High precision optical fiber dispersion measurement based on Fourier domain mode-locked laser sweet spot location

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ABSTRACT

Precise dispersion measurement is important for various applications, including optical communications, laser cavity design, and nonlinear optics. In this work, we present a dispersion measurement method for the fiber under test inside the Fourier domain mode-locked (FDML) laser by locating the sweet spot regime under the different driving frequencies of the Fabry-Perot tunable filter. The group delay resolution achieved is 2.88 ps, an order of magnitude higher than other dispersion measurement methods based on phase shift or pulse delay. The proposed dispersion measurement method has high resolution and simple configuration, making it promising for measuring the dispersion of special fibers or conventional fibers near their zero-dispersion wavelengths.

Keywords: Fourier domain mode-locked laser, dispersion measurement, sweet-spot

1. INTRODUCTION

The group velocity is different for different frequencies due to chromatic dispersion, which is one of the fundamental characteristics of optical fibers. Dispersion will broaden the pulses and cause overlapping of adjacent pulses, thus limiting the signal bandwidth in the communication system.[1] In addition, for nonlinear optics applications such as mode-locked lasers,[2] on-chip frequency comb,[3] and nonlinear frequency conversion,[4] it is important to balance dispersion and nonlinearity. Therefore, accurate dispersion measurements are necessary for the control and optimization of fiber optic communication and nonlinear optical systems. Three main techniques, interference, time-of-flight, and phase shift, have been used to measure dispersion.[5] Although the interference method provides the highest group delay resolution of less than a few hundred femtoseconds and a simultaneously measurable wavelength range of more than 500 nm,[6, 7] the maximum length of the fiber under test is limited to several meters, which limits the resolution of the second-order dispersion parameter. In addition, the interference method requires scanning the length of the reference arm or the wavelength of the light source, which is time consuming. Time delay and phase shift methods provide a group delay resolution of tens of picoseconds and can measure long fibers in the kilometer range.[8, 9] Besides the conventional methods, a fast Fourier domain mode-locked (FDML) laser has also been proposed to realize ultrafast dispersion measurement with update rates > 100 Hz.[10] Using the optical frequency comb, a novel dispersion measurement can realize a group delay uncertainty of 16 ps and a second-order dispersion parameter uncertainty of 200 fs/nm/km for a 1 km long single-mode fiber (SMF).[11] However, in some applications such as laser cavity design where near zero-dispersion measurement is important,[12, 13] higher resolution in the order of picoseconds or beyond is desirable.

The FDML laser is a novel swept laser that can avoid laser rebuilding from spontaneous emission by inserting a long SMF into the laser cavity to buffer the entire swept signal. If the driving frequency of the tunable filter is well matched with the round-trip of a certain wavelength, the low-noise sweet spot region can be achieved in an FDML laser. In other words, the sweet spot location of the FDML laser can be observed by changing the driving frequency of the tunable filter corresponding to different wavelengths due to different group velocities. Therefore, the dispersion of the SMF near its zero-dispersion wavelength can be derived. In this paper, we demonstrate a high precision optical fiber dispersion measurement method with a group delay resolution of 2.88 ps for a double-passed 1.743-km SMF in the FDML laser within 40 seconds. This high-resolution dispersion measurement with a simple configuration can also be applied to other

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wavelength bands, which is significant for dispersion engineering in fiber optic communication and nonlinear optical systems.

2. EXPERIMENTAL SETUP AND PRINCIPLE

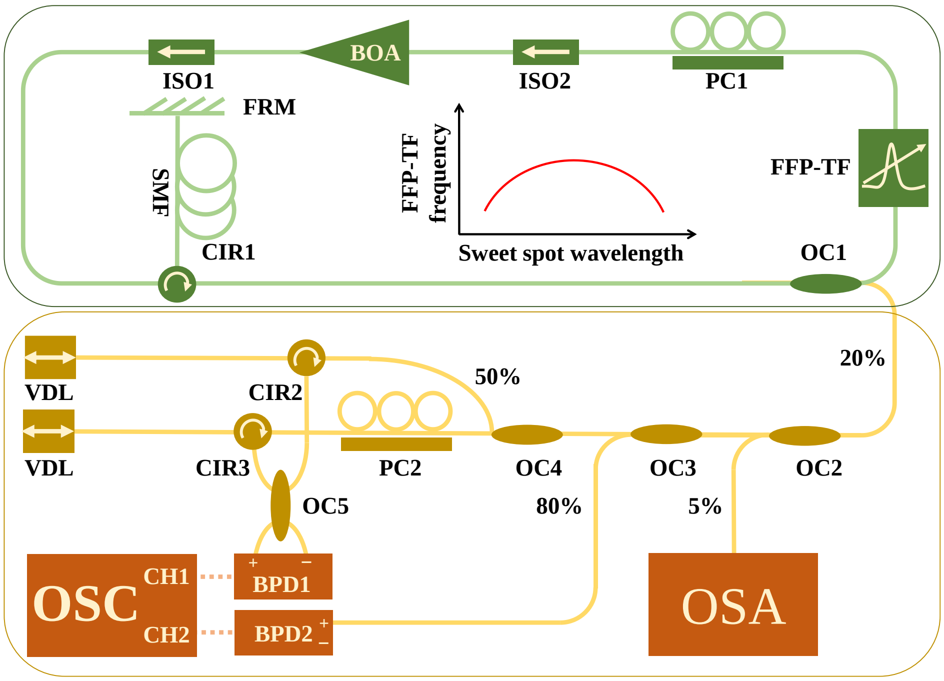

Figure 1. Experimental setup of the FDML laser and dispersion characterization system.

Figure 1 shows the experimental setup. The green components show the configuration of the FDML laser, the double-pass 1.743-km SMF is used to store the wavelength-swept signal in the cavity and to avoid laser rebuilding from the amplified spontaneous emission. The combination of circulator (CIR) and Faraday rotating mirror (FRM) is used to avoid the influence of random birefringence in the SMF. A fiber Fabry-Perot tunable filter (FFP-TF) is driven by a sinusoidal signal from an arbitrary waveform generator (AWG, Keysight, 33600A). The booster semiconductor optical amplifier (BOA, Thorlabs, BOA1004S) provides gain to the FDML laser. The polarization controller (PC) optimizes the polarization of the input light into the BOA to maximize gain and flatten the laser spectrum. Two isolators (ISOs) are used to ensure unidirectional laser emission. Twenty percent of the laser signal is coupled out of the cavity by an optical coupler (OC).

The driving frequency of the FFP-TF is tuned to match the round-trip time of the zero-dispersion wavelength according to Eq. (1.1)

$$f_0 = \frac{c}{n_0 l_c}, \tag{1.1}$$

where f_0 is the driving frequency of the FFP-TF corresponding to the round-trip time of the zero-dispersion wavelength, c is the speed of light in vacuum, n_0 is the reflective index at the zero-dispersion wavelength, and l_c is the cavity length. The sweet-spot region can be observed when the driving frequency of the FFP-TF matches well with the round-trip time of a certain wavelength. The sweet spot region can be characterized by low relative intensity noise (RIN).[14] Two different sweet-spot regions corresponding to wavelengths λ_1 and λ_2 can be identified in the temporal waveform due to the coexistence of normal and abnormal dispersion near the zero-dispersion wavelength. In the experiment, we determine the location of the sweet spot by adjusting the driving frequency of the FFP-TF with a frequency step of 10 mHz. The group delay can be expressed as

$$GD(\lambda_1,\lambda_2)=\frac{1}{f_0-n(\lambda_1,\lambda_2)f_s}-\frac{1}{f_0}, \tag{1.2}$$

where $n(\lambda_1,\lambda_2)$ is the frequency steps required for λ_1 and λ_2 to achieve sweet-spot operation.

The yellow components show the dispersion characterization system. Five percent of the laser output signal is detected by an optical spectrum analyzer (OSA, Yokogawa, AQ6370D). Twenty percent of the OC3 output signal is inserted into a Mach-Zehnder interferometer (MZI), whose interference signal is detected by a balanced photodetector (BPD1, Thorlabs PDB480C) and acquired by an oscilloscope (OSC, Keysight, DSAX96204Q, 160 GSa/s). A PC is placed in the MZI to ensure identical polarization between the two arms. The BPD1 detects the interference signal from the MZI with a 3 mm optical path difference using two variable delay lines (VDL). Eighty percent of the light from the OC3 is detected by a second balanced photodetector (BPD2) (Coherent, BPDV2120R, 43 GHz) and acquired by the OSC to observe the temporal waveform.

3. EXPERIMENTAL RESULTS AND DISCUSSION

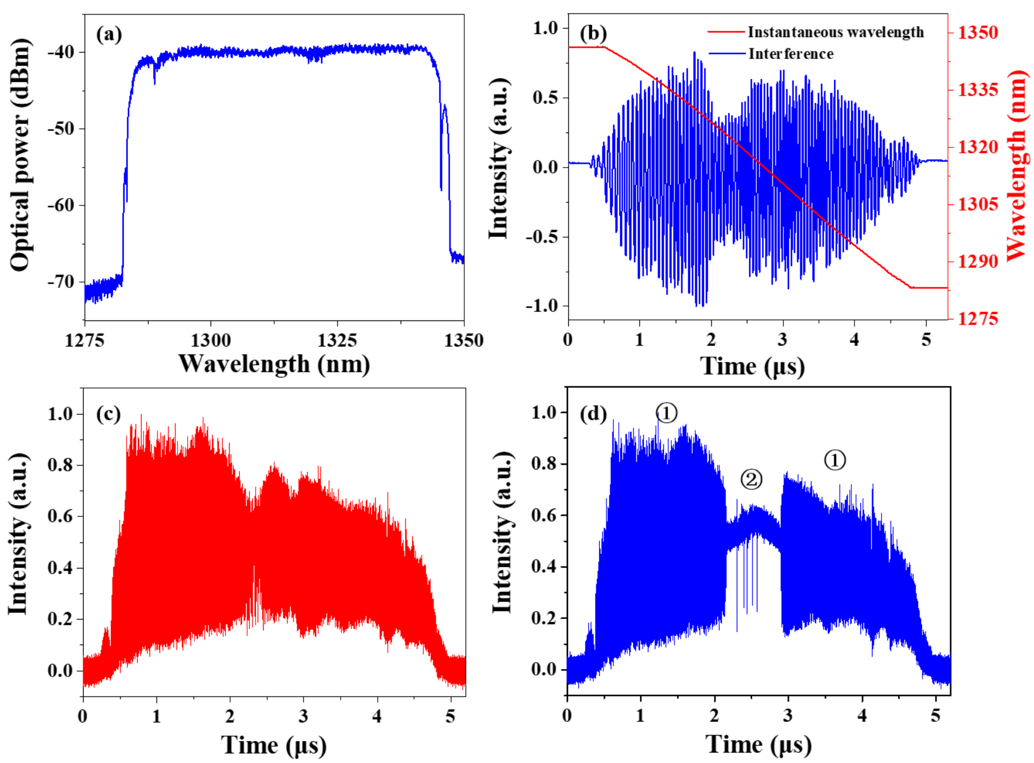

Figure 2. (a) The optical spectrum of the FDML laser. (b) The interference signal and the demodulated instantaneous wavelength. (c) The temporal waveform with the FFP-TF driving frequency at 58936.85 Hz and (d) at 58936.84 Hz.

Figure 2(a) shows the optical spectrum measured by the OSA, where the center wavelength is 1314.7 nm and the bandwidth is 63.24 nm. The interference signal shown by the blue curve in Fig. 2(b) is filtered by a digital low-pass filter with a cutoff frequency of 20 MHz. The instantaneous wavelength shown by the red curve is demodulated by the Hilbert transform based on the interference signal. In our experiment, when the driving frequency of the FFP-TF is 58936.85 Hz, it coincides with the round-trip time of the zero-dispersion wavelength. As shown in Fig. 2(c), the sweet spot region is located between the two high-frequency noise regions in the temporal waveform. According to the time-wavelength mapping relationship shown by the red curve in Fig. 2(b), the zero-dispersion wavelength is 1319.0 nm. When the driving frequency of the FFP-TF is adjusted to 58936.84 Hz, the high-frequency noise (marked with ① in Fig. 2(d)), Nozaki-Bekki holes (marked with ② in Fig. 2(d)),[15, 16] and the sweet spot can be observed simultaneously as shown in

Fig. 2(d). The sweet spot region is where the high RIN region transitions to Nozaki-Bekki holes or vice versa. The two sweet spot wavelengths λ_1 and λ_2 are 1312.2 nm and 1324.1 nm, respectively, based on the time-wavelength mapping. According to Eq. (1.2), their group delay $GD(\lambda_1,\lambda_2)$ relative to the zero-dispersion wavelength is 2.88 ps given that f_0=58936.85 Hz, f_s=0.01 Hz, n=1. Repeating this process and decreasing the driving frequency of the FFP-TF from 58936.85 Hz to 58936.40 Hz, the group delay of all wavelengths within the optical spectrum is measured and plotted in Fig.3 by the blue scatter plot. The measured group delay agrees well with the theoretical group delay (red curve) derived from the Sellmeier equation,[17] where the zero-dispersion wavelength and the zero-dispersion slope are set to 1318.2 nm and 0.086 ps/(nm^2·km), respectively.

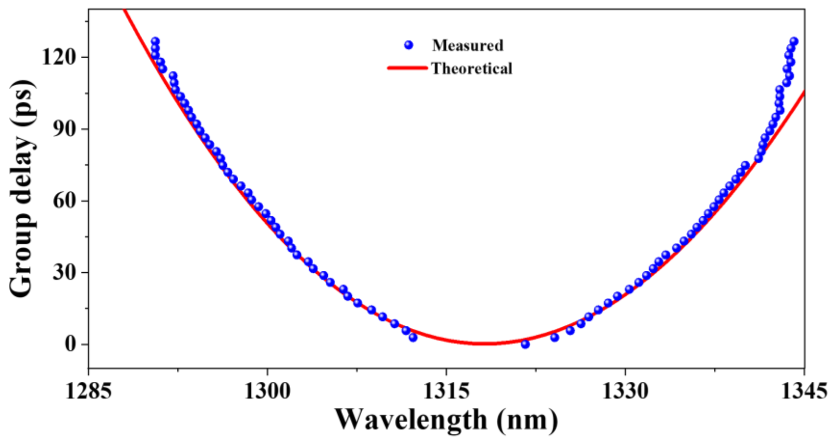

Figure 3. The measured and theoretical group delay.

4. CONCLUSION

We demonstrate that the location of the sweet spot in the laser signal trace of an FDML laser can be used to measure the group velocity dispersion of the fiber inside the FDML laser cavity with a group delay resolution as high as 2.88 ps. The dispersion measurement results are in good agreement with the theoretical results from the Sellmeier equation. The proposed group velocity dispersion method can be used to measure kilometer-level fibers in arbitrary bands and various types of special fibers, such as photonic crystal fibers and anti-resonant hollow-core fibers, whose dispersion is very small.

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