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Fiber chromatic dispersion measurement based on wavelength-to-time mapping using a femtosecond pulse laser and an optical comb filter

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Abstract

A novel method for the measurement of chromatic dispersion of an optical fiber based on wavelength-to-time mapping using a femtosecond pulse laser (FSPL) and an optical comb filter is proposed and experimentally evaluated. In the proposed approach, the spectrum of an ultrashort optical pulse generated by an FSPL is sliced by an optical comb filter. The spectrum-sliced optical pulse is then coupled into the optical fiber under test. Thanks to the chromatic-dispersion-induced wavelength-to-time mapping in the optical fiber under test, a time-domain waveform similar to the sliced spectrum is generated at the output of the optical fiber, with different frequency components having different time delays. The time delay vs. frequency data are then recorded for the estimation of the chromatic dispersion by using least square fitting. Chromatic dispersions of two types of optical fibers with different lengths are tested. The measured dispersion values agree well with those measured by the conventional modulation phase shift (MPS) method.
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Keywords: Chromatic dispersion measurement; Optical fiber; Femtosecond pulse laser; Comb filter; Microwave pulse generation

1. Introduction

Chromatic dispersion is one of the key impairments that limit the transmission distance of an optical communications system. Chromatic dispersion is resulted from the variations in group velocity for different optical spectral components traveling in an optical fiber. These variations in group velocity cause pulse broadening, limiting the data rate of an optical communications system. Different techniques have been developed to compensate for the chromatic dispersion in an optical fiber link. For chromatic dispersion compensation and management, it is essential to measure accurately the chromatic dispersion.

Many techniques have been developed in the past to measure the chromatic dispersion of an optical fiber [1–7]. In general, these techniques can be classified into three categories, the time-of-flight (TOF) method [1,2], the modulation phase shift (MPS) method [3–5], and the optical-interferometry-based method [6,7]. The TOF method is the most direct way to measure chromatic dispersion, in which the spectrum of a broadband pulse source is filtered by a tunable optical filter or a monochromator. By tuning the center wavelength of the optical filter or the monochromator, time-domain electrical pulse with different time delays are measured, which are used to calculate the chromatic dispersion of the fiber under test [1,2]. The MPS method is a well-established technique and has become an industrial standard for dispersion measurement [3–5]. However, this approach requires an expensive vector network analyzer to measure the electrical phase response.

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The optical-interferometry-based method has the highest measurement accuracy, but the length of the fiber under test is typically limited to a few meters [6]. Abedin et al. [7] proposed a method to measure chromatic dispersion of a long fiber using a Sagnac interferometer, where an off-centered phase modulator was placed in the ring interferometer, to which a swept-frequency RF signal is applied. There are also other chromatic dispersion measurement and monitoring methods, such as dispersion measurement employing dispersion-flattened fiber [8], residual dispersion measurement based on self-phase modulation and optical filtering [9], dispersion monitoring based on four-wave mixing [10], dispersion monitoring using side band optical filtering, and clock phase shift detection [11].

In this paper, we propose a novel one-time measurement method to estimate the chromatic dispersion of an optical fiber based on wavelength-to-time mapping using a femtosecond pulse laser (FSPL) and an optical comb filter. In the proposed approach, a femtosecond pulse from the FSPL is first spectrum-sliced by the optical comb filter, which is then applied to the optical fiber under test. Thanks to the chromatic-dispersion-induced wavelength-to-time mapping in the optical fiber under test, a time-domain waveform similar to the sliced spectrum is generated, with different frequency components having different time delays. The proposed approach actually falls into the TOF category. However, it is different from the conventional TOF approach, where a tunable filter or a monochromator with one narrow transmission peak is used [1,2]; the approach proposed here uses an optical comb filter with multiple transmission peaks. In our approach, the wideband spectrum of the ultrashort pulse is sculptured by the comb filter and then passing through the dispersive optical fiber under test. The dispersive fiber exhibits a group velocity that is dependent on the optical wavelength. Hence, the dispersion of the fiber performs wavelength-to-time mapping that converts the spectral shape to a temporal waveform that is recorded by an oscilloscope. The dispersion value of the fiber under test can be estimated by using multiple sets of time delay vs. wavelength data, which could be implemented with a one-time measurement of the sliced spectrum and the temporal waveform. The key difference between the proposed method and the conventional approaches is that in the conventional approaches a tunable filter or a monochromator is used with multiple measurements by selecting different wavelengths. The chromatic dispersion estimation based on one-time measurement alleviates the effect of time variation of the devices in the system, such as the pulsed laser source and the optical filter, which affects the measurement accuracy. The proposed method provides a fast and simple way for an accurate measurement of the chromatic dispersion of an optical fiber.

2. Theory

The schematic diagram of the proposed scheme is shown in Fig. 1. The key devices in the setup are the FSPL and the optical comb filter. The FSPL is a passively mode-locked fiber laser that generates femtosecond pulse train. The optical comb filter can be an unbalanced Mach–Zehnder interferometer or a Sagnac-loop filter (SLF), which offers multiple transmission peaks within the optical spectrum of the FSPL. The pulses from the FSPL are first spectrum-sliced by the optical comb filter. The output from the optical comb filter is then fed to a 95:5 coupler, one output port of the coupler is connected to the optical fiber under test, and the other port is connected to an optical spectrum analyzer (OSA), to monitor the sliced optical spectrum. Thanks to the chromatic-dispersion-induced wavelength-to-time mapping in the optical fiber under test, the time-domain waveform similar to the sliced spectrum is generated at a photodetector (PD), which is monitored by a digital sampling oscilloscope (OSC). The OSC is operating in the trigger mode with a trigger signal from the FSPL.

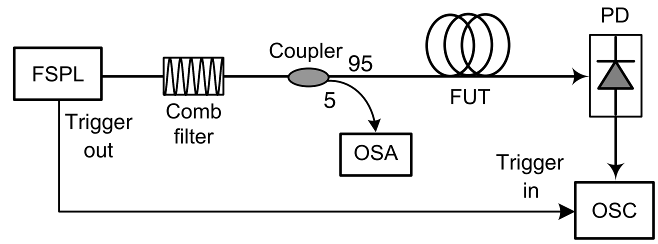

Fig. 1. Experimental setup for the measurement of fiber chromatic dispersion (FSPL: femtosecond pulse laser; FUT: fiber under test; PD: photodetector; OSA: optical spectrum analyzer; OSC: sampling oscilloscope).

The proposed approach is different from the conventional TOF method, where a tunable filter or a monochromator is required to generate at least two sets of time delay vs. wavelength data by tuning the center wavelength of the filter or the monochromator. In [12], Tong et al. proposed a method that can measure the chromatic dispersion with a single measurement. However, the approach requires the use of an ultrashort pulse source with a special spectral shape, which may increase the complexity and the cost of the system. In addition, the approach in [12] can provide only a few reference points, which may limit the measurement accuracy. In our approach, a commercially available FSPL and a fixed optical comb filter are used. A one-time measurement would generate multiple sets of time delay vs. frequency data. The use of the multiple sets of data with least square fitting would increase the chromatic dispersion estimation accuracy.

In theory, the electrical field of an ultrashort transform-limited Gaussian pulse after propagating through an optical fiber under test with length L can be modeled as [13]

$$E_L(t) = \exp\left(-\frac{t^2}{\tau^2}\right)\exp\left(-\mathrm{j}\frac{t^2}{2\beta_2 L}\right) \tag{1}$$

where β_2 is the second-order derivative of the propagation constant with respect to the angular frequency, and 2τ is the $1/e$ width of the Gaussian pulse after experiencing the chromatic dispersion. Here, we assume $\beta_2 L/\tau^2 << 1$, which means that the input pulse duration is much smaller than that after the dispersive fiber. This is always true for sub-picosecond pulses propagating in a few hundred of meters of standard single mode fiber (SSMF) [14].

The impulse response of the comb filter can be expressed as

$$h_f(t) = \frac{1}{2}[\delta(t) + \delta(t - t_0)], \tag{2}$$

where t_0 is the time delay difference between the two taps in the comb filter. For simplicity without losing generality, here we only consider a filter with two taps, such as an SLF with one section of polarization maintaining fiber (PMF).

After propagating through the comb filter, the output electrical field is

$$\begin{aligned} E_{L,f}(t) &= E_L(t) * h_f(t) \\ &= \frac{1}{2}\exp\left(-\frac{t^2}{\tau^2}\right)\exp\left(-j\frac{t^2}{2\beta_2 L}\right) + \frac{1}{2} \\ &\quad \times \exp\left[-\frac{(t-t_0)^2}{\tau^2}\right]\exp\left[-j\frac{(t-t_0)^2}{2\beta_2 L}\right], \end{aligned} \tag{3}$$

where $*$ denotes the convolution operation.

The electric current at the output of the PD is proportional to the intensity of the input electrical field, which can be expressed as

$$\begin{aligned} I_{L,f}(t) &= \Re|E_{L,f}(t)|^2 \\ &= \frac{1}{4}\Re\exp\left[-2\frac{t^2}{\tau^2}\right] + \frac{1}{4}\Re\exp\left[-2\frac{(t-t_0)^2}{\tau^2}\right] \\ &\quad + \frac{1}{2}\Re\exp\left[\frac{-t^2-(t-t_0)^2}{\tau^2}\right]\cos\left(\frac{t_0}{\beta_2 L}t\right), \end{aligned} \tag{4}$$

where $\Re$ is the responsivity of the PD.

It can be deduced from (4) that the output signal is a microwave pulse with a frequency

$$f = \frac{t_0}{2\pi\beta_2 L} = \frac{1}{|DL|\Delta\lambda} \tag{5}$$

and a period

$$T = \frac{2\pi|\beta_2 L|}{t_0} = |DL|\Delta\lambda, \tag{6}$$

where D is the fiber dispersion coefficient in ps/nm/km, $\Delta\lambda$ is the free spectral range (FSR) of the comb filter in nm. Therefore, the dispersion parameter of the fiber can be estimated according to the temporal period of the generated microwave pulse.

A simulation is performed to verify the model in (4). In the simulation, we assume that the input pulse is Gaussian shaped with a FWHM of 350 fs, the time delay difference of the comb filter is 10.0 ps (corresponding to a FSR of 0.8 nm at the 1550 nm band), and the dispersion coefficient of the SSMF is 17 ps/nm/km. After spectrum slicing, the pulse is experiencing the chromatic dispersion in a 4 km SSMF. The generated time-domain waveform is obtained at the output of the PD. Fig. 2 shows the time-domain waveforms by simulation and the given model in (4). An excellent match is observed, which approves the correctness of the given model.

If the fiber under test has higher order dispersions, i.e. $\mathrm{d}D/\mathrm{d}\lambda \neq 0$ the resultant microwave pulse will be chirped, which corresponds to the nonlinear wavelength-to-time mapping. The period of the generated waveform is related to the first- and second-order dispersion parameters D_{λ_0} and $\mathrm{d}D/\mathrm{d}\lambda|_{\lambda_0}$ of the fiber at wavelength λ_0 as

$$T = D_{\lambda_0} L\Delta\lambda + \frac{1}{2}\frac{\mathrm{d}D}{\mathrm{d}\lambda}\bigg|_{\lambda_0} L(\Delta\lambda)^2. \tag{7}$$

The relationship of the wavelength difference between the adjacent peaks in the sliced spectrum and the time delay difference between the adjacent peaks in the time-domain waveform after the chromatic dispersion is illustrated in Fig. 3.

It is worth pointing out, in addition to the application of the proposed approach for chromatic dispersion measurement, the same experimental setup can also be used to generate microwave or millimeter-wave signals. The frequency of the generated waveform is $f = 1/(|DL|\Delta\lambda)$, which is determined by the FSR of the comb filter and the total dispersion in the system.

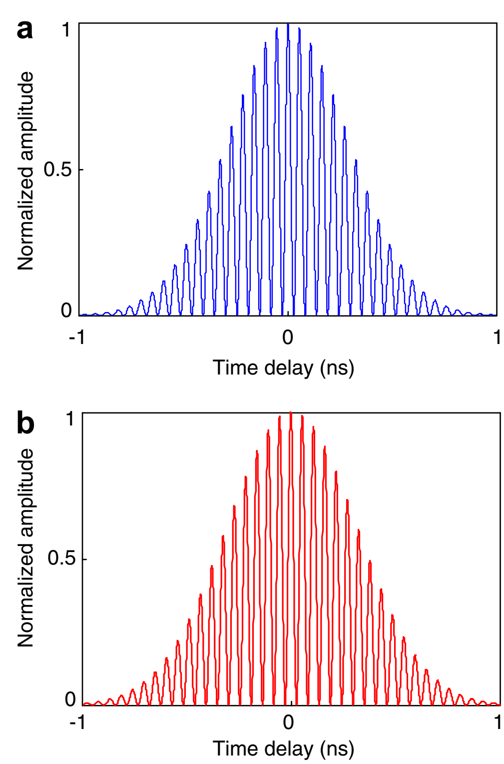

Fig. 2. Time-domain waveforms obtained (a) by simulation and (b) by the given model. The FSR of the SLF is 0.8 nm; the length of the SSMF is 4 km.

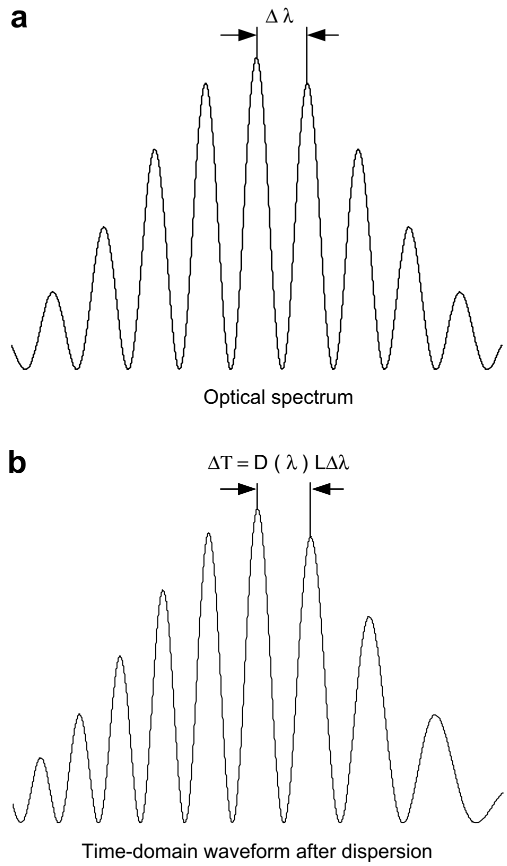

Fig. 3. (a) Spectrum of the femtosecond pulse after slicing by the optical comb filter and (b) the corresponding time-domain waveform after propagating through the fiber to be test.

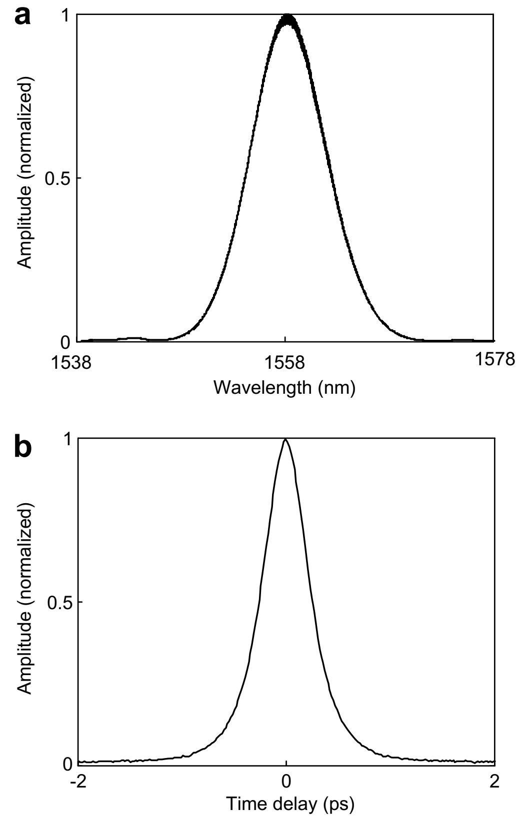

Fig. 4. (a) The femtosecond pulse laser spectrum and (b) the autocorrelation trace.

3. Experimental results and discussion

An experiment is performed based on the setup shown in Fig. 1. In the experimental setup, the FSPL is a commercially available passively mode locked fiber laser that can generate a pulse train with a pulse width of 350 fs and a repetition rate of 48.6 MHz. The output power of the FSPL is 2.5 mW. To avoid nonlinearity-induced distortions, an optical attenuator (9 dB) is inserted between the FSPL and the SLF to reduce the power to the fiber under test. We then compare the optical spectra before and after the fiber under test. It is found that the spectra are almost identical except for some attenuation, which confirms that the propagation of the pulse through the fiber is dominated by the chromatic dispersion. The optical spectrum and the autocorrelation trace of the pulse from the FSPL are shown in Fig. 4a and b. The 3 dB spectrum width of the femtosecond pulse is around 8 nm. The optical comb filter in the experiment is a SLF with one section of PMF. Two polarization controllers (PCs) are placed in the loop to control the polarization state of the light [15]. The FSR of the SLF is dependent on the length and the birefringence of the PMF. The SLF configuration and its power transmission spectrum are shown in Fig. 5a and b.

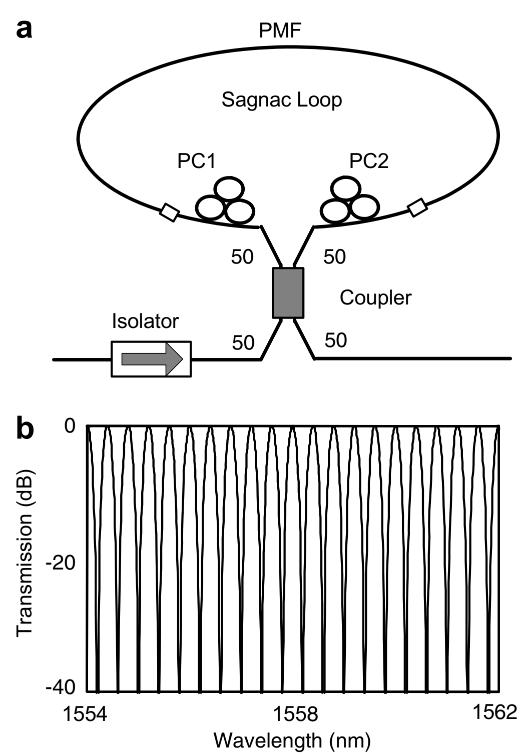

Fig. 5. (a) The Sagnac-loop filter with one section of PMF and (b) the transmission spectrum of the Sagnac-loop filter with an FSR = 0.4 nm. PMF: polarization maintaining fiber.

The sliced spectrum of the femtosecond pulse by the SLF with an FSR of 0.4 nm and its corresponding time-domain waveform after propagating through a 4 km SSMF are shown in Fig. 6. The similarity between the sliced spectrum and the time-domain waveform after dispersion is observed. However, a pedestal in the time-domain waveform appears, as shown in Fig. 6b, which is not expected in our theoretical prediction based on (4) and the simulation result as shown in Fig. 2. This is caused by the non-flat frequency response of the PD and the RF amplifier used in the experiment. The gain of the PD at frequencies over 20 GHz is lower than that at the dc for about 2 dB, which leads to a lower modulation depth in the experiment. However, for chromatic dispersion measurement, the pedestal does not have a negative effect, since we are only concerned with the time delay values at peaks of the waveform.

In the experiment, two types of optical fiber samples are tested. The first sample is a 4 km SSMF. The second is a nonzero dispersion shifted fiber (NZ-DSF) with a length of 25 km. The experimental results of the time delay vs. wavelength measurement are shown in Fig. 7a. The dispersion parameters D at different wavelengths are calculated using least square fitting. The calculated D vs. wavelength is shown in Fig. 7b.

For comparison, the dispersion parameters of the two samples are also measured using the MPS method. In the measurement, a tunable laser, a Mach–Zehnder modulator (MZM) and a vector network analyzer (VNA) are used. The VNA is used to measure the phase response of the fiber under test with different input wavelengths while keeping the modulation frequency. The group delay and the dispersion parameter of the fiber under test are calculated according to the recorded wavelength vs. phase response data. The modulation frequencies for the measurement of 4 km SSMF and 25 km NZ-DSF are chosen to be 600 MHz and 300 MHz, respectively. The results are shown in Fig. 7b, which agree well with the results by the proposed method. A comparison of the measured values and the nominal values provided by manufacturer is provided in Table 1. The measurement resolution of ±0.02 ps/nm/km for the 25 km

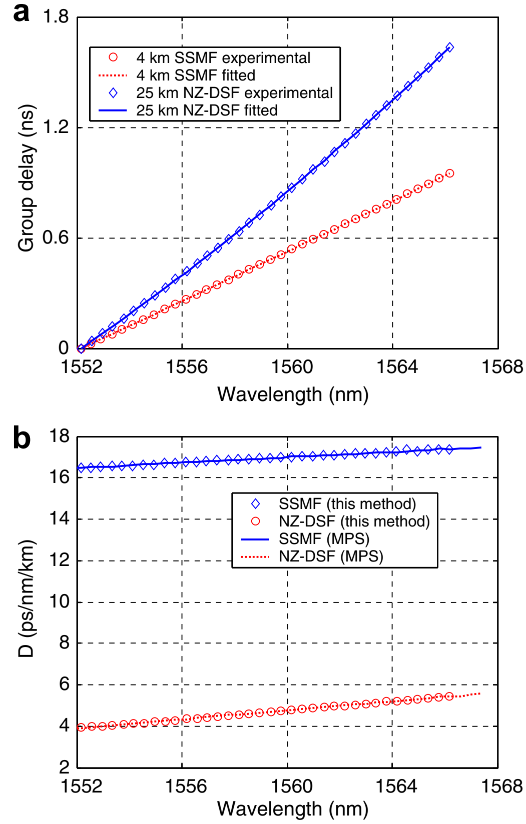

Fig. 7. Experimental results. (a) The measured group delays, and (b) the calculated dispersion parameters. The dispersion parameters measured by the MPS method are also shown for comparison.

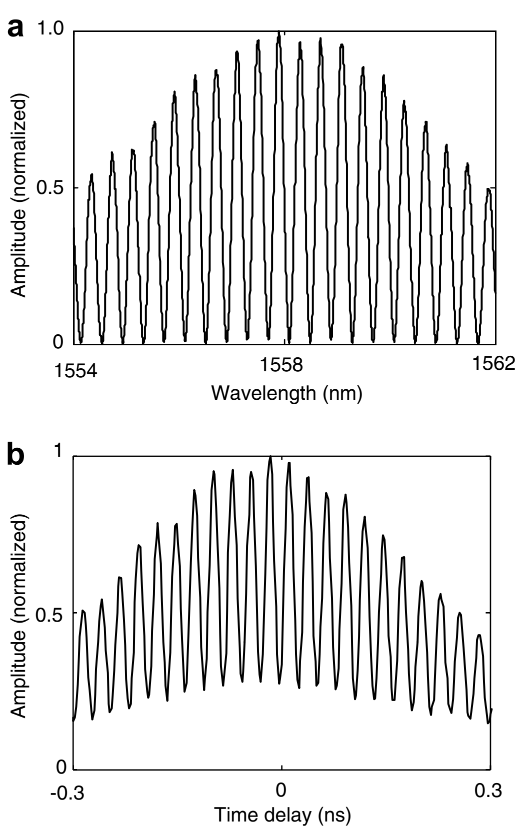

Fig. 6. (a) The spectrum of the sliced femtosecond pulse laser by the Sagnac-loop filter with an FSR of 0.4 nm and (b) its corresponding time-domain waveform after propagating through 4 km of SSMF.

Table 1
Comparison of the measured dispersion parameters and the nominal values provided by manufacturer

Fiber type		SSMF	NZ-DSF
This method	@1552 nm	$D = 16.51 \pm 0.05$	$D = 3.93 \pm 0.02$
	@1560 nm	$D = 17.01 \pm 0.05$	$D = 4.77 \pm 0.02$
MPS method	@1552 nm	$D = 16.54$	$D = 3.92$
	@1560 nm	$D = 16.94$	$D = 4.79$
Nominal values		$D \leqslant 17$ @1550 nm	$D = 2.0–6.0$ @ 1530–1565 nm

NZ-DSF and ±0.05 ps/nm/km for the 4 km SSMF are estimated based on the 0.01 nm spectral resolution of the optical spectrum analyzer and the 1 ps temporal resolution of the applied oscilloscope. As can be seen, the dispersion parameters obtained from the proposed approach match well with the MPS results and the nominal values provided by the manufacturers, which demonstrate the accuracy of the proposed method. Note that the second-order dispersion can also be estimated by this method according to (7). In addition, the second-order dispersion parameters found by the least squares fitting are $\mathrm{d}D/\mathrm{d}\lambda = 0.064$ ps/nm^2/km for the SSMF and $\mathrm{d}D/\mathrm{d}\lambda = 0.11$ ps/nm^2/km for the NZ-DSF, both at 1552 nm.

The major error sources of the measurement come from the wavelength reading errors on the OSA and the time delay reading errors on the oscilloscope, if the measurement error of the fiber length is not considered. The above reading errors on the accuracy of the dispersion estimation are alleviated in our approach by the least square fitting using the multiple wavelength vs. time delay data obtained in a one-time measurement. In addition, the use of a comb filter with a higher finesse (that means sharper wavelength peaks) would increase the measurement precision.

We know that the frequency of the generated waveform is $f = 1/(|DL|\Delta\lambda)$. Therefore, the smallest dispersion that can be measured is determined by the maximum frequency that can be supported by the experimental setup (i.e. photodiode and the oscilloscope). For a comb filter with a given period, we have $|DL|_{\min} = 1/(f_{\max}\Delta\lambda)$. For example, in our experiment $\Delta\lambda = 0.4$ nm and $f_{\max} = 50$ GHz, the minimum dispersion that can be measured is $|DL|_{\min} = 50$ ps/nm. To measure a fiber with a smaller dispersion, the use of a comb filter with a larger period should be employed.

In our experiment, the wavelength range of the dispersion measurement is limited by the spectrum width of the FSPL. For wider wavelength range measurement, the use of an FSPL with a wider spectrum width or two or more FSPLs with different spectral coverage could be considered. The use of a supercontinuum light source can also provide a wider wavelength range measurement [2].

Since the time-domain and the wavelength-domain profiles of the waveform are both symmetrical, as shown in Fig. 6, the proposed method cannot tell whether a longer or shorter wavelength travels faster, therefore the sign of the chromatic dispersion is not distinguishable. But this is not a major concern; in practical applications the dispersion sign of an installed fiber is usually known.

Another important feature of the proposed approach is that the system can be used to generate pulsed microwave or millimeter-wave signals. As can be seen from Fig. 6b, the time-domain waveform has a period of 27.8 ps, which corresponds to a millimeter-wave pulse with a frequency of 36 GHz. The frequency of the generated waveform can be increased by simply reducing the length of the dispersive fiber and by using a dispersive fiber with smaller chromatic dispersion [16].

4. Conclusions

In this paper, a novel method for the measurement of chromatic dispersion of an optical fiber using an FSPL and an optical comb filter was proposed and experimentally evaluated. The approach is based on wavelength-to-time mapping in a dispersive fiber. The spectrum of the optical pulse from the FSPL was first sliced by a comb filter. Due to the chromatic-dispersion-induced pulse chirping, the time-domain waveform after chromatic dispersion would have a waveform similar to the sliced spectrum, with different spectral components having different time delays. The dispersion parameters were estimated based on least square fitting using the multiple time delay vs. frequency data. The measured fiber dispersion parameters were well matched with those measured by the MPS method. The key feature of the approach is that a one-time measurement would generate multiple sets of time delay vs. frequency data, which would enable the estimation of the chromatic dispersion with higher accuracy. The method may be applied to a wide range of fibers.

Acknowledgements

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