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

Naum K. Berger *, Boris Levit, Baruch Fischer

Department of Electrical Engineering, Technion, Israel Institute of Technology, Haifa, 32000, Israel

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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].

* Corresponding author. Tel.: +972 4 8294628; fax: +972 4 8295757.
E-mail address: chrberg@techunix.technion.ac.il (N.K. Berger).

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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

$$F_{out}(\omega)=F_{in}(\omega)\exp[-i\beta_2L\omega^2/2+i\varphi_{nq}(\omega)], \qquad (1)$$

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

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

where $E_{out}(t)$ is the complex pulse amplitude at the output of the tested fiber and the periodic modulation function $f_{\text{mod}}(t)$ 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

$$F_{\text{mod}}(\omega)=\sum_{n=-N}^{N}c_nF_{out}(\omega-n\omega_m). \qquad (3)$$

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

$$F_{\text{mod}}(\omega)=\sum_{n=-N}^{N}c_nF_{in}(\omega-n\omega_m)\exp\{-i[\beta_2L(\omega-n\omega_m)^2/2]+i\varphi_{nq}(\omega-n\omega_m)\}. \qquad (4)$$

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

$$I_{\text{mod}}(\omega)=|F_{\text{mod}}(\omega)|^2\approx|F_{in}(\omega)|^2\sum_{s=-2N}^{2N}B_s\exp[is\beta_2L\omega_m\omega-is\omega_m\varphi_{nq}'(\omega)],$$
$$B_s=\sum_{k=-N}^{N}c_{k+s}c_k^*\exp\{-i[(k+s)^2-k^2]\beta_2L\omega_m^2/2\}, \qquad |k+s|\le N, \qquad (5)$$

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 $\exp(is\beta_2L\omega_m\omega)$ 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 $\Delta f_s=1/(s\beta_2L\omega_m)$. 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, $\Psi_{\text{mod}}(t)$, of the measured spectrum (5) of the modulated stretched pulses can be written as

$$\Psi_{\text{mod}}(t)=\sum_{s=-2N}^{2N}\Psi_s(t-s\beta_2L\omega_m), \qquad (6)$$

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 4 N + 1 peaks spaced approximately by the temporal interval $\beta_2L\omega_m$. 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 $\Psi_s(t-s\beta_2L\omega_m)$. From its position $\tau_s=s\beta_2L\omega_m$, we extract the value of the first-order dispersion

$$\beta_2L=\tau_s/(s\omega_m). \qquad (7)$$

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 $\beta_2L\omega^2/2$ 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