

Fig. 2. Measured temperature dependences of the dispersion of two DMF spans.

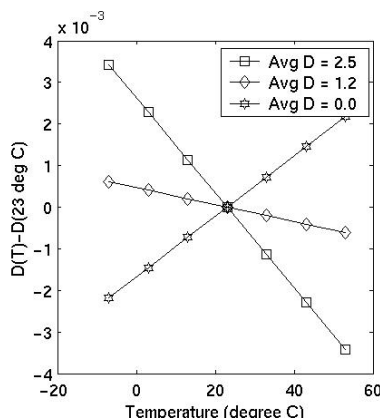


Fig. 3. a)

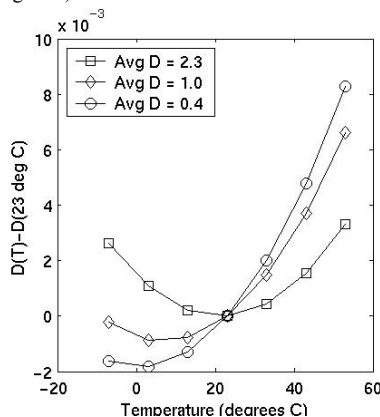


Fig. 3. b)

Fig. 3. Calculated temperature dependences of the dispersion for a hybrid DMF using a linear fit (Fig. 3. a) and a quadratic fit (Fig. 3. b) for the temperature dependence of the DSCF.

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Chromatic Dispersion Mapping by Sensing the Power Distribution of Four-Wave Mixing Along the Fiber Using Brillouin Probing

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A new method for chromatic dispersion mapping in optical fibers is presented. It is based on measuring the CW four-wave mixing distribution created by two beams along the fiber using a Brillouin-OTDA. Experimental results demonstrate the feasibility of the technique.

1. Introduction

One of the most recent issues in ultrahigh-speed fiber transmission is random chromatic dispersion fluctuations along optical fibers. In fact, random chromatic dispersion variations along an optical fiber can be a very important source of pulse broadening, both in soliton transmission [1] and conventional pulse propagation [2]. Thus, mapping chromatic dispersion in optical fibers should be useful to ensure stable soliton transmission, accurate dispersion management (specially short-period dispersion management) and optimized WDM planning (avoiding any four-wave mixing-related impairments). Furthermore, such knowledge would allow making an adequate selection of uniform fibers for devices such as parametric amplifiers, phase conjugators and wavelength converters. These kind of devices are heavily impaired if random dispersion variations are present [3].

Several works have already proposed solutions to the problem of chromatic dispersion mapping [4-9]. The aim of this paper is to propose a novel technique for retrieving the dispersion distribution, which is based on the probing of four-wave mixing power

distribution along the fiber using Brillouin optical time domain analysis (BOTDA). We also report the first experiments performed using this technique. Our preliminary results indicate that the technique is actually able to retrieve the proper information and can potentially produce dispersion maps with higher spatial resolution than methods reported so far.

2. Theory

We consider the case of two CW lasers (λ_L , λ_K) delivering a few milliwatts (5-10 mW) of power at the fiber input ($z=0$). The wavelengths of the two lasers are separated by a quantity $\Delta\lambda$. If the wavelengths are relatively close and the dispersion is not too large, a four-wave mixing process will occur in the fiber. By means of this four-wave mixing process, a Stokes wave ($\lambda_S=\lambda_K+\Delta\lambda$) and an anti-Stokes wave ($\lambda_A=\lambda_L-\Delta\lambda$) will be generated. At a distance z from the fiber input, the power of the anti-Stokes (and Stokes) wave depends on the accumulated phase mismatch between the four waves involved in the process ($\Delta\beta=2\beta_L\beta_K-\beta_A$ for the Anti-Stokes wave), which in turn depends on the dispersion distribution along the fiber. Neglecting fiber losses, the distribution of power of the Anti-Stokes wave in that case can be expressed as:

$$P_{FWM}(z) \propto \frac{1}{\Delta\beta^2} \sin^2\left(\frac{\Delta\beta z}{2}\right)$$

where $\Delta\beta$ can be written as a function of the dispersion:

$$\Delta\beta = 2\pi c \left(\frac{\Delta\lambda}{\lambda}\right)^2 D(\lambda_f)$$

Thus, for reasonable values of dispersion the power of the four-wave mixing periodically varies along the fiber with a frequency that can be linearly related to the dispersion.

The goal is therefore to measure the power distribution of the Stokes or Anti-Stokes wave along the fiber. With this power distribution and by a simple frequency analysis, we should be able to extract the dispersion map along the fiber. A method using this feature has already been reported [6]. Two strong (~1 W) pulses were launched at the beginning of the fiber and the oscillatory behavior of the FWM was recorded using the backscattered light. The main problem arising using this technique is modulation instability if the dispersion is small and positive, as a result of the large pulse powers used. The measurement will consequently be strongly altered. In our case an entirely different probing is used based on Brillouin-OTDA, as we will show in the next

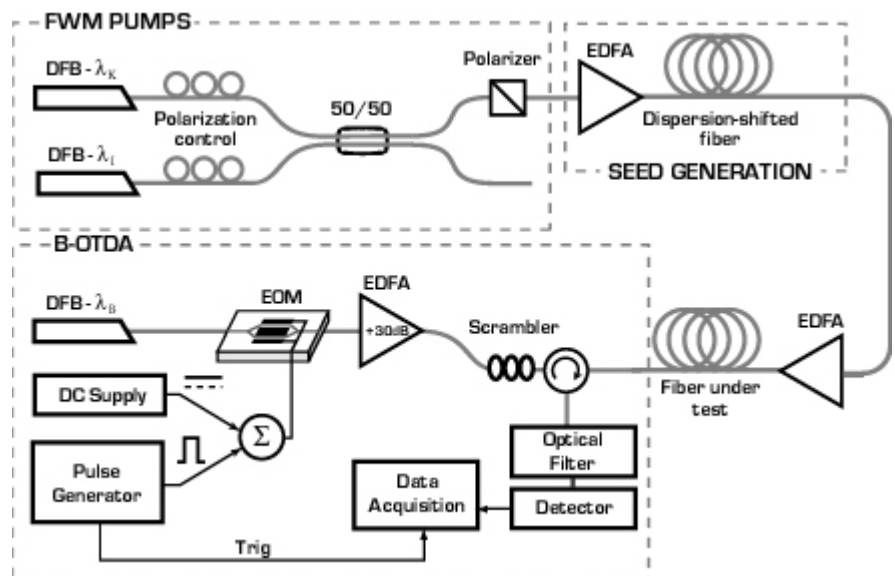


Fig. 1. Experimental setup EOM, electro-optical modulations.

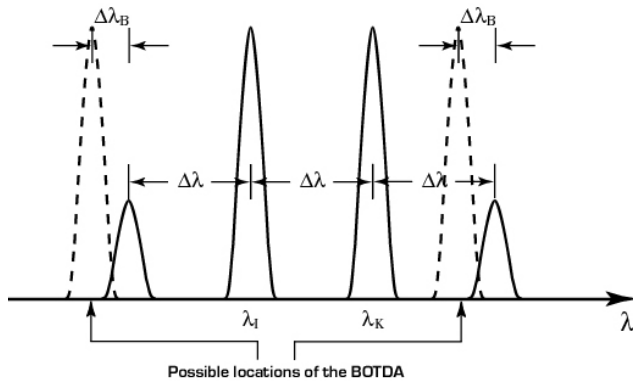


Fig. 2. Possible arrangement of the wavelengths of the three lasers. $\Delta\lambda_B$ is the Brillouin frequency shift expressed in nm (~ 0.088 nm).

section. By contrast with the method described in [6], we benefit from the fact that Brillouin scattering is very efficient in optical fibers, and so our method can rely on continuous-wave, low-power (~ 10 mW) four-wave mixing, which should be well below the threshold for modulation instability. Our theoretical analysis reveals that as long as the Brillouin gain is not too large, the shape of the FWM evolution should be adequately retrieved.

3. Experimental setup and preliminary results

The experimental setup that we use to measure the FWM distribution along the fiber is depicted in Figure 1. Two temperature-tuned DFB lasers act as FWM pumps. The polarizations of the two lasers are carefully aligned, so that the maximum FWM is obtained. A fiber polarizer ensures this condition. After the polarizer, an EDFA re-amplifies the power of the input waves to saturation. Note that the power balance of the two waves can be easily controlled by means of the polarization controls. A power ratio of 1:2 can be interesting to achieve if the powers are too high, to correct

power-dependent phase mismatches. In the conditions of our first experiments, however, these effects turned out to be negligible. As a result of the interaction of the two FWM pumps, a Stokes (anti-Stokes) wave will be generated at the frequency f_S (f_A), following the model described in the previous section. The wavelength of the BOTDA can be tuned to either $f_S + v_B$ or $f_A + v_B$, where v_B is the Brillouin shift (see figure 2). In our case, the wavelength of the BOTDA is tuned to $f_A + v_B$. Hence, the system analyzes the dispersion at wavelength λ_I . If it were tuned to $f_S + v_B$, it would analyze the dispersion at λ_K . The rough tuning of the frequencies is done by tuning the temperatures of the lasers, while the fine tuning is done by modifying their currents. To achieve a bigger signal in the examined fiber, a coherent seed is generated in a dispersion-shifted fiber (DSF) just after the FWM pumps. This seed enhances the power oscillations within the fiber (due to interference) and it facilitates greatly the tuning of the instrument. After the DSF the power is re-amplified. In any case, however, the power at the Stokes wave-

length in the BOTDA fiber end does never exceed $10 \mu\text{W}$. The polarization of the BOTDA is scrambled, so that any polarization-dependent variations of Brillouin gain are averaged out.

Some of the results obtained are shown in Figure 3. The fiber under test is 4.5 km long and shows a dispersion of ~ 16 ps/nm.km at 1555 nm. A periodic signal with the expected periodicity is measured, even with wavelength separations in the FWM pumps as big as 1.4 nm. However, there is some noise as a result of the random walk-off between the wavelengths of the three lasers. This walk-off is slightly bigger than the Brillouin gain and hence the effective Brillouin gain is broadened and reduced accordingly. We believe that relatively simple modifications in the experiment accounting for the stability between the lasers would further improve the quality of the acquired signal. It is important to note that similar traces are retrieved from the other fiber end. Our preliminary tests with a very long (25 km) dispersion-shifted fiber (DSF) also turn out to give adequate values for the dispersion, although the wavelength separation between the two FWM pumps has to be greatly increased to obtain periodicities in the range of 500 meters. Regarding the measurement range, our preliminary tests seem to indicate that it can reach well beyond 25 km, although probably this parameter is strongly dependent on the fiber type and the wavelength separation between the two FWM pumps.

In conclusion these results demonstrate that Brillouin probing can be an efficient way to retrieve the FWM distribution map and thus to have access to the local dispersion value. As a result of the high efficiency of the Brillouin interaction we expect to obtain FWM maps with a significantly improved spatial resolution with respect to other methods, together with a reduced acquisition time. The main issue is related to the relative frequency stability of the three lasers, that must be kept within a few MHz to result in an efficient Brillouin amplification.

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4. References

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Dispersion Compensation with an SBS-Suppressed Fiber Phase Conjugator Using Synchronized Phase Modulation

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204km, 10Gb/s standard optical fiber transmission is successfully demonstrated using mid-span spectral inversion (MSSI) technique with a SBS-suppressed fiber phase conjugator, which we proposed recently. Transmission performance has been improved compared with a conventional phase conjugator.

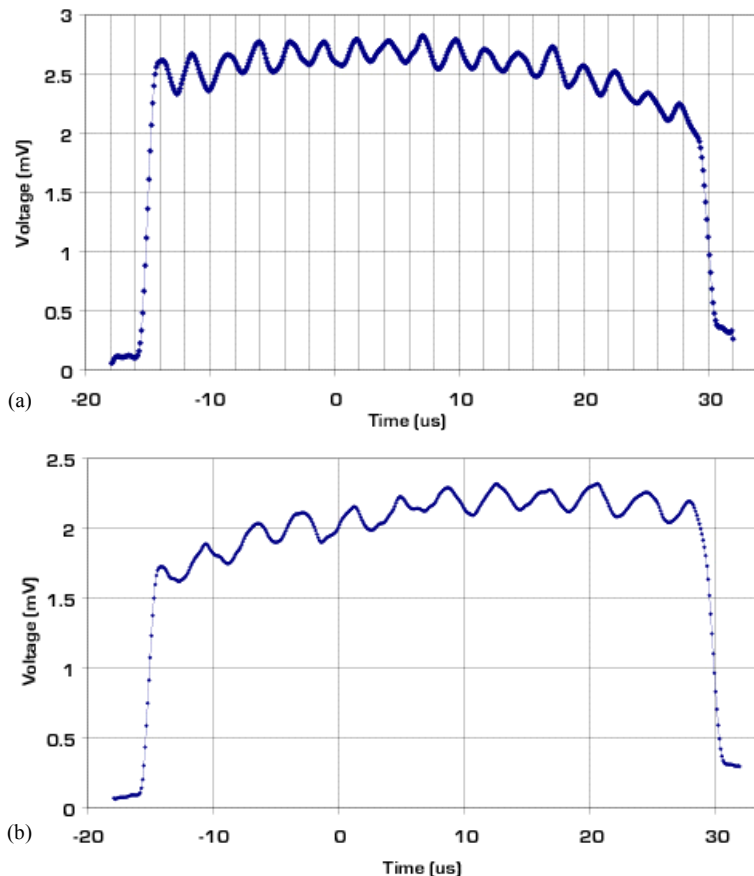


Fig. 3: Recorded traces with (a) $\Delta\lambda = 1.37$ nm and (b) $\Delta\lambda = 1.14$ nm. The fiber under test is 4.5 km long and shows a dispersion of 16 ps/nm.km in the 1.55 μm region. In both cases the Brillouin pulse width is 1 nsec.