Chapter #

Measurements of the nonlinear coefficient n_2/A_{eff} using a self-aligned interferometer and a Faraday mirror

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Abstract A simple, all-fiber implementable method for the measurement of the nonlinear coefficient n_2/A_{eff} in telecom fibers at 1550 nm is demonstrated. The method is based on the interferometric detection of the Kerr phase shift acquired by a laser pulse along the fiber under test. The detection is made by an all-fiber self-aligned interferometer incorporating a Faraday mirror. The self alignment characteristic allows for an easy and quick initial adjustment of the interferometer and leads to a good robustness as the two interferometer arms are always automatically matched.The Faraday mirror, whose property is that it transforms any input polarization state to the orthogonal one upon reflection, completely removes any polarization transformation of the fiber under test. In the same way, any fluctuations of the polarization state due to environmental perturbations (temperature, pressure changes) are removed. The polarization state re-entering the self-aligned interferometer on the backwards path is therefore fixed, so that it can be adjusted once-for-all for maximum visibility at its output. The presence of the Faraday mirror makes the setup robust, leading to a good accuracy in the n_2/A_{eff} value. Moreover, the fiber under test can be easily replaced without necessitating any further readjustment of the interferometer. The proposed scheme is therefore well suited to routinely measure the nonlinear coefficient.

1. INTRODUCTION

The implementation of Erbium-doped fiber amplifiers and chromatic dispersion compensation allows for long distance data transmission. Along with the technique of wavelength division multiplexing (WDM), this leads to an important amount of power inside the fiber over long distances, and optical nonlinearities start to play a significant role. Their magnitudes depend on the ratio n_2/A_{eff}, where n_2 is the nonlinear refractive index of the fiber and A_{eff} the effective area of the lightmode. There are different methods to measure n_2/A_{eff}, based on SPM or XPM [1] induced phase shift detection using interferometric and non-interferometric schemes. The interferometric detection scheme [2] has the advantage that it can be implemented more easily - a disadvantage is however its susceptibility to environmental perturbations leading to a poor stability. A considerable improvement of this technique, is presented in the following, using a self-aligned interferometer [3] with a Faraday mirror. The suggested method has the advantage to be simple and all fiber implementable, and the fluctuations due to environmental perturbations are completely removed.

2. PRINCIPLE OF OPERATION

Due to the power dependence of the refractive index (optical Kerr effect), the phase acquired by a pulse with peak power P and wavelength λ that travels through a fiber of length L is given by

$$f(P) = f_l + f_{nl} = n_0 kL + kL_{eff} \frac{n_2}{A_{eff}} Pm \tag{1}$$

The decrease in pulse power from the fiber attenuation is accounted for by L_{eff}. The polarization parameter m depends on the polarization characteristics of the test fiber and the input signal polarization state. For the case of a high birefringent fiber and light coupled into one axis only, $m = 1$. For the case of a long standard telecom fiber with a complete polarization scrambling, it was demonstrated that $m = 8/9$ [4]. Measuring the acquired phase shift, Eq.1 allows to determine the ratio n_2/A_{eff}.

The setup of the self-aligned interferometer we have used in order to measure this phase shift is shown in Fig.1. High peak power pulses from an EDFA are split at the entry of the first coupler (coupling ratio 50/50) and move along the two arms of the interferometer. These arms are different in length such that the two pulses do not interfere when they recombine at the second coupler (coupling ratio 90/10). Due to the asymmetry of the coupler, the two pulses enter the fiber under test (FUT) with different powers, and according to Eq.1, they will acquire different amounts of phase shift during propagation. The pulses are then reflected at the Faraday mirror (FM) and return back through the FUT and interferometer towards the first coupler. Four different paths are possible during the go- and return trip through the interferometer. A double pass of the long-arm (LL), of the short-arm (SS), and a forward pass of the short (long) arm with a return pass through the opposite arm (SL and LS, respectively). Because of the different arm lengths, three different arrival times at the detector can be discerned. Only the middle pulse, arising from the interference between the SL and the LS pulses, is analyzed. The power of this pulse depends on the phase relationship between the two interfering signals and it can be exploited to calculate the nonlinear phase shift experienced in the FUT. It is important to note that contrary to regular Mach-Zehnder interferometers, the balancing of the interferometer arms is not critical here as the path lengths of the two interfering signals are automatically matched (self-aligned).

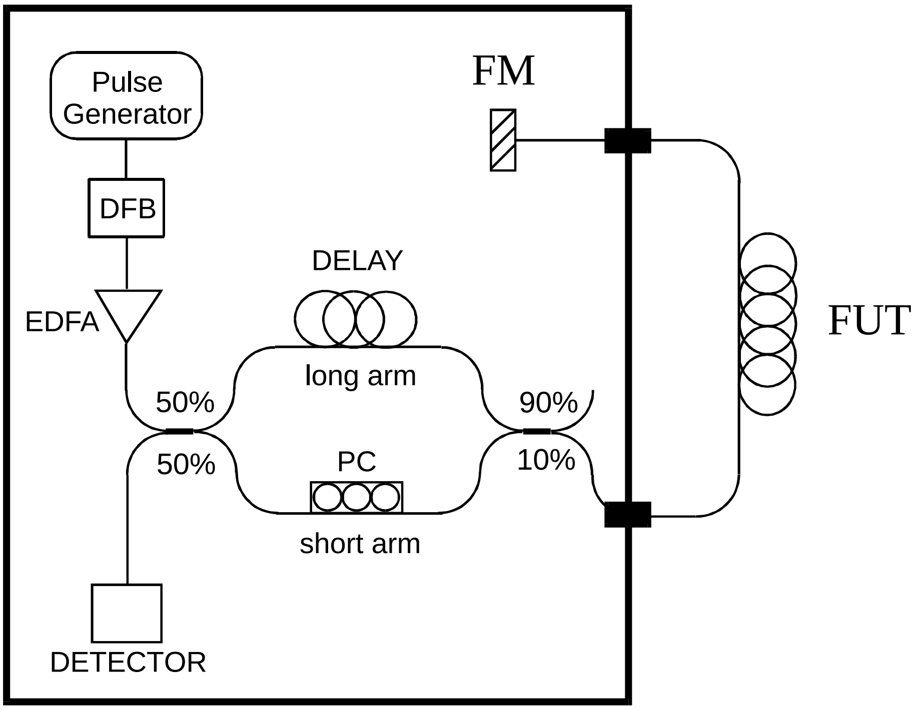

Figure 1. Experimental setup of the self-aligned interferometer. DFB distributed feedback laser, EDFA Erbium doped fiber amplifier, PC polarization controller, FUT fiber under test, FM Faraday mirror, D detector

To calculate the detected power of the middle pulse we have to consider the state of polarization (SOP) of the two interfering pulses. Let R_L, R_S, and R_{FUT} be the polarization transformation operators for the long and short arm of the interferometer and for the FUT, respectively. Knowing that the action of the FM is such that upon reflection, the SOP of the reflected light is always orthogonal to the incoming one, we can describe the double pass of the FUT as

$$m_g = R_{FUT}{}^{-1} - FR_{FUT} m_0 = R_{FUT}{}^{-1}(-(R_{FUT} m_0)) = -R_{FUT}{}^{-1} R_{FUT} m_0 = -m_0$$

So for the pulses that travel through the LS (SL) path, the SOP m_{LS} (m_{SL}) at the exit of the interferometer is given by:

$$\begin{aligned} m_{LS} &= R_S{}^{-1}\left(R_{FUT}{}^{-1} F R_{FUT}\right) R_L m_0 = R_S{}^{-1}(-R_L m_0) = -R_S{}^{-1} R_L m_0 = Am_0 \\ m_{SL} &= R_L{}^{-1}\left(R_{FUT}{}^{-1} F R_{FUT}\right) R_S m_0 = R_L{}^{-1}(-R_S m_0) = -R_L{}^{-1} R_{SL} m_0 = Bm_0 \end{aligned}$$

To have maximum visibility at the exit of the interferometer the two pulses need to have the same SOP, i.e. A=B. This can be done by adjusting the polarization controller (PC) inserted in one of the interferometer arms, e.g. such that $R_S=R_L$. Note that using a standard mirror in place of the FM, an additional PC would be required [5], making the initial adjustment of the interferometer more difficult. Moreover, both PCs would have to be readjusted for every new FUT. With the FM instead, the interferometer does not require any adjustments after its initial calibration.

Another important point is the possibility to adjust the bias of the interferometer. In the experiment, the PC was adjusted in such a way that the above requirement of A=B was fulfilled. Consequently, all the light was directed towards the detector at the first coupler.

Taking into account this and Eq. (1), the detected power P_{OUT} for a standard fiber becomes

$$P_{OUT}(P) \propto P \cos^2\left(\Delta f\right) \tag{2}$$

where $\Delta\phi$ is the acquired nonlinear phase shift [5],

$$\Delta f\left(P\right) = \frac{2p}{l} P L_{eff} \frac{16}{45} \frac{n_2}{A_{eff}} \tag{3}$$

3. RESULTS

The pulse source used in the experiment was a directly modulated DFB laser diode. Its wavelength was 1559 nm, the pulse duration 28 ns, and the repetition rate 1 kHz. Note that in some fibers, such long pulses can excite acoustic waves through electrostriction, leading to an erroneous measurement of n_2/A_{eff}.

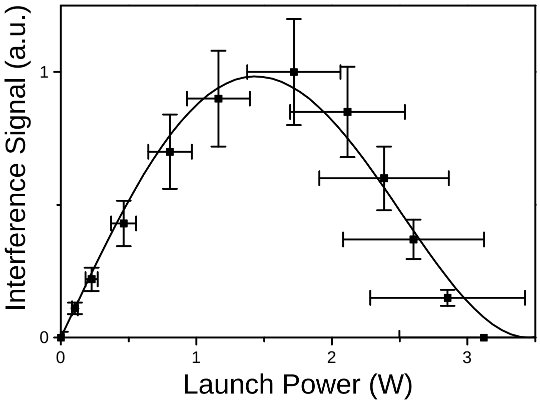

Figure 2. Detected interference signal power as a function of launch power: (squares) measured data, (solid line) theoretical fit

The results for a standard telecom fiber with a length of 1100 m are shown in Fig.2. The interference signal power is plotted as a function of the launch power P. The experimental values (squares) are increasing almost linearly in the beginning, demonstrating that nonlinear effects are of little importance up to about 0.8 W of launched power. Then they set in quite heavily, and the measured power eventually starts to decrease with increasing launch power. The maximum of the interference signal power is reached at a lunch power of 1.4 W, whereas a null value, corresponding to a full $\pi/2$ nonlinear phase shift, is obtained for 3.1 W. From this value, n_2/A_{eff} can be calculated using Eq.2. The precision is however much better if the whole curve is fitted. This fit is represented by the solid line in Fig.2. As can be seen, the measured data and the fitted values correspond well, with $\chi^2=3x10^{-3}$. From the fit we obtain a value of $(2.76\pm0.04)\ 10^{-10}\ W^{-1}$ for the nonlinear coefficient n_2/A_{eff}.

4. CONCLUSION

We have presented a simple method for the measurement of the nonlinear coefficient n_2/A_{eff} based on an all fiber, self-aligned interferometer. Self-alignment not only allows for an easy and quick initial adjustment of the interferometer, but along with the use of a Faraday mirror also makes it robust against environmental perturbations. This leads to a good accuracy for the measured n_2/A_{eff} values. The proposed method is well suited to routinely measure the nonlinear coefficient, as the fiber under test can be easily exchanged without necessitating any further readjustments of the interferometer.

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