Dispersion measurement of Yb-doped fiber by a spectral interferometric technique

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Received April 7, 2009

The dispersion of Yb-doped fiber is measured by a spectral interferometric technique. The experimental verification is achieved by comparing the measured data with published data of the Nufern 1060xp fiber and the measurement relative error is 1.36%. The parameters of the experimental system, such as minimum required source bandwidth and minimum fiber length, are introduced and analyzed in the measurement. The minimum required source bandwidth predicted through theoretical calculation at the center wavelength of 1070 nm is 19.3 nm, which perfectly agrees with the experimental value.

OCIS codes: 060.2300, 060.2400, 230.2285, 230.7370.
doi: 10.3788/COL20100803.0262.

The group velocity dispersion, or the wavelength dependence of the group index, is one of the fundamental characteristics of an optical fiber. It affects the bandwidth of a high-speed optical transmission system through pulse broadening and nonlinear optical distortion. For the same reason, it also leads to pulse stretching, an obstacle in generating the short pulse in Yb-doped fiber. In order to reduce the dispersion effect, several methods have been used. For instance, dispersion compensation is a well-known technique[1]. Moreover, another technology is also applied in chirped-pulse amplifier (CPA), in which the pulse is stretched first by using the pulse's dispersion characteristics and then amplified to obtain high energy[2]. As such, the dispersion curve of the fiber is a key factor that could aid us in avoiding and utilizing the pulse broadening.

In general, the dispersion measurement of optical fiber is achieved through two widely used methods: the time-of-flight method[3], which measures relative temporal delays for pulses at different wavelengths, and the modulation phase shift technique[4,5] which measures the phase delay of a modulated signal as a function of wavelength. However, both methods require a long fiber, from several tens of meters to several kilometers. Therefore, they are not desirable for characterizing short length fiber. The white-light interferometry based on the well-known standard Michelson[6] or Mach-Zehnder interferometer is considered as one of the best tools for dispersion characterization of short length optical fibers[7]. This technique usually utilizes either a temporal method[8,9] or a spectral method[10−13]. For the temporal method, a precision of 0.0015 ps/nm measured on a 0.8-m-long photonic crystal fiber[14] was recently reported. But a tracking laser is typically required to calibrate the delay path length. The spectral interferometry is generally more stable because the arms of the interferometer are kept stationary to collect data and no tracking laser is needed. Recently, the dispersions of standard fiber[15], photonic crystal fiber[14,16], and even tapered fiber[17] were measured by white-light interferometry, but the dispersion measurement of rare-earth doped fiber has not been mentioned.

The dispersion value of Yb-doped fiber is measured with fiber spectral interferometric technology in this letter. Before the measurement, the experimental system was verified using the Nufern 1060xp fiber. We also analyzed the parameters of our system, such as required source bandwidth, fiber length, and wavelength resolution of the measurement.

The schematic diagram of the experimental setup is shown in Fig. 1. The configuration is based on a fiber Michelson interferometer with a broadband amplified spontaneous emission (ASE) source and an optical spectrum analyzer (OSA). A 3-dB (2×2) fiber coupler is applied to split light into two different arms. The test fiber is inserted into one arm of the interferometer, while the other arm has free space propagation with one collimator. There is a fixed mirror to reflect light back to the test fiber in arm 1. Another mirror is fixed on the stage to change the free space light path length in arm 2. The light of the fiber-coupled ASE source is injected into port 1 of the fiber coupler, and the interference fringe is monitored by OSA in port 2. The maximum visibility in an interferometric fringe is achieved by adjusting a fiber polarization controller (PC).

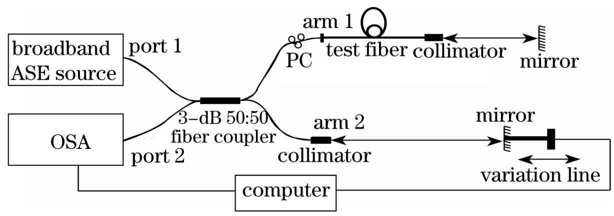

Fig. 1. Experimental arrangement for dispersion measurement by spectral interferometric technique.

1671-7694/2010/030262-04

According to the experimental configuration, E_s and E_r represent the electric field of the signal light traveling in the test fiber and the reference light traveling in the free space arm, respectively. We likewise assume that the light intensities of the two paths are equal. Thus, the interferential intensity would be expressed as

$$I(\lambda) = |E_s + E_r|^2 \propto 1 + \cos[\phi(\lambda)], \tag{1}$$

where $\phi(\lambda) = 2[\beta_s(\lambda)L_{\text{fiber}} - \beta_r(\lambda)L_{\text{air}}]$, β_s and β_r are propagation constants for the signal light and reference light, λ is the wavelength, and L_{fiber} and L_{air} are the test fiber length and the free space arm length, respectively.

If we expand β_s and β_r in Taylor series about the center frequency ω_0, and consider the frequency $\omega = 2\pi c/\lambda$, where c is the light velocity in vacuum, then $\phi(\lambda)$ can be expressed as

$$\begin{aligned}\phi(\lambda) &= \phi_0 + 2\left[\beta_1(\lambda_0)L_{\text{fiber}} - \frac{L_{\text{air}}}{c}\right] \\ &\times \left(\frac{2\pi c}{\lambda} - \frac{2\pi c}{\lambda_0}\right) + \frac{1}{2} \times 2\beta_2(\lambda_0)L_{\text{fiber}}\left(\frac{2\pi c}{\lambda} - \frac{2\pi c}{\lambda_0}\right)^2 \\ &+ \frac{1}{6} \times 2\beta_3(\lambda_0)L_{\text{fiber}}\left(\frac{2\pi c}{\lambda} - \frac{2\pi c}{\lambda_0}\right)^3 + \cdots,\end{aligned} \tag{2}$$

where β_1, β_2, and β_3 represent the 1st-, 2nd-, and 3rd-order derivatives of the propagation constant β_s, respectively. The second term of Eq. (2) is zero at the center wavelength. Moreover, we apply Eq. (2) to fit the interferential fringe by changing ϕ_0, β_2, and β_3. Considering the relationship $D = -2\pi c\beta_2/\lambda^2$, the dispersion of the fiber at the center wavelength can be obtained.

The dispersion of a short piece of single-mode Yb-doped fiber was measured with the experimental system. The simulated result was compared with the experimental spectrum. Parameters, such as the wavelength resolution of measurement, the minimum required source bandwidth, and the minimum fiber length, among other parameters, are analyzed in this system with Yb-doped fiber.

The measurement system was verified using the standard Nufern 1060xp fiber, the standard dispersion curve of which is available to the public. We used a 1.6-m Nufern 1060xp fiber and an ASE source with 100-nm bandwidth in experiment. The interferogram is shown in Fig. 2(a), with the center wavelength at 1046.1 nm. After simulation, we get the dispersion value of –39.170 ps/(km·nm) at 1046.1 nm, while the data from Nufern Inc. is –39.030 ps/(km·nm). Figure 2(b) shows our calculated dispersion curves and the reported value by Nufern Inc. The relative error in our measurement is 1.36%.

The verified system was utilized to measure a 1.3-m single-mode Yb-doped fiber. It is well known that the light near the 980-nm wavelength will be absorbed by the Yb-doped fiber, while the light at the wavelength range of 1030–1060 nm can be propagated with a small absorption. Hence, we chose an ASE source with the wavelength ranging from 1000 to 1100 nm. The spectral emission curve is shown in Fig. (3). Considering the source spectrum, we chose a fiber coupler whose center wavelength was 1050 nm, thus splitting the source light into two equal intensity paths.

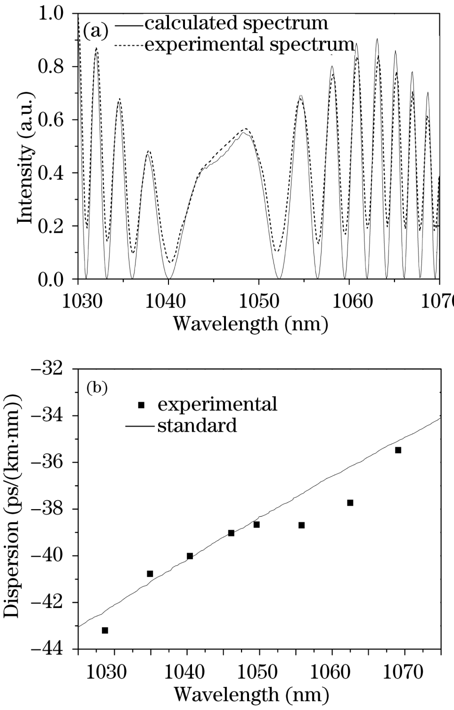

Fig. 2. (a) Interferogram of the Nufern 1060xp fiber at the center wavelength of 1046.1 nm, (b) comparison between the standard and the experimental dispersion value.

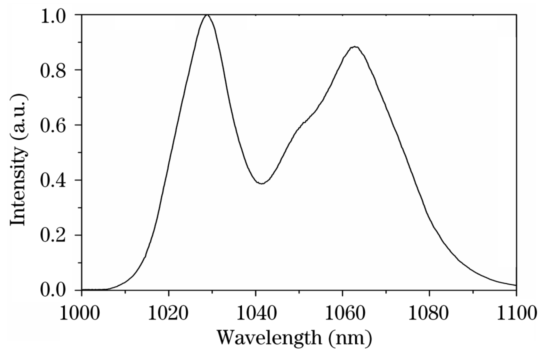

Fig. 3. Spectrum of ASE source in our experimental system.

Figure 4(a) shows the interferogram at the center wavelength of 1070 nm. After curve fitting, the dispersion of the fiber is measured to be –31.608 ps/(km·nm) at this center wavelength. The simulated figure does not agree with the experimental spectral figure perfectly, because the background light caused by the reflection from the fiber coupler is also detected by OSA. Therefore, the maximum visibility, as mentioned by the theory, cannot be achieved in the experiment. We also measured many other dispersion values from 1040 to 1075 nm. The dispersion curve is shown in Fig. 4(b), and the fitting curve is also expressed in this figure.

Using Eq. (2), we introduce some parameters of the system to analyze the dispersion measurement of the Yb-doped fiber. The parameters are discussed as follows.

The wavelength resolution is related to the minimum step size of the mirror translation in the arm 2 and decides the position of the center wavelength λ_0. Its expression, derived from Eq. 2, can be given as

$$\delta\lambda_0 = \frac{\delta L_{\text{air}}}{cL_{\text{fiber}}D(\lambda_0)}, \tag{3}$$

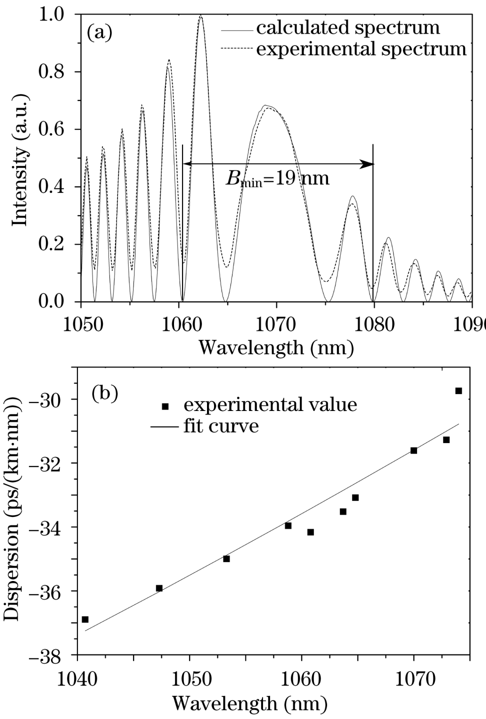

Fig. 4. (a) Interferogram of the Yb-doped fiber at the center wavelength of 1070 nm, (b) experimental dispersion curve and the fit curve of the Yb-doped fiber.

where $\delta\lambda_0$ and $\delta L_{\rm air}$ are the shift of center wavelength and the mirror translation in the reference arm, respectively, and D represents the dispersion of test fiber. Equation (3) is the same as the expression of the wavelength resolution of measurement about the single-arm three-wave interferometer[18], but this is derived from the relative refractive index $n_{\rm eff}$ and also proven to be applicable to three-wave interferometers. Using the Yb-doped fiber, the wavelength resolution of measurement can be calculated. In the measurement, the minimum step size of mirror translation is 1.5 μm. The value of $\delta\lambda_0$ will thus be 0.12 nm, which means that we can measure the dispersion coefficient every 0.12 nm. Equation (3) can also be applied to confirm the abnormal dispersion region and the normal dispersion region. If the product of $\delta\lambda\times\delta L$ is negative, that is to say, when we increase (decrease) the air path, therefore shifting the center wavelength to shorter (longer) wavelengths, the center wavelength will lie in the normal dispersion range of the fiber, and vice versa. In our measurements, this fact has been confirmed.

In Fig. 5, we simulate the interference fringe of a Gaussian spectrum and introduce the definition of the minimum required source bandwidth $B_{\rm min}$. The other two adjacent peaks or four troughs should be contained in the source wavelength range in order to decide the center wavelength. The approximate expression of $B_{\rm min}$ is shown as

$$B_{\rm min} \geq 2|\lambda_2 - \lambda_0| = 2\frac{\lambda_0}{\sqrt{|cL_{\rm fiber}D(\lambda_0)|}}. \quad (4)$$

Equation (4) can be feasible to the normal dispersion and abnormal dispersion. The calculation value of $B_{\rm min}$ is 19.3 nm when the Yb-doped fiber is measured at the center wavelength of 1070 nm. In Fig. 4(a), the value of $B_{\rm min}$ in the experimental spectrum interferogram is 19 nm.

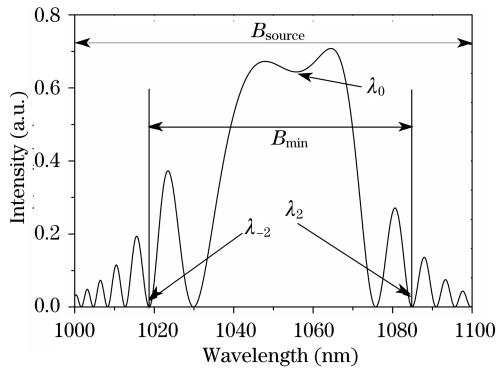

Fig. 5. Interferogram of the simulation and the ranges of the minimum required source bandwidth $B_{\rm min}$ and the source band $B_{\rm source}$. λ_2 and λ_{-2} denote the minimum wavelength and the maximum wavelength of the minimum required source $B_{\rm min}$, respectively.

It is well known that the source bandwidth and the minimum required source bandwidth $B_{\rm min}$ decide the measurable range of the center wavelength. From Fig. 5, the relationship among measurable bandwidth $B_{\rm measure}$, available source bandwidth $B_{\rm source}$, and the minimum required source bandwidth $B_{\rm min}$ is shown as

$$\begin{aligned} B_{\rm measure} &= B_{\rm source} - B_{\rm min} \\ &= B_{\rm source} - \frac{2\lambda_0}{\sqrt{|cL_{\rm fiber}D(\lambda_0)|}}. \end{aligned} \quad (5)$$

The ASE source is utilized in our measurement, with the value of $B_{\rm min}$ at 19.3 nm. From Eq. (5), the value of $B_{\rm measure}$ can be achieved. At 80.7 nm, this $B_{\rm measure}$ is adequate for application in this study.

The parameters mentioned above are related to the test fiber length, so the minimum fiber length is a critical parameter in this interferometry system. If the test fiber is too short, $B_{\rm min}$ will be larger than $B_{\rm source}$. Maintaining the relationship $B_{\rm min} \leq B_{\rm source}$, and applying Eq. (4), we get

$$L_{\rm fiber} \geq \frac{4\lambda_0^2}{B_{\rm source}^2 c|D(\lambda_0)|}. \quad (6)$$

Using Eq. (6), the minimum fiber length $L_{\rm fiber}$ of 0.048 m can be achieved. The fiber that we utilized for the test was 1.3-m long. We opted to use a longer fiber because it can provide more center wavelength and will make the results more precise.

In conclusion, we measure the dispersion value of Yb-doped fiber using fiber spectrum interferometric technology. The Nufern 1060xp fiber is adopted to verify the system, with a relative error of 1.36%. After measurement and calculation, we achieve a dispersion value of –31.608 ps/(km·nm) at the center wavelength of 1070 nm. We likewise measure the Yb-doped fiber and analyze the system parameters with this technology. The minimum required source bandwidth $B_{\rm min}$ is found to be 19.3 nm, which agrees with the experiment perfectly.

This work was supported by the National Natural Science Foundation of China under Grant No. 60537060.

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