Distributed Measurements of Chromatic Dispersion and Nonlinear Coefficient in Low-PMD Dispersion-Shifted Fibers

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***Abstract*—We report on the investigation of distributed chromatic dispersion (CD) and distributed nonlinear coefficient (NLC) measurements based on phase mismatched four-wave mixing in dispersion-shifted fibers (DSFs). Experimental results of the distributed CD maps for low polarization-mode dispersion (PMD) DSF fibers are discussed. We also report how nonnegligible values of PMD can adversely affect the distributed CD measurements. A new method to measure the distributed NLC map in low-PMD DSF fibers is also proposed and demonstrated experimentally.**

***Index Terms*—Chromatic dispersion (CD), dispersion-shifted fibers (DSFs), distributed measurements, four-wave mixing (FWM), nonlinear coefficient (NLC), polarization-mode dispersion (PMD).**

I. Introduction

OPTICAL nonlinearities play a significant role in contemporary fiber-optic transmission networks because of the long distances and the high powers present in the optical fibers. In fact, it is well known that nonlinear effects, such as four-wave mixing (FWM) and cross-phase modulation, may seriously affect optical transmission network systems, for example, in dispersion-shifted fibers (DSFs). The efficiency of these processes depends on both the chromatic dispersion (CD) profile and the nonlinear coefficient (NLC) $n_2/A_{\rm eff}$ profile. It is, therefore, highly interesting to have a nondestructive technique that allows us to map these parameters as a function of fiber distance in order to design ultrahigh capacity fiber-optic transmission networks.

In this letter, we report on the investigation of distributed CD measurements based on the method first proposed by Mollenauer *et al.* [1], where we obtained a spatial resolution of 250 m with a high accuracy. The experimental results for the case of fibers with low and nonnegligible values of polarization-mode dispersion (PMD), in particular in the presence of high values of the polarization coupling length (i.e., the distance over which the E field of the travelling wave loses memory of its initial distribution between the local polarization eigenstates) are also discussed. We found that, for nonnegligible values of PMD that can typically be found in the old installed DSF cables, the method is severely limited and data elaboration needs to be refined. At the same time, we propose and also experimentally demonstrate, for the first time to the best of our knowledge, a new method based on the aforementioned one to measure the distributed NLC map in low-PMD DSF fibers.

II. Theory

The optical time-domain reflectometer-like method for measuring a distributed CD map is based on the detection of the fringe periods of the Rayleigh back-scattered FWM signal, either Stokes or anti-Stokes, generated from the fiber under test (FUT), by injecting two powerful lights (pump and probe) with powers P_1 and P_2 and frequencies ω_1 and ω_2 ($\omega_1 < \omega_2$). If we focus on the FWM generated from the Stokes frequency $\omega_S = 2\omega_1 - \omega_2$, the phase-mismatching Δk is given by [1]

$$\Delta k = \Delta k_L + \Delta k_{NL} = -D(\lambda_1)c2\pi\left(\frac{\Delta\lambda}{\lambda_1}\right)^2 + \gamma\,(2P_1 - P_2) \tag{1}$$

where $\gamma = n_2\omega_0/cA_{\rm eff}$. The above equation shows that the phase-mismatching Δk depends on both the local CD $D(\lambda)$ (linear term) and NLC γ (nonlinear term). The Stokes signals can also be expressed as a spatial intensity oscillation with period λ_{SP}. Thus, the temporal oscillation frequency ν_T in intensity of the Rayleigh back-scattered light can be expressed as

$$\begin{aligned}\nu_t &= \frac{c}{2n}\,\frac{1}{\lambda_{Sp}} \\ &= \frac{c}{2n}\,\frac{\Delta k}{2\pi} \\ &= \nu_L + \nu_{NL} \\ &= -\frac{c}{2n}\,Dc\left(\frac{\Delta\lambda}{\lambda}\right)^2 + \frac{c\gamma}{4n\pi}\,(2P_1 - P_2).\end{aligned} \tag{2}$$

If $P_2 = 2P_1$ is satisfied, then the nonlinear term disappears and a measurement of the local frequency provides information of the local CD value versus fiber distance.

It is important to note that (1) does not take into account any polarization-dependent effects. However, it is clear that the relative polarization states of pump and probe will vary according to the PMD of the FUT. This change in their relative state of polarization (SOP) can be characterized by the spatial correlation of the pump and probe SOPs ($\mathbf{S_1}$ and $\mathbf{S_2}$) at the output of the FUT.

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When PMD is present, one finds [2] that the correlation between pump and probe SOPs is proportional to $\mathbf{S}_1\mathbf{S}_2\exp(-\langle\Delta\tau\rangle^2)$ where $\langle\Delta\tau\rangle$ is the overall PMD. This change in the relative SOP has two consequences. First, the FWM efficiency η ($\eta = (1+\mathbf{S_1S_2})^{1/2}$) is polarization dependent. This implies that the total detected signal oscillations correspond to the sum of the Stokes signal—intensity oscillations related to the phase mismatch (i.e., the local CD)—and an additional modulated signal due to the change in the FWM efficiency by the PMD. However, this effect is usually not important because the length scale of this polarization-dependent fluctuation is normally very short compared with the Stokes signal oscillation scale, so that it is averaged away. The second consequence, however, implies that the phase seen by the pump and the probe can be different because of the local birefringence, thereby introducing an additional term (nonlinear term) to (1). As discussed later, this effect can be important in fibers with little polarization-mode coupling (large values of coupling length) and sufficiently high PMD. In such fibers, polarization-dependent phase shifts of the order of the ones from the CD (which is small in DSF fibers) can be picked up and strongly vary the oscillation frequency of the Stokes signal intensity.

It is interesting to note that in the case of fibers with small values of PMD, once a CD map $D(z, \lambda)$ for a particular fiber is obtained, we can retrieve information of the local NLC $\gamma(z)$ (i.e., n_2/A_{eff}) if we consider a ratio for the pump and probe powers different from two. Unfortunately, local variations due to the coupling length will not allow us to obtain good and reproducible maps of the NLC. An alternative way [3] consists of performing two different measurements keeping the ratio $\alpha = P_1/P_2$ constant (and different from two), but attenuating of the same factor α^* both pump and probe powers. It follows that the difference between the temporal frequencies of two measurements $\Delta\nu_t$ is independent of the CD (the linear term in (2) is equal for both cases, and so it is cancelled out) but contains a dependence in γ

$$\Delta\nu_t = \nu_t(\alpha = 1) - \nu_t(\alpha = \alpha^*) = \frac{c\gamma}{4n\pi}(2P_1 - P_2)\frac{1-\alpha^*}{\alpha^*}. \quad (3)$$

This allows us to obtain a map of the NLC versus fiber distance. Note that typical variations of the refractive index n along FUT will not significantly contribute to the $\Delta\nu_t$ term.

III. Experimental Setup

The experimental setup used for measuring the distributed CD is similar to the one of Mollenauer *et al.* [1] and is shown and described in detail in [3]. Measurements were made on different DSF fibers. The data for the two DSF fibers reported here are as follows. NIST fiber: length $= 9700$ m, PMD $= 0.02$ ps/$\sqrt{}$km. AC-2 fiber: length $= 7400$ m, PMD $= 0.19$ ps/$\sqrt{}$km. The PMD was measured by using a PMD analyzer (IQ-5500, EXFO).

IV. Distributed CD Map Measurements

Fig. 1 shows the Stokes signal intensity for the NIST fiber, for different input SOPs into the FUT, when pump and probe SOPs are set identical. No significant dependence of the results on the input polarizations was expected for this fiber because the pump and probe lights had no time to acquire significantly different phases due to the frequent coupling among the fast and slow axes and the low value of PMD. Indeed, our results show that we obtained very small changes in both the amplitude and the location of the Stokes signal maxima. The inset of Fig. 1 shows the CD maps obtained from lights launched into the FUT from both ends (one of the profiles was inverted), resulting in good reproducibility and accuracy. A spatial resolution of CD typically of 250 m with a high accuracy was observed.

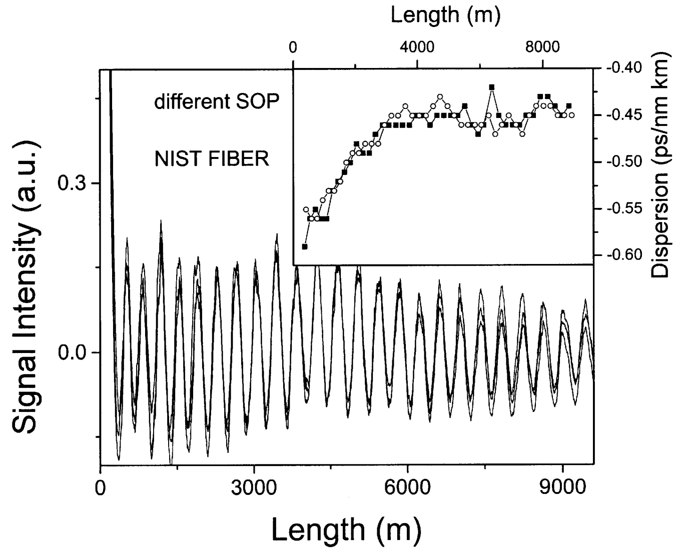

Fig. 1. Measured typical traces of the Rayleigh back-scattered FWM signals from a DSF fiber with low PMD (NIST fiber) for different input SOPs. Inset figure shows the two CD maps when the lights enters from the different fiber ends resulting in a less than $\pm 4\%$ difference of CD magnitudes.

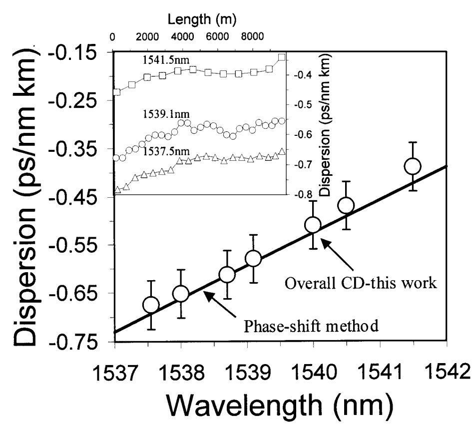

Fig. 2. Overall CD at different wavelengths (open circles) compared with phase-shifted method (solid line), for the NIST fiber. In the inset: CD maps for different wavelengths.

Fig. 2 gives the overall CD at different wavelengths, where open circles are obtained from summing up the FWM dispersion map and the bold line represents results obtained with an EXFO FTB-5800 analyzer using a phase-shift technique [4]. The two methods produce results in excellent agreement. The inset figure in Fig. 2 shows the distributed CD maps at different wavelengths. It clearly appears that CD maps have similar tendencies except for the dispersion values' offset at the different wavelengths.

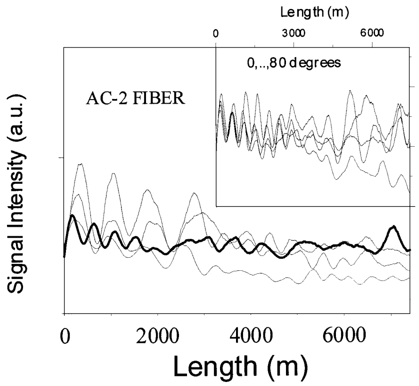

Fig. 3. Measured back-scattered FWM signal intensity profiles for the PMD DSF fiber (AC-2) with different input SOPs. The bold line shows a progressive averaging of the signals during scrambling of pump and probe polarization states. In the inset: the measured FWM signals from the other fiber end.

Fig. 3 shows the data relative to the PMD fiber (AC-2). As it can be seen, the maxima (minima) locations of the Stokes signal vary strongly with the presence of an additional phase due to the PMD. The shift in the maxima (minima) depends on the input SOPs. In fact, the CD 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 group-velocity dispersion should then be retained. Note that averaging over all the possible SOPs during an acquisition by means of a polarization scrambler (see bold line in Fig. 3) does not give a useful result as it simply corresponds to the sum of the different individual traces giving a curve that is basically flat due to arbitrary positions of the different maxima.

V. Distributed $n_2/A_{\rm eff}$ Measurement

As discussed in Section II, when the ratio P_2/P_1 is kept different from 2, the fiber nonlinearities produce an additional phase mismatching. Therefore, it is important to maintain $P_2/P_1 = 2$ at any position along the fiber in order to extract an accurate local CD value. However, as discussed before, this effect [i.e., the presence of both linear and nonlinear terms in (1)] can be exploited to obtain a distributed map of the NLC (i.e., $n_2/A_{\rm eff}$). The method consists of taking at least two measurements while keeping $P_2/P_1 \neq 2$, and inserting a different attenuation for the two different measurements [see (3)]. Fig. 4 shows two FWM signal traces when the launched pump and probe powers had a difference of 10 dB. Two fringes are missed when the attenuation is introduced. This agrees with our theoretical simulation very well [see Fig. 4(a)]. Extracting a distributed NLC map from these curves is possible, as shown in Fig. 4(b) for a distributed NLC ($n_2/A_{\rm eff}$) map versus fiber length. However, our first results are not accurate enough mainly because of the uncertainty in measuring high peak powers of launched pulses and the noise on the measurements. Note that the NLC map would also be sensitive to power fluctuation along fiber.

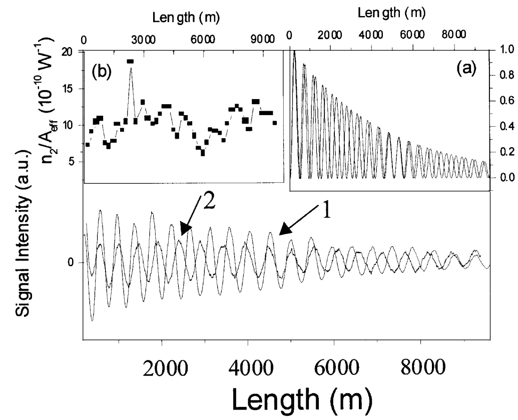

Fig. 4. Measured FWM intensity oscillations versus fiber distance for the low-PMD fiber (NIST fiber) at the wavelength 1541.3 nm for 1) $P_{10} = P_{20} = 1150$ mW and 2) $P_{10} = P_{20} = 115$ mW. In the inset: (a) theoretical simulation and (b) an NLC map.

VI. Discussion and Conclusion

We have demonstrated highly spatially resolved and accurate distributed CD measurements in low-PMD DSF fibers based on phase mismatched FWM. Because of the sensitivity of the FWM efficiency and the PMD-induced phase mismatching, this method could be severely limited in the determination of accurate and meaningful CD maps for fibers having nonnegligible values of PMD, as reported here for the case of a fiber with PMD > 0.2 ps/$\sqrt{\rm km}$. Further investigations between the interplay of PMD, coupling length, and FWM are in progress. Fortunately, for low-PMD fibers, the input SOP has little effect on the CD map. Thus, it is possible to extract meaningful information about distributed CD values from the detected Stokes signal oscillations. For recently installed fibers with low PMD, precision measurements can be carried out by averaging over all SOPs to avoid ambiguities. We have also demonstrated a useful measurement range of 40 km when using reclity.

Moreover, we have presented a new method in order to measure a distributed map of the NLC $n_2/A_{\rm eff}$. Preliminary results confirmed the feasibility and the reproducibility of the method and further work is in progress.

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