Distributed measurements of chromatic dispersion and of the nonlinear coefficient in DSF fibers with non negligible values of PMD

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Abstract:
We report on the influence of PMD and especially of the polarization coupling length on the distributed chromatic dispersion measurement in DSF. We further demonstrate how to obtain distributed values for the nonlinear coefficient n_2/A_{eff} .

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1. Introduction

The implementation of Erbium-doped fiber amplifiers allows for high-bit rate transmission over transoceanic distances. At the same time, the technique of wavelength division multiplexing (WDM) is used to increase the transmission rate, leading to an important amount of power inside the fiber. Because of the long distances and high powers, optical nonlinearities start to play a significant role. In dispersion shifted fibers (DSF), four wave mixing (FWM) leads to important transmission impairments. The FWM efficiency depends on both the chromatic dispersion profile and the nonlinear coefficient n_2/A_{eff}. It is therefore highly interesting to have a non-destructive technique that allows to map these parameters as a function of distance along the fiber. A convenient approach to measure the chromatic dispersion map in a DSF fiber was proposed by Mollenauer et al. [1].
We compare measurements of DSF fibers with different values of the polarization coupling length h, and find that for the large h values typically found in the older installed DSF cables, the method is limited and data elaboration needs to be refined. Further, we demonstrate how the method can be exploited to obtain information on the distributed value of the nonlinear coefficient n_2/A_{eff}.

2. Theory

The measurement method [1] is based on the detection of the fringe period of the Rayleigh backscattered FWM signal generated in the fiber under test (FUT) by injecting two powerful waves with frequencies ω_1 and ω_2 ($\omega_1<\omega_2$). Concentrating on the FWM generated Stokes frequency $\omega_S = 2\omega_1 - \omega_2$ for simplicity, one can show that the phase mismatch Δk between the pump (ω_1) and the generated Stokes signal (ω_S) becomes [2]

$$\Delta k = \Delta k_L + \Delta k_{NL} = D(\lambda_1) c 2\pi \left(\frac{\Delta\lambda}{\lambda_1}\right)^2 + \gamma\left(2P_1 - P_2\right) \qquad (1)$$

As the equation shows, the phase matching depends on the local chromatic dispersion D and on a nonlinear term depending on the local nonlinear coefficient γ. The phase-mismatch Δk leads to a temporal intensity oscillation of $c/2n\ \Delta k/2\pi$ of the Rayleigh backscattered Stokes signal, which is detected in an OTDR-like fashion to map it on a distance scale. Typically, for the dispersion mapping, one should choose a seed power twice as large as the pump power ($P_2=2P_1$), so that the dependence on the local nonlinear coefficient disappears.
Eq.1 does not take into account any polarization dependent effects. However, it is clear that the relative polarization states of pump and seed will vary according to the PMD of the FUT. This change can be characterized by the spatial correlation of the pump and seed SOP at the output, and for relatively large PMD values one finds [3]

$$\mathrm{corr}(\vec{S}_1^{\,out}\vec{S}_2^{\,out}) = \vec{S}_1^{\,in}\vec{S}_2^{\,in}\ \exp\left(-\Delta\varpi^2\ \frac{3\pi}{8}\frac{<\Delta\tau>^2}{3}\right) \qquad (2)$$

where $<\Delta\tau>$ is the overall PMD. This change in the relative polarization states will bring about two consequences. First, the FWM efficiency η is polarization dependent,

$$h = \frac{1}{2}\left(1+\vec{S}_1\vec{S}_2\right) \qquad (3)$$

Consequently, on top of the signal intensity oscillations of the Stokes signal related to the phase mismatch (i.e. local chromatic dispersion), one gets an additional modulation due to the change in efficiency. However, this is usually not dramatic as the length scale of this polarization dependent fluctuation is normally quite short so that its effect is averaged away. As a second consequence of PMD however, the phase seen by pump and seed can be different because of the local birefringence, thereby introducing an additional term to Eq.1. As is discussed in the results section, this can be important in fibers with little polarization mode coupling. In such fibers, polarization dependent phase shifts of the order of the ones from the chromatic dispersion (which is small in DSF fibers) can be picked up, thereby strongly varying the oscillation frequency of the Stokes signal intensity.

As suggested by Eq.1, it should be possible in a similar way to extract the distribution of the nonlinear coefficient γ once the dispersion map is measured. One simply has to choose a ratio of seed to pump power $P_2/P_1 \neq 2$. However, the polarization variations can again deteriorate the measurement. A much better approach is therefore to perform - directly after the first one - a second measurement with the same ratio of P_2/P_1 but smaller absolute powers. The difference between the two corresponding temporal oscillations does no longer depend on the chromatic dispersion:

$$\Delta\nu_t = \frac{c\gamma}{4n\pi}\left(2P_1 - P_2\right)\frac{(1-\alpha)}{\alpha} \qquad (4)$$

where α is the power attenuation factor between the two measurements.

3. Experimental set-up

The experimental setup for the measurements is shown in Fig.1. The light source consists of two tunable distributed feedback lasers (DFB) in cw mode. The SOP of the two waves is controlled via two polarization controllers (PC1, PC2), and made equal in order to maximize FWM (Eq. 1). The two waves are then amplified by a SOA modulated with a frequency of 4 kHz and a pulse width of 30 nsec, and further amplified by an EDFA. Typically, peak power values in the range 150-1500 mW are used. The SOP of both waves launched into the FUT is varied simultaneously by a third polarization controller (PC3). The Rayleigh backscattered signal from the FUT is collected from the circulator, and the Stokes component of interest is isolated by a tunable filter (40 dB attenuation @ ±1 nm). The oscillation of the Stokes power is monitored as a function of distance by controlling the SOA and the detector with an OTDR. From this trace, the dispersion and γ map are then elaborated according to eqs.1 and 4.

4. Results

First, we map the chromatic dispersion for two different DSF fibers, one with a small and one with a large polarization coupling length h (determined from (polarization sensitive) Optical Frequency Domain Reflectometer traces). In both fibers, the overall PMD is small (<0.2 ps/√km). Fig.2 shows the Stokes signal power for the low coupling length fiber for different input SOPs into the FUT (pump and seed input polarizations are kept identical). No significant dependence of the results on the input polarization is expected for such a fiber, as the pump and seed signals have no time to acquire significantly different phases due to the frequent coupling among the fast and slow axes. Indeed, the figure demonstrates that only small changes in the amplitudes, but not in the locations of the Stokes signal maxima are obtained. For completeness, inset (a) shows the chromatic dispersion map as obtained from entering the fiber from both ends (one of the profiles is inverted), demonstrating the good reproducibility and accuracy of the results. Inset (b) gives the overall dispersion at different wavelengths, where the open circles were obtained from summing up the FWM dispersion map, and the bold line from an alternative method. Good agreement between the two methods can be observed.

Fig.3 shows the results for the long coupling length fiber. As can be seen, the maxima locations of the Stokes signal vary strongly due to the additional phase from PMD, which depends on the input polarization states. In fact, the chromatic dispersion map can no longer be estimated from a single trace alone, as the frequency at a given location depends on the (arbitrary) relative polarization states at that location for that input SOP. To remove this arbitrary component, different profiles, each corresponding to a different input SOP, have to be taken. For a given location, the mean value of GVD should then be retained. Note that averaging over all the possible SOP during an acquisition (by using a polarization scrambler, bold line in the inset of Fig.3) will not give a meaningful result, as it simply corresponds to a sum of the different individual traces giving -due to arbitrary positions of the different maxima - a curve that is basically flat.

Finally, Fig.4 shows some first results for the distributed nonlinear coefficient γ of the low coupling fiber. Both experimental results and simulation (inset a) show that the oscillation frequency is lower for lower input powers, as expected. The corresponding γ coefficient obtained according to Eq.4 is shown in inset (b).

5. Conclusions

We have shown that mapping of chromatic dispersion in DSF fibers is strongly affected by their polarization coupling length. Nevertheless, the possibility to obtain a meaningful dispersion map in a fiber with low polarization coupling still exists. However, it requires averaging of the dispersion values at a given location for different input SOP. First results for the extraction of the distributed nonlinear coefficient n_2/A_{eff} are promising.

6. References

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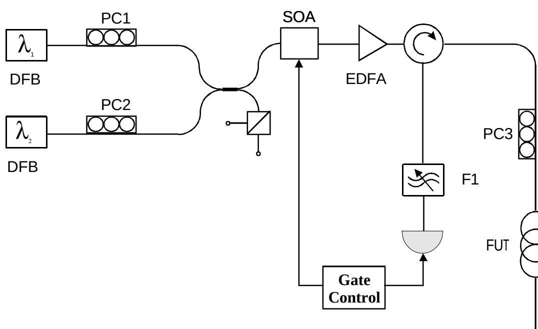


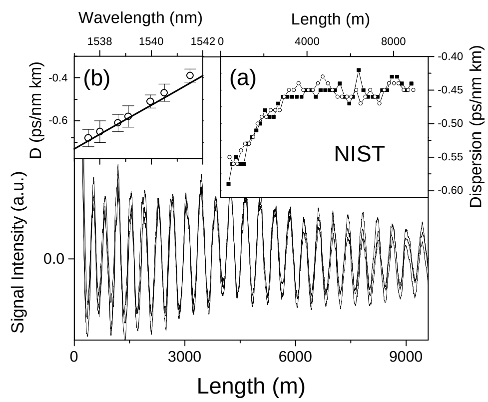
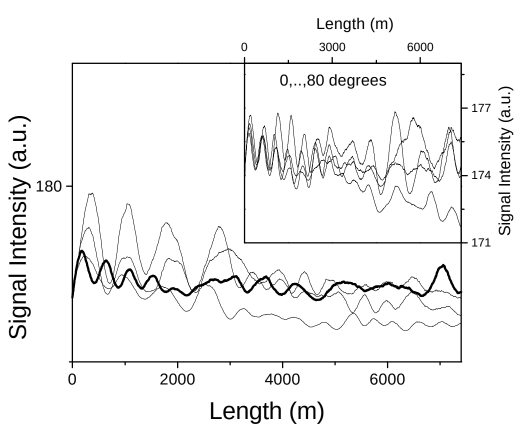


Fig. 1. Experimental setup.

Fig. 2. Results for the short coupling length fiber.



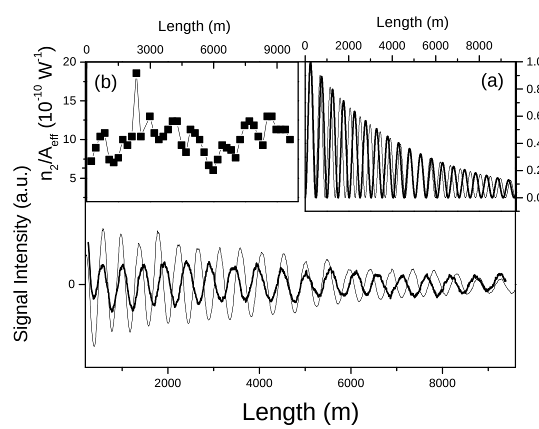


Fig. 3. Signal intensity profiles for the long coupling length fiber.

Fig. 4. Map of the nonlinear coefficient for the short coupling length fiber.