. Starting from the coupled non-linear Schr¨odinger equations an analytical solution for the evolution of the state of polarization, valid for fibers with large linear birefringence and quasi cw input light with arbitrary polarization, is given.

Keywords : Optical Fiber, Polarization, Switching.

I. INTRODUCTION

The potential of nonlinear polarization rotation (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 [1-6], logic gates [7], multiplexers [8], intensity discriminators [9], nonlinear filters [10], or pulse shapers [11]. However, an inherent problem to all these applications is the stability of the output state of polarization, generally subjected to fluctuations of the linear birefringence caused by temperature changes and perturbations in the fiber environment. Of course, the same problem was also encountered in the few experiments dealing with the characterization and measurement of the NPR itself. In Ref. [12], the fluctuations of the output polarization were too strong to allow meaningful measurement of NPR in a polarization-maintaining fiber at 1064 nm, and in Ref. [13], where 514 nm light was injected into a 60m long fiber with a beat length of 1.6 cm, a complicated arrangement had to be employed for the extraction of the changes caused by temperature drifts. As the fluctuations become worse for fibers with a large birefringence, and as the effect of NPR is proportional to the inverse of the wavelength, it is hard to measure NPR directly in a polarization-maintaining (PM) fiber at the telecom wavelength of 1.55μm. In this work, we propose a method for removing the overall linear birefringence, and therefore also its fluctuations, in a passive way by employing a Faraday mirror [14] (FM) and a double pass of the fiber under test.

II. THEORETICAL BACKGROUND

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 [15-18, 19] (the effect is consequently often called polarization ellipse self-rotation and its representation on the Poincare sphere is shown in Fig. 1.1(a). Measuring this ellipse rotation is one of the standard ways to evaluate the cubic optic nonlinearity of the medium [20-24]. 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. To formulate this more precisely, we start with the coupled non-linear Schr¨odinger equations describing the propagation of light in an optical fiber.

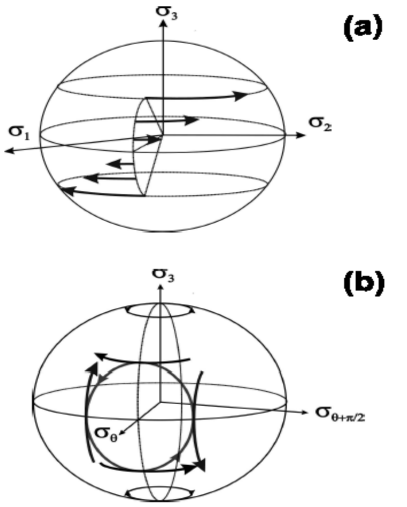

Figure 1.: Evolution of the state of polarization as represented on the Poincare sphere. (a) Polarization ellipse self-rotation in an isotropic medium. The Stokes vector rotates around the s^3 axis with an angle proportional to the length of the medium, the input intensity, and the sin of the input ellipticity. (b) High birefringence fiber. The rotation of the Stokes vector mainly consists of a fast rotation around the axis of linear birefringence sq, whereas the slow rotations due to the nonlinear birefringence can be considered as small perturbations.

For cw input light, time derivatives drop out, and we can write the equation in a form similar to that of Menyuk [25,40] when assuming a lossless, linearly birefringent fiber and by neglecting polarization mode coupling:

$$\partial_z \psi = -i\left(\omega B \sigma_\theta + \omega\alpha < \sigma_3 >_\psi \sigma_3\right)\psi;\; B \gg \alpha \quad (1.1)$$

$\psi = (E_1, E_2)^t$ is the Jones column vector representing the two components of the complex transverse electric fields $E_1(z)$ and $E_2(z)$ at position z along the fiber. The first term on the right-hand side describes the linear birefringence, where ω is the optical frequency and B the birefringence (in s/m). Note that B is assumed to be independt of ω, an excellent approximation fostandard fibers. The phase birefringence ωB is muiplied by $\sigma_\theta = \sigma_1 \cos(\theta) + \sigma_2 \sin(\theta)$, corresponding to linear birefringence in the θ direction, with $\sigma_{1,2,3}$ being the 2x2 Pauli matrices. The second term on the righthad side of Eq. (11) accounts for the nonlinear birefringence, with and $\alpha = \frac{n_2 P}{3cA_{eff}}$, and $<\sigma_3>\psi_z = \frac{|E_1|^2-|E_2|^2}{|E_1|^2+|E_2|^2}$.P is the total light power, n^2 the nonlinear refractive index, A_{eff} the effective mode area, and c the speed of light.

For an intuitive understanding of the action of the two terms on the right-hand side of Eq. (1.1), it is better to revert to the Stokes formalism. On the Poincare Sphere, the first term describes a rotation of the polarization vector (Stokes vector) around axis σ_θ, lying on the equator and corresponding to linear birefringence. Similarly, the second term is a rotation around the vertical axis corresponding to nonlinear birefringence. However, Eq. (1.1) shows that the speed and the rotation direction in this case depend on the polarization state through $< \sigma 3 >\psi$, as is illustrated in Fig. 1.1(b). Consequently, the two rotations are linked in a complicated manner, and the resulting evolution of the polarization vector is not obvious.

Fortunately, in standard telecom fibers, the speed of rotation around the vertical axis is much smaller than the one around the birefringent axis σ_θ even at considerable power levels. This is because in such fibers $B >> \alpha$ (see Eq. (1.1)). For example, a fiber with a beat length of 10 m has B≈ 0.5 $\pi\sigma$/km while $\alpha \approx 0.006$ ps/km for a power of 10 Watts (l=1550 nm, $n_2=3.2\cdot10{-}20$, $A_{eff}=60\ \mu m2$) (note that in this work, a PM fiber will be used with a beat length in the mm range, making the ratio B/α as large as 10^7). The slow rotation due to the nonlinear birefringence can therefore be treated as a perturbation that merely changes the angular frequency of the fast rotation caused by the linear birefringence. This becomes more obvious by rewriting Eq. (1.1) as

$$\sigma_2\psi = -i\omega B\sigma_\theta - i\omega\alpha\frac{1}{2}(<\sigma_3>)_\psi\,\sigma_3 + (1 - \sigma_\theta + \frac{\pi}{2} >_\psi \sigma_\theta + \frac{\pi}{2} - \ (<\sigma_\theta>)_\psi\,\sigma_3))_\psi \quad (1.2)$$

where the identity $\psi = <\sigma>_\psi \sigma\psi$, valid for all ψ, has been used. The term proportional to y affects only the global phase and can be neglected. Further, the two terms $<\sigma_3>_\psi \sigma_3$ and $<\sigma_{\theta+\pi/2}>_\psi \sigma_{\theta+\pi/2}$ cancel each other to first order - this can be intuitively understood from Fig. 1.1(b) and was confirmed by numerical simulations – producing only a small (second order) precession of the instantaneous rotation axis. Hence, we obtain the following approximation for the evolution of the polarization vector:

$$\sigma_2\psi = -\omega B_{eff}\,\sigma_\theta\psi \quad (1.3)$$

with the effective birefringence

$$B_{eff} = B - \frac{\alpha}{2} < \sigma_\theta >_\psi \quad (1.4)$$

depending on the intensity and the polarization state of the input light signal. Note that Eq. (1.3) preserves the square norm $|\psi|^2$ reflecting that we did not take into account losses. Note further that when applying Eq. (1.3) for linearly polarized input light we obtain the same formula as in Ref. [9].

The solution of Eq. (1.3) is straightforward, $\psi_z = exp(-\iota\omega B_{eff}\,\sigma_\theta z)\psi_0$, and corresponds to a rotation of the input polarization vector around the linear birefringence axis σ_θ, with a rotation angle β given by

$$\beta = \omega\left(B - \frac{\alpha}{2}m_\theta(0)\right)z. \quad (1.5)$$

$m_\theta(0)$ is the projection of the input polarization vector on the birefringence axis σ_θ, and z *is* the distance from the input end. In principle, the NPR, caused by the nonlinear response of the single-mode fiber to the input state, could now be measured by varying the input power and observing the corresponding change in the output polarization vector. However, from a practical standpoint, this will be hardly possible as Eq. (1.5) shows that the slightest changes in the linear birefringence B will completely cover the nonlinear, intensity-dependent ones (remember that $B>>\alpha$ for reasonable input power levels). Indeed, earlier work [26- 35] greatly suffered from temperature and pressure-induced changes of B always present in a lab environment, even though they were using short fibers.

Nowadays, a simple and efficient way to get rid of any kind of fluctuations in the intrinsic birefringence is to make a double pass of the fiber under test using a Faraday mirror [36-40] (FM). The linear birefringence accumulated during the forward path is then automatically compensated on the return path. However, it is not a priori clear what will happen to the nonlinear birefringence. To investigate this point, we rewrite the solution of Eq. (1.3) in the Stokes formalism

$$m(L) = \ \hat{R}_\theta(\beta(L))_m(0) \quad (1.6)$$

where m(0) is the input Stokes vector, $\hat{R}_\theta$is a rotation operator around the axis σ_θ, and β is as given by Eq. (1.5). Applying the action of the FM, $m^F(L) = -m(L)$ (the suffix F indicates the state of polarization after reflection from the FM), and of the return path, $\hat{R}_\theta^{-1}$, we get

$$m^F(2L) - \hat{R}_\theta^{-1}[\omega L(B - \frac{\alpha}{2} m_\theta^F(L)]\hat{R}_\theta[\omega L\left(B - \frac{\alpha}{2} m_\theta(0)\right] m(0) = \hat{R}_\theta[\omega\alpha(m_\theta(0))]m(0) \quad (1.7)$$

The result shows that the rotation due to the nonlinear birefringence of the forward and return path does not cancel out but adds, giving twice the angle compared to a single (forward) trip through the fiber (Eq. (1.5)). This is because the rotation direction of the nonlinear birefringence is different for the upper and lower hemisphere of the Poincare sphere (see Fig. 1.1(b)) contrary to birefringence in linear optics. Therefore, after reflection at the FM, which transforms the polarization state to its orthogonal counterpart (i.e. flipping it to the other hemisphere), the sense of rotation of the NPR during the return path will be the same as the forward path and the effects add up.

III. EXPERIMENTAL SET-UP

The experimental setup used to measure the NPR is shown in Fig. 2. The light source is a distributed feedback laser diode (DFB) operated in pulsed mode at a wavelength of 1559 nm, consecutively amplified by an EDFA (small signal gain 40dB, saturated output power 23dBm). Typically, pulses with a duration of 30 ns, a repetition rate of 1 kHz, and a peak power of up to 6W were used.

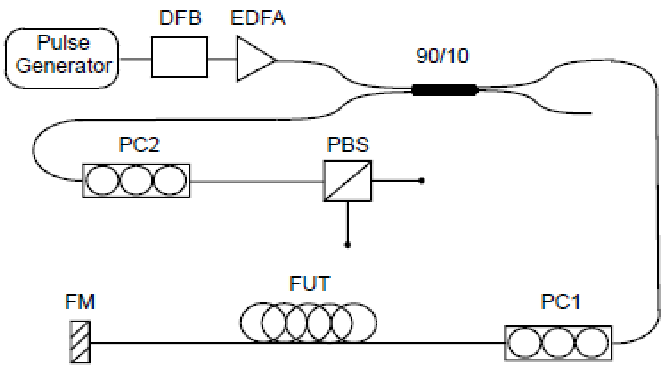

Figure 2.: Experimental setup of the NPR measurement. DFB distributed feedback laser, EDFA Erbium-doped fiber amplifier, PC polarization controller, FUT fiber under test, FM Faraday mirror, PBS polarizing beam splitter The light is then launched into the test fiber via a 90/10 coupler and a polarization controller. The coupler was inserted for the detection of the backward traveling light after the double pass of the test fiber, with its 90-output port connected to the source to maintain the high launch powers into the test fiber. The polarization controller, PC1, allowed to adjustment of the polarization of the light launched into the test fiber, which is important for the strength of the NPR as demonstrated by Eq. (1.5). To satisfy the assumption of neglectable polarization mode coupling used in the previous section, a highly birefringent, polarization maintaining (PM) fiber was used as the test fiber. Its linear birefringence *B* is of the order of 5 ps/m, corresponding to a beat length in the mm range. The fiber length was 200 m, giving a total of 400 m round-trip length of the light reflected by the FM. The polarization state of the light after the double pass of the test fiber was 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 was calibrated to give a 50/50 output of the PBS for low-power

signals where no nonlinear polarization rotation occurs. Finally, 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 controller PC1 was adjusted 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.

IV. RESULTS

The experimental results are shown in Figures 3 and 4. In Fig. 3, the minimum output power (squares) of the monitored PBS channel is given as a function of the peak power in the test fiber. Note that the reported output power was normalized to account for the analyzer losses and corrected for the PBS extinction ratio. Consequently, without any NPR, the reported output power would equal half of the power in the test fiber (solid line). As can be seen in Fig. 3, the effect of NPR is negligibly small up to about 0.5 W. For higher launch powers, NPR manifests itself by a reduction of the power in the monitored PBS channel. Its action becomes so strong that for launch powers above about 2.5 W, the output power starts actually to decrease despite the linear increase that would be experienced in the absence of NPR. In principle, this power drop should continue until the nonlinear rotation of the input polarization is such that all the power is in the other PBS channel. However, as Fig. 3 shows, this is not happening. The observed increase in the minimum output power could be related to modulation instability a phenomenon in which a CW signal becomes amplitude and phase-modulated as a result of the interplay between the nonlinearity and the dispersion of the medium (this effect manifests itself with the appearance of two sidebands one shifted up in frequency and the other shifted down by the same amount): above 4.5 W launch power, a Stokes and Anti- Stokes sideband shifted by 2 nm concerning the laser peak appeared. These sidebands are generated in a distributed fashion along the test fiber, which means that the compensation of the linear fiber birefringence is failing. Therefore, and due to the large birefringence B of the PM fiber used, the sidebands will be almost randomly polarized at the output.

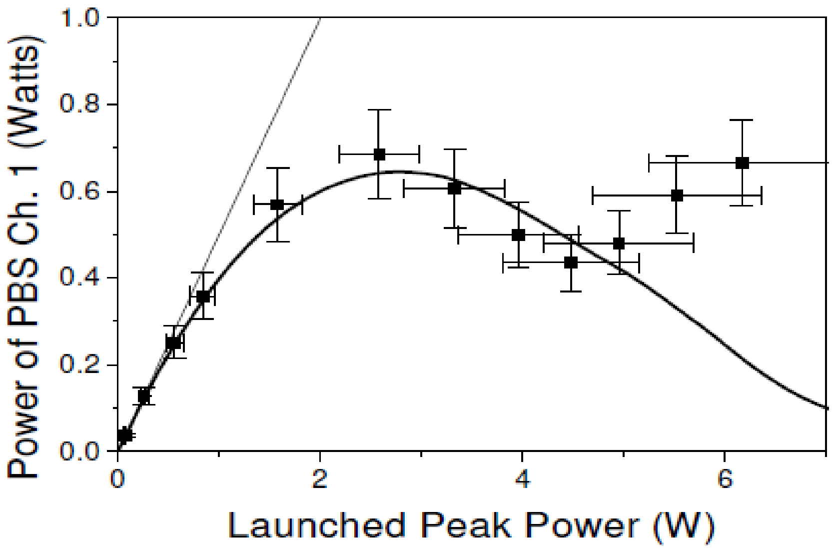

Figure 3.: Minimum output power of PBS channel 1 as a function of the launched power for a 200 m long PM fiber. Squares: measured data, solid curve: prediction from our model, straight line: prediction in the absence of

NPR. The deviations of the experimental data from the predicted values at high powers are due to modulation instability not included in the model.

Further, the measured results were compared to the ones predicted by Eq. (1.7) taking into account the analyzer calibration and the adjustment of PC1 as used in the experiment. The parameters used in the computation were the ones from the experiment, i.e. a fiber length of L=200 m, and a nonlinear coefficient of n_2 =3.4·10–20 m^2/W. The effective core area of A_{eff} = 41 μm^2 was chosen to give a good match with the experimental results as we had no exact value from the manufacturer. $m_1(0)$, the projection of the input state of polarization on the birefringent axis, was varied to give a minimum output power from the PBS channel, exactly like in the experiment.

The solid line in Fig. 3. shows these computed results. The figure clearly illustrates that the measured data corresponds very well to the computed one. This validates our measurement method of NPR in optical fibers and demonstrates that the linear birefringence and its detrimental fluctuations are successfully removed by the FM. Above an input power of 4.5 W, the curves deviate as expected from the onset of MI which was not included in the analytical model.

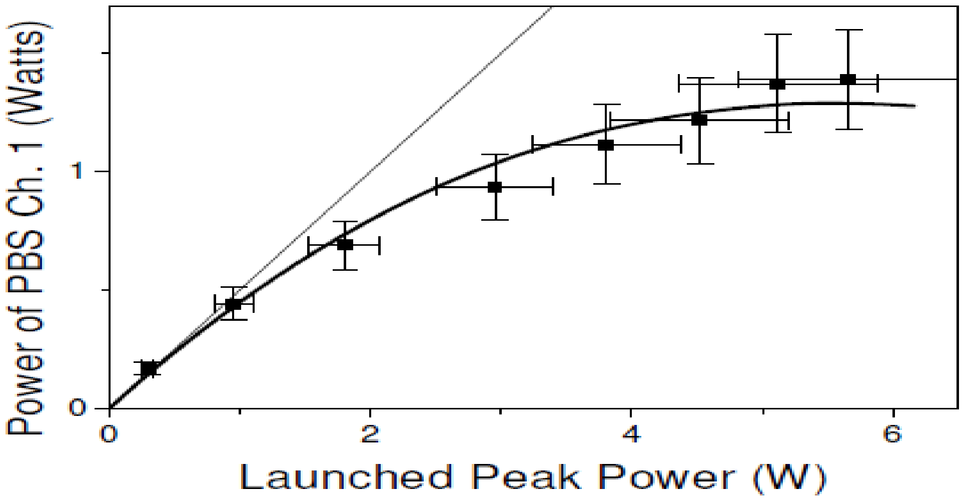

Figure 4.: Minimum output power of PBS channel 1 as a function of the launched power for a 100 m long PM fiber. Squares: measured data, solid curve: prediction from our model, straight line: prediction in the absence of NPR.

Fig. 4 shows experimental and computed results for a fiber length of 100 m. Note that to avoid cutting our 200 m piece, we emulated the 100 m fiber length by introducing a 20dB attenuation for the reflected light. Consequently, the light power on the return trip is too low to induce NPR and serves only to compensate for the linear birefringence of the forward trip. As the figure demonstrates, NPR is indeed reduced by a factor of 2 compared to the measurements without an attenuator, as expected from Eq. (1.7). Twice the launch power is required to compensate for the shortened length to get the same amount of NPR. Again, experimental and computed data are in excellent agreement. The experimental results of this section demonstrate that one can indeed use an FM to remove the overall linear birefringence, which allows observing the smallest nonlinear effects otherwise hidden within the noisy linear birefringence. Note that the change in the output polarization due to environmental perturbations is especially pronounced in PM fibers (when the input is not aligned with one of the two fiber axes) due to its short beat length in the mm range. For example, when not using an FM, the output polarization changed drastically from just the body heat when approaching the PM fiber spool, inhibiting any meaningful measurement.

V. CONCLUSION

Starting from the non-linear Schr¨odinger equations, an analytical solution for the evolution of the state of polarization in a high birefringence optical fiber has been developed. It allows for a simple modeling of go and return paths as e.g. in interferometers with standard or Faraday mirrors. Using this model, we showed that it is possible to remove the overall linear birefringence in a double-pass arrangement with an FM while leaving at the same time the nonlinear birefringence, resulting in NPR, unchanged. Only this allowed to measure the NPR in a long PM fiber at telecom wavelength in a lab environment where it is otherwise hidden by the changes in the output polarization caused by temperature and pressure fluctuations.

The experimental results for the NPR obtained with a 200 m long PM fiber at a wavelength of 1.55 μm were in excellent agreement with the theoretical predictions from our model for launch power up to 4.5 W. Above that value deviations due to modulation instability, not included in our model, were present.

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Cite this Article

Dr. Reena Kumari, Dr. K. B. Singh, Prof. (Dr.) Mahesh Chandra Mishra, "Study of Non-Linear Polarization Rotation and Optical Switching in Optical Fibers", International Journal of Scientific Research in Science and Technology (IJSRST), Online ISSN : 2395-602X, Print ISSN : 2395-6011, Volume 11 Issue 2, pp. 395-403, March-April 2024.
Journal URL : https://ijsrst.com/IJSRST52411197