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Measurement of fiber chromatic dispersion using spectral interferometry with modulation of dispersed laser pulses

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ABSTRACT

We propose and experimentally demonstrate a method for fiber dispersion measurement based on the modulation of laser pulses stretched by the fiber under test. The measured spectrum of the modulated pulses is the result of the interference between the stretched pulse spectra shifted by the modulation harmonics. The interference pattern is processed as in Fourier transform spectral interferometry. Unlike to conventional spectral interferometry, environmental conditions do not affect the interferogram due to the lack of any interferometer; additionally, large dispersions can be characterized by the method proposed. Its high accuracy is demonstrated in experimental comparison with the widely used phase shift technique.

1. Introduction

The chromatic dispersion of optical fiber is one of the key factors for designing long-haul high-speed optical communication systems. The management of the dispersion requires fast and accurate measurements over a wide spectral range not only of the first order but also higher orders of dispersion. A variety of techniques for dispersion measurement were developed [1]. The phase shift between the beating of the modulation sidebands and the reference signal is measured in the phase shift method [2]. The shift is approximately equal to $t_{gr}(\omega)\omega_m$, where ω_m is the modulation frequency and $t_{gr}(\omega)$ is the frequency dependent group delay of the fiber under test. The phase $\varphi(\omega)$ acquired by light in a dispersive element can also be exactly obtained by such experiments [3]. The amplitude response for the swept modulation frequency was also used to give the first-order dispersion [4]. These techniques are suitable for characterization of large dispersions with temporal resolution on the order of picoseconds. Determination of group delay from measurement of the optical path length in an interferometer [5] can provide a resolution up to 0.1 fs [6], but it is only applicable to short fibers. All of these methods need the scanning of the wavelength, and therefore require a long data acquisition time. The pulse delay technique [7] with supercontinuum pulses spectrally sliced by an etalon provides a fast measurement over a wide spectral region [8], but the possible temporal resolution is limited in this case by the response time of a photodiode and an oscilloscope.

In spectral interferometry [9–11], the spectrum of the light passed through an interferometer is analyzed by a spectral device [9–15] or by scanning of the wavelength of a laser source [16,17]. The dispersive element to be tested is placed in the signal arm of an interferometer. The fiber dispersion was also measured by spectral interferometry in the temporal domain [18]. The temporal interference pattern, acquired by an oscilloscope, gave a spectral interferogram using the linear relationship between the temporal and spectral scales for pulses propagating in long fibers. The phase difference between the signal and reference lights can be obtained from the measured spectral interferogram by using Fourier transform technique [11–13,17,18], by determining the positions of maxima and minima of the interference pattern [14,15] or measuring the shift of the interferogram for different delays [15]. The advantages of spectral interferometry applied for dispersion measurements are high accuracy and the ability to perform fast measurements of interferograms. However, it is only suitable for short optical fibers. For instance, the lengths of the tested fibers in [9,14,15]) were of about 1 m. The technique based on swept-wavelength spectral interferometry [17], used in the Optical Vector Analyzer (Luna Technologies), allows increasing the fiber length up to 150 m and provides dispersion measurement with a rate of 30 ms/nm and an accuracy of 5 ps/nm. The additional drawback of conventional spectral interferometry is that the measurement results are extremely sensitive to environmental conditions. An improvement was obtained by using self-tracking interferometry that reduced the phase drift in an interferometer from 1.33 π to 0.04 π [16].

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In the present paper, we propose and experimentally demonstrate a novel method for dispersion measurement based on modulating laser pulses that pass the fiber under test and the measurement of the spectrum of the modulated pulses. Our method is similar to shearing spectral interferometry used for optical pulse characterization [10], in which the phase difference $\Delta\varphi(\omega)=\varphi(\omega)-\varphi(\omega-\Delta\omega)\approx\varphi'(\omega)\Delta\omega$ between the pulse spectrum and its shifted replica is measured, where $\Delta\omega$ is the frequency shift and $\varphi'(\omega)$ is the derivative of the spectral phase. We show that the measured spectrum of the modulated pulses can be regarded as resulting from the interference between the spectra of the stretched pulses shifted by the modulation harmonics. The information on the fiber dispersion is extracted by the method used in Fourier transform spectral interferometry [11]. As we do not use an interferometer for the implementation of spectral interferometry, this technique is less sensitive to variations of environmental conditions. Measuring the phase difference $\Delta\varphi(\omega)$ (instead of$\varphi(\omega)$) allows us to test fibers with large dispersions. The magnitude of the measured dispersions can be readily tailored by the proper choice of the modulation frequency.

2. Measurement principle

In our dispersion measuring method, a short laser pulse is first stretched by the dispersive element under test (in our work — an optical fiber) and then temporally modulated by an intensity or phase modulator, synchronized with the laser pulse. We emphasize that in our technique, unlike others, the RF modulation is performed after the light passes the fiber. The spectrum of the modulated pulse is measured by an optical spectrum analyzer (OSA).

We represent the spectral phase acquired by the pulse propagating in the dispersive element as the sum of the quadratic component (first-order dispersion) and the non-quadratic component $\varphi_{nq}(\omega)$ (higher-order dispersion). Then the spectrum at the output of the tested fiber can be written as

$$F_{out}(\omega) = F_{in}(\omega)\exp[-i\beta_2 L\omega^2/2 + i\varphi_{nq}(\omega)], \tag{1}$$

where $F_{in}(\omega)$ is the spectrum of the input laser pulse, β_2 and L are the group velocity dispersion coefficient and the length of the tested fiber, respectively. The complex amplitude of the modulated pulse can be written as

$$E_{\mathrm{mod}}(t) = f_{\mathrm{mod}}(t)E_{out}(t) = E_{out}(t)\sum_{n=-N}^{N} c_n \exp(in\omega_m t), \tag{2}$$

where $E_{out}(t)$ is the complex pulse amplitude at the output of the tested fiber and the periodic modulation function $f_{\mathrm{mod}}(t)$ is expanded into the Fourier series with the coefficients c_n, $2N+1$ is the number of nonzero modulation harmonics. It is important to emphasize that our derivation is equally valid for any kind of modulation: amplitude, phase or amplitude-phase modulation. The Fourier transform of Eq. (2) gives the expression for the field spectrum of the modulated pulse

$$F_{\mathrm{mod}}(\omega) = \sum_{n=-N}^{N} c_n F_{out}(\omega - n\omega_m). \tag{3}$$

It can be seen from Eq. (3) that the spectrum of the modulated pulse is the weighted sum of the spectra of the stretched pulse shifted by $n\omega_m$. Unlike to conventional spectral interferometry with two interfering spectra, there are here $2N+1$ superimposed spectra. Substituting Eqs. (1) into (3), we obtain

$$F_{\mathrm{mod}}(\omega) = \sum_{n=-N}^{N} c_n F_{in}(\omega-n\omega_m)\exp\{-i[\beta_2 L(\omega-n\omega_m)^2/2] + i\varphi_{nq}(\omega-n\omega_m)\}. \tag{4}$$

The intensity spectrum of the modulated pulse measured by an OSA can be obtained from Eq. (4)

$$I_{\mathrm{mod}}(\omega) = |F_{\mathrm{mod}}(\omega)|^2 \approx |F_{in}(\omega)|^2 \sum_{s=-2N}^{2N} B_s \exp[is\beta_2 L\omega_m\omega - is\omega_m\varphi_{nq}{}'(\omega)],$$
$$B_s = \sum_{k=-N}^{N} c_{k+s}c_k{}^{*}\exp\{-i[(k+s)^2-k^2]\beta_2 L\omega_m^2/2\}, \qquad |k+s|\le N, \tag{5}$$

where $\varphi_{nq}{}'(\omega)$ is the derivative of $\varphi_{nq}(\omega)$ and the symbol * denotes complex conjugation. In the derivation of Eq. (5), we assumed that the spectral phase of the laser pulse is zero. Otherwise, the laser spectral phase can be taken into account, as can be seen below. Besides, it was assumed in Eq. (5) that $F_{in}(\omega-n\omega_m)\approx F_{in}(\omega)$ and $\varphi_{nq}(\omega-n\omega_m)\approx\varphi_{nq}(\omega)-\varphi_{nq}{}'(\omega)n\omega_m$, since the modulation frequency in the experiment (14 GHz) is much smaller than the full width of the pulse spectrum (~2000 GHz) and the number of the modulation harmonics is limited. It can be seen from Eq. (5) that the envelope of the spectral interference pattern is approximately the spectrum of the laser pulse $|F_{in}(\omega)|^2$. This means that the fiber dispersion is measured in our method within the spectral range equal to the full width Δf_{pul} of the laser pulse spectrum.

The factor $\exp(is\beta_2 L\omega_m\omega)$ in Eq. (5) is an analog to the $\exp(i\tau\omega)$ term in conventional spectral interferometry with the time delay τ between the two arms of an interferometer. This factor describes a sinusoidal interference pattern observed on the screen of an OSA with a distance between the spectral fringes of $\Delta f_s = 1/(s\beta_2 L\omega_m)$. For $F_{in}(\omega)$ and $\varphi_{nq}{}'(\omega)$ that are slowly varying functions of frequency, the sinusoidal patterns are amplitude and phase modulated. The distinction from conventional spectral interferometry is that the spectrogram consists of 2 N sinusoidal interference patterns corresponding to the different values of s in the sum in Eq. (5). In addition, it is important to emphasize that the spectral interferometry is implemented in this case without use of any interferometer. The spectrum measured by an OSA can be considered, according to Eqs. (3) and (5), as resulting from the interference between the spectra of the stretched pulse shifted by $n\omega_m$.

We use the same processing of an OSA spectrogram as in Fourier transform spectral interferometry [11], performing its Fourier transform. The Fourier transform, $\Psi_{\mathrm{mod}}(t)$, of the measured spectrum (5) of the modulated stretched pulses can be written as

$$\Psi_{\mathrm{mod}}(t) = \sum_{s=-2N}^{2N} \Psi_s(t - s\beta_2 L\omega_m), \tag{6}$$

where $\Psi_s(t)$ is the Fourier transform of the function$B_s|F_{in}^2(\omega)|^2\exp[-is\omega_m\varphi_{nq}{}'(\omega)]$. It can be seen from Eq. (6) that the Fourier transform of the spectrum measured by an OSA consists of $4N+1$ peaks spaced approximately by the temporal interval $\beta_2 L\omega_m$. It is important in the processing that the peaks would be separated from each other. It can readily be made by the proper choice of the modulation frequency ω_m and, accordingly, the interval between the peaks. In the processing, we select the sth peak $\Psi_s(t-s\beta_2 L\omega_m)$. From its position $\tau_s = s\beta_2 L\omega_m$, we extract the value of the first-order dispersion

$$\beta_2 L = \tau_s/(s\omega_m). \tag{7}$$

Then we shift the sth peak by $-\tau_s$to obtain $\Psi_s(t)$and calculate its inverse Fourier transform, which gives $B_s|F_{in}^2(\omega)|^2\exp[-is\omega_m\varphi_{nq}{}'(\omega)]$. Calculating the argument of the inverse Fourier transform, we obtain $-s\omega_m\varphi_{nq}{}'(\omega)$. The numerical integration of the found argument gives the non-quadratic component $\varphi_{nq}(\omega)$ of the fiber spectral phase. The spectral phase $\varphi(\omega)$ of the tested fiber is calculated as the sum of the quadratic component $\beta_2 L\omega^2/2$ and non-quadratic component $\varphi_{nq}(\omega)$. It is important to note that our result does not depend on the coefficients B_s containing, according to Eq. (5), the Fourier coefficients c_n of the modulation function. This means that our method is equally suitable for any kind of modulation: amplitude, phase or even combined amplitude-phase modulation. The depth of phase modulation determines the

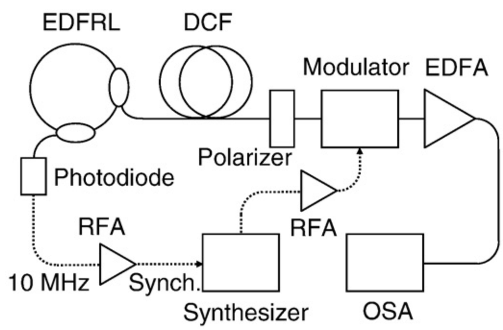

Fig. 1. Schematic of the experimental setup. Solid (dotted) lines are used for optical (electrical) signals. EDFRL, erbium-doped fiber ring laser; DCF, dispersion compensating fiber; EDFA, erbium-doped fiber amplifier; RFA, RF amplifier; Synch., synchronization; OSA, optical spectrum analyzer.

number of modulation harmonics and consequently the number of the independent measurements of dispersion obtained from one spectrogram.

The dispersion values that can be measured by the method proposed are determined from the following conditions. First, as pointed above, the peaks in the Fourier transform of the modulated spectrum should be separated. This implies that the temporal interval between the peaks, $\beta_2 L\omega_m$, should be greater than the full width $\Delta\tau$ of the peaks. This leads to the lower limit of the measured dispersion values

$$\beta_2 L \geq \Delta\tau / \omega_m \tag{8}$$

For low dispersions, $\Delta\tau$ is determined by the width of the laser pulse. To decrease the lower limit for the given modulation frequency, we have to use shorter laser pulses. Expression (7) is exact only if the envelope of the interference pattern does not vary with frequency. For the slowly varying envelope, the error is reduced when the number of the interference fringes within the envelope is increased. This number, $\Delta f_{pul}/\Delta f_s$, should be greater than the fringe number N determined by the required accuracy. Inserting the expression for Δf_s, we obtain the second condition for the lower limit of dispersion values

$$\beta_2 L \geq N / (\Delta f_{pul}\omega_m). \tag{9}$$

Comparing conditions (8) and (9), we see that condition (9) is stronger. The upper limit of dispersion values can be obtained from the condition that the fringe width, Δf_s, should be greater than the resolution Δf_{OSA} of an OSA

$$\beta_2 L < 1 / (\Delta f_{OSA} s_{max} \omega_m), \tag{10}$$

where s_{max} is the maximum order of the peaks used for the dispersion measurement. It can be seen from Eq. (10) that high dispersion values are unlimited because the modulation frequency can be lowered to the required value. Only fiber losses will practically limit the measurement of large dispersions.

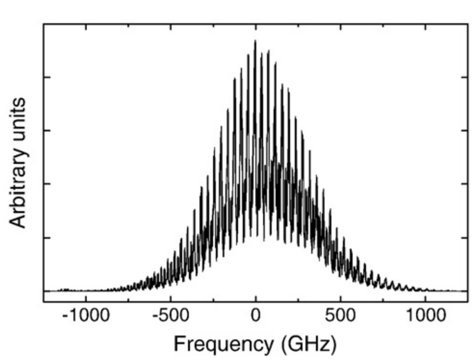

Fig. 2. Measured spectrum of the laser pulses dispersed by the DCF and sinusoidally phase modulated with a frequency of 14 GHz.

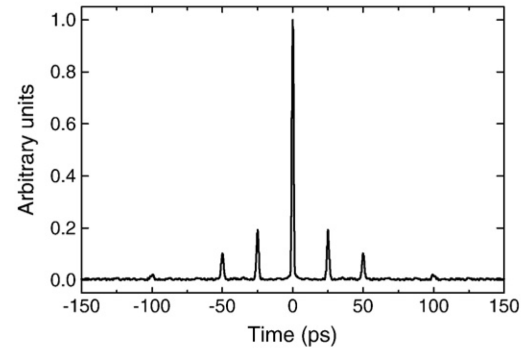

Fig. 3. Fourier transform of the spectrum shown in Fig. 2.

3. Experimental setup and results

The experimental setup is shown in Fig. 1. A passively mode-locked erbium-doped fiber ring laser (EDFRL) was used as the optical pulse source. It was operated at a wavelength of $\approx$1550 nm and generated $\approx$1 ps optical pulses with a 10 MHz repetition rate. For the fiber under test, we used 2.039 km of dispersion compensating fiber (DCF). The laser pulses were first stretched by the fiber to be measured and then sinusoidally phase modulated by an electro-optic modulator with a modulation frequency of 14 GHz. The detected RF signal of 10 MHz from the laser was used for the synchronization of an RF synthesizer supplying a sinusoidal voltage to the modulator.

The spectrum of the modulated dispersed pulses (spectral interference pattern) measured by means of an OSA with a resolution of 0.015 nm is shown in Fig. 2. It can be seen from Fig. 2 that the full width of the pattern envelope as well as of the laser pulse spectrum is equal $\Delta f_{pul} \approx 2000$ GHz. Fig. 3 shows the Fourier transform of the spectrum presented in Fig. 2. We recorded four times the spectral interference patterns and performed processing for the two peaks ($s = 1, 2$) in their Fourier transforms (see Fig. 3) as described above. From these results we found the averaged values of $\beta_2 L$ and the non-quadratic component $\varphi_{nq}(\omega)$ of the DCF spectral phase shown in Fig. 4. The averaged spectral phase $\varphi(\omega)$ was calculated as the sum of the quadratic and non-quadratic components. If the contribution of the spectral phase of the laser pulse is not negligible, it can be taken into account in the following way: an additional fiber is taken and the spectral phase difference $\Delta\varphi(\omega)$ is measured separately for each of these fibers (one of them is the fiber under test) and for the two fibers connected together. From the three measurements, each of the

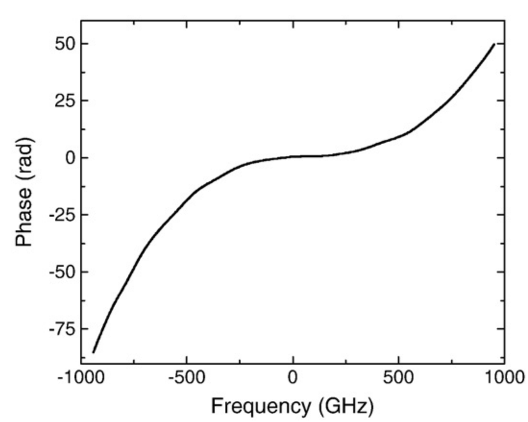

Fig. 4. Non-quadratic component $\varphi_{nq}(\omega)$ of the DCF spectral phase measured by our method.

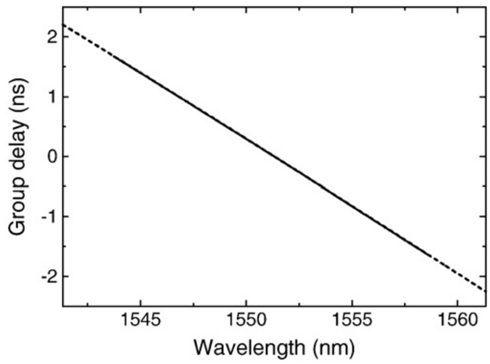

Fig. 5. Group delay of the DCF measured by our method (solid line) and by the phase shift method (dashed line).

dispersions as well as the laser pulse spectral phase can be obtained. We verified that for our experiments the pulse spectral phase can be neglected.

The group delay of the fiber can be found as $t_{gr}(\omega) = -\mathrm{d}\,\varphi(\omega)/\mathrm{d}\,\omega$. The averaged measured group delay of the DCF is shown in Fig. 5 as a function of wavelength (solid line). The dispersion at the central wavelength ($\lambda_0 = 1551.32$ nm) averaged over eight measurements was found to be -223.2 ± 0.3 ps/nm with a dispersion slope of -0.65 ± 0.02 ps/nm^2. This corresponds to relative errors for the dispersion and its slope of 1.3×10^{-3} and 3.1×10^{-2}, respectively.

For testing our method, we also measured the dispersion of the DCF by the widely used phase shift technique. We modulated the intensity of a cw light from a tunable semiconductor laser with a modulation frequency of 2.5 GHz and then transmitted it trough the DCF. The detected signal was recorded with a 50 GHz oscilloscope. The laser wavelength was scanned and the appropriate phase shift of the oscilloscope signal, averaged over sixteen oscilloscope scannings, was measured. We performed nine measurements and the averaged group delay as a function of wavelength is shown in Fig. 5 (dashed line). The averaged measured dispersion and the dispersion slope at the central wavelength was found to be -223.1 ± 1.2 ps/nm and -0.48 ± 0.11 ps/nm^2, respectively. The relative errors of these two quantities are 5.4×10^{-3} and 0.23, respectively.

We can see the excellent agreement between the results obtained by the two methods. The difference between the lines in Fig. 5 does not exceed 5.8 ps. The relative difference between the averaged dispersions, measured by the two methods, is 4.5×10^{-4}. However, the relative errors of the dispersion and dispersion slope measurements for our method are lower than what is obtained in the phase shift method by factors of 4.0 and 7.4, respectively. The difference between the measured values of $\tau_1$and $\tau_2/2$ for the first and second peaks, respectively, in the Fourier transform of the same interference pattern characterizes the error of our method. The averaged relative difference was found to be 2×10^{-3}, that is approximately equal to the accuracy of the spectrum analyzer and to the relative error of the dispersion measurements. The larger error of the phase shift method can be explained by three reasons: variations of the dispersion with time [4] due to long measurement time (about half an hour for one dispersion measurement), inaccuracy in the measurement of a time interval with the oscilloscope ($\approx$7 ps), and instability of the oscilloscope triggering.

We can estimate the lower limit of dispersion values that could be measured in our experiments. Substituting $N = 5$, $\Delta f_{\mathrm{pul}} = 2000$ GHz, $\omega_m/(2\pi) = 40$ GHz into Eq. (9), we obtain for dispersion 9.95 ps^2 or 7.8 ps/nm what corresponds to 70 m of the DCF used in the dispersion measurement.

4. Conclusions

In conclusion, we have presented a method for measuring the chromatic dispersion of optical fibers that is based on modulating dispersed laser pulse and the measurement of its spectrum by an optical spectrum analyzer. The experimental comparison of the proposed and conventional methods showed excellent agreement, but our technique provides lower errors. Its additional advantages are simplicity and ability to perform fast measurements over a broad wavelength range (the scanning time for an OSA is 500 ms). Unlike conventional spectral interferometry, the technique proposed does not employ an interferometer, and is less therefore affected by environmental conditions. In addition, it allows characterization of large dispersions what is important for installed fiber links.

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