

Fiber chromatic dispersion measurement with improved measurement range based on chirped intensity modulation

Shangjian Zhang,* Xinhai Zou, Heng Wang, Yali Zhang, Heping Li, and Yong Liu

State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Information, University of Electronic Science & Technology of China, Chengdu 610054, China

*Corresponding author: sjzhang@uestc.edu.cn

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A novel method for accurately measuring chromatic dispersion of optical fibers is proposed based on the use of chirped intensity-modulated signals. Unlike the conventional method, the proposed method utilizes the configurable transfer function of optical fibers caused by the residual chirp of intensity modulation, which not only eliminates the chirp error but also improves the measurement range through adjusting the chirp parameter of the intensity modulator. Our method is applicable for measuring both the magnitude and sign of chromatic dispersion of optical fibers or other dispersive devices at different operating wavelengths by using a vector network analyzer. © 2014 Chinese Laser Press

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1. INTRODUCTION

Chromatic dispersion of optical fibers is a major consideration and must be accounted for when developing or deploying optical equipment for use in high-speed optical fiber communications and microwave photonics links [1]. A variety of techniques have been demonstrated for measuring the chromatic dispersion of optical fibers, including the time-of-flight method [2], phase shift method [3], interferometric method [4,5], and transfer function method [6,7]. Among these methods, the widely used phase shift method and transfer function method are suitable for characterization of large dispersions with temporal resolution on the order of picoseconds [8]. However, the phase shift method needs complicated systems to compensate the fiber length variation caused by the thermal fluctuation with a reference light [4]. The traditional transfer function method requires chirp-free operation of intensity modulators, or at least two notches for correcting the chirp error, which leads to a limited measurement range [8,9].

The chirp parameter varies with the applied bias voltage of the modulator. In the case of chirped intensity modulation, the fiber transfer function will depend on both the fiber dispersion and the chirp parameter; that is to say, the transfer function can be tuned by operating the modulator at different chirp parameters through adjusting the applied bias voltages. In this paper, we propose a novel method that achieves high accuracy over a large range for measuring the fiber dispersion by using chirped intensity-modulated optical signals. In contrast to the traditional method, the proposed method requires one notch rather than two notches, which not only eliminates the chirp error but also achieves an improved measurement range through adjusting the chirp parameters (bias voltages) of intensity modulators. Moreover, it allows fast and

accurate measurement of the magnitude and sign of chromatic dispersion at different operating wavelengths for any kind of optical fibers simply by using a vector network analyzer (VNA).

2. OPERATING PRINCIPLE

As is shown in Fig. 1, an optical carrier at the wavelength λ is intensity modulated by a microwave sinusoid signal at the frequency f . The optical field of the intensity-modulated signal can be expressed as [10,11]

$$E_i(f, t) = \sqrt{I_0(1 + m \cos(2\pi ft))} \cdot \exp j\left(\frac{2\pi ct}{\lambda} + \frac{\alpha}{2} m \cos(2\pi ft)\right) \quad (1)$$

with α being the chirp parameter, m the modulation index, and I_0 the average optical power. After fiber propagation, the chromatic dispersion will introduce an additional phase shift to each optical sideband depending on its frequency offset relative to the optical carrier, and result in the partial fading of the intensity-modulated signal. Under the small-signal approximation, the transfer function, relating the instantaneous optical intensity after and before fiber propagation, can simply be given by [7,10,11]

$$H(f) = \left| \cos \frac{\pi \lambda^2 D_T f^2}{c} - \alpha \sin \frac{\pi \lambda^2 D_T f^2}{c} \right|, \quad (2)$$

where the total fiber dispersion D_T is related to the group velocity dispersion parameter β_2 by $D_T = -2\pi\beta_2 Lc/\lambda^2$ with the fiber length L . We did not take into account the absolute

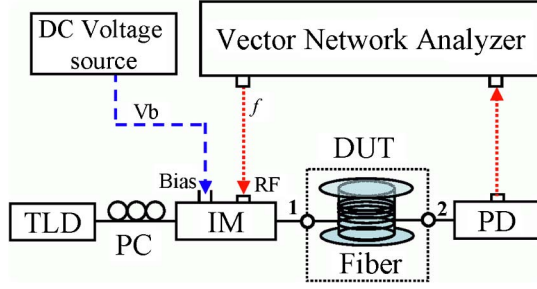


Fig. 1. Schematic diagram of the proposed method. V_b , bias voltage; TLD, wavelength tunable laser diode; PC, polarization controller; IM, intensity modulator; DUT, device under test; PD, photodiode.

phase and group delay, because both terms produced only phase delay of the optical carrier signal. The transfer function H acts as a function of the total dispersion D_T and the chirp parameter α , which periodically achieves null (zero) at the notch frequencies corresponding to

$$f_u^2 = \frac{c}{\lambda^2 |D_T|} \left(u - \frac{1}{2} - \frac{\arctan \alpha}{\pi} \right), \quad (u = 1, 2, 3, \dots), \quad (3)$$

with u being the order of the notch. It is obvious that the notch frequency depends on not only the total dispersion of optical fibers but also the chirp parameter of the intensity modulators.

Conventionally, there are two methods of eliminating the chirp error when extracting the chromatic dispersion from the measured transfer function. The chirp-free method employs zero chirp intensity modulation and determines the chromatic dispersion with one notch frequency as

$$|D_T| = \frac{c}{\lambda^2 f_u^2} \left(u - \frac{1}{2} \right), \quad (u = 1, 2, 3, \dots), \quad (4)$$

in which the minimum measurable dispersion $D_{T \min}$ is restricted to be

$$\left| \frac{D_{T \min} \lambda^2 f_{\max}^2}{c} \right| \geq \frac{1}{2}, \quad (\alpha = 0), \quad (5)$$

with f_{\max} being the maximum modulation frequency. Alternatively, the double-notch method is to extract the chromatic dispersion by subtracting two notch frequencies as

$$|D_T| = \frac{kc}{\lambda^2 (f_{u+k}^2 - f_u^2)}, \quad (u, k = 1, 2, \dots), \quad (6)$$

in which the minimum measurable dispersion $D_{T \min}$ is as follows:

$$\left| \frac{D_{T \min} \lambda^2 f_{\max}^2}{c} + \frac{\arctan \alpha}{\pi} \right| \geq \frac{3}{2}, \quad (\alpha \neq 0). \quad (7)$$

One can see from Eqs. (5) and (7) that the chirp-free method holds much larger measurement range but requires chirp-free intensity modulation; meanwhile, the double-notch method alleviates the chirp error at the expense of a smaller measurement range.

To take care of both the chirp error and the measurement range, we develop a single-notch method by introducing an associated frequency of the first-order notch. As we know, the transfer function will achieve a null at the notch frequency, corresponding to

$$\alpha = \cot \left(\frac{\pi \lambda^2 D_T f_1^2}{c} \right). \quad (8)$$

The transfer function can be expressed with the notch frequency as

$$H(f) = \left| \cos \frac{\pi \lambda^2 D_T f^2}{c} - \cot \frac{\pi \lambda^2 D_T f_1^2}{c} \sin \frac{\pi \lambda^2 D_T f^2}{c} \right|. \quad (9)$$

Here, we choose an associated frequency of the first-order notch given by

$$f_h = f_1 / \sqrt{2} \quad (10)$$

and substitute Eq. (10) into Eq. (9), leading to

$$\begin{aligned} H(f_h) &= \left| \cos \frac{\pi \lambda^2 D_T f_h^2}{c} - \cot \frac{2\pi \lambda^2 D_T f_h^2}{c} \sin \frac{\pi \lambda^2 D_T f_h^2}{c} \right| \\ &= \left| \frac{1}{2} \sec \frac{\pi \lambda^2 D_T f_h^2}{c} \right|, \end{aligned} \quad (11)$$

which allows us to extract the fiber dispersion with a very simple expression given by

$$|D_T| = \frac{c}{\pi f_h^2 \lambda^2} \arccos [2H(f_h)]. \quad (12)$$

Since only one notch is required, the minimum measurable dispersion $D_{T \min}$ meets

$$\left| \frac{D_{T \min} \lambda^2 f_{\max}^2}{c} + \frac{\arctan \alpha}{\pi} \right| \geq \frac{1}{2}. \quad (13)$$

Figures 2(a) and 2(b) show the minimum measurable dispersion as a function of the chirp parameter for the normal dispersion ($D_T > 0$) case and for the anomalous dispersion ($D_T < 0$) case, respectively, where $\lambda = 1550$ nm and $f_{\max} = 20$ GHz are set. Similar results can also be obtained for other wavelengths and frequency ranges. In fact, one can conclude from Eqs. (5), (7), and (13) that our method has the smallest minimum measurable dispersion and the largest measurement range in both the normal and anomalous dispersion regimes regardless of any chirp parameter.

The measurement range can be further improved by optimizing the chirp parameter of the optical modulators. From Fig. 2, it is a favorable characteristic for the measurement range to have a positive chirp parameter that is as large as possible in the normal dispersion regime and a negative chirp parameter that is as large as possible in the anomalous dispersion regime. For example, the minimum measurable dispersion in the normal dispersion regime will be $D_{T \min} > 19.53$ ps/nm in the case of $\alpha = 5$, corresponding to a 1.15 km length of standard single-mode fiber (SMF) at 1550 nm. In comparison, the measurable dispersion of the double-notch method is $D_{T \min} > 331.72$ ps/nm, corresponding to a

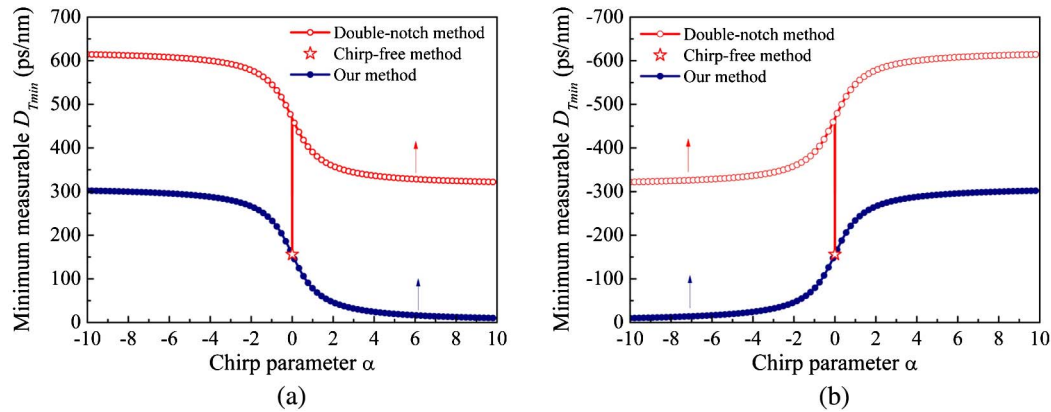


Fig. 2. Minimum measurable dispersion as a function of the chirp parameter (a) for the normal dispersion case and (b) for the anomalous dispersion case.

19.51 km length of SMF at 1550 nm. A similar conclusion can also be drawn in the anomalous dispersion regime with a negative chirp parameter. In practice, a positive or negative chirp parameter can be achieved by changing the applied bias voltage of an optical external modulator, such as a Mach-Zehnder modulator [11] or electro-absorption modulator [12]. It has been demonstrated that the chirp parameter can be tuned from -10 to 10 as a function of the bias voltage for a typical electro-absorption modulator [12].

3. EXPERIMENT AND RESULT

In our measurement, an electro-absorption modulator (OKI OM5653C) is used as the optical modulator with a tunable chirp parameter. As is shown in Fig. 1, the optical carrier at 1550.20 nm from a tunable laser diode is intensity modulated by a sinusoidal microwave signal and sent to a length of SMF under test. With a full two-port calibration, an HP8720D VNA is used to generate the microwave swept frequency signal within 20 GHz and to measure the fiber transfer function of the chirped intensity-modulated signal. At first, port 1 and port 2 are directly connected to determine the response contributions of the modulator and receiver as an optical-to-optical reference. Then, the dispersive fiber is connected between port 1 and port 2 to measure the total response including the modulator, dispersive medium, and receiver. The fiber transfer function is therefore obtained by dividing the response with the optical fiber by the response without the optical fiber, in order to exclude the influence of the modulator and receiver. It should be noted that the fiber loss is normalized from the measured transfer function. A similar measurement procedure can also be found in Refs. [7,9].

Figure 3 shows the measured transfer function of a 25.4 km SMF at different bias voltages of the intensity modulator. The transfer function, in the case of a bias voltage of -1.4 V, holds two notches at 6.215 and 18.335 GHz, respectively, from which the fiber dispersion can be extracted to be $D_T = 419.27$ ps/nm with the double-notch method based on Eq. (6). Meanwhile, the associated frequency of the first-order notch is $f_h = 4.394$ GHz and $H(f_h) = -5.838$ dB, and the fiber dispersion can also be determined to be $D_T = 420.06$ ps/nm with our method based on Eq. (12). When the applied bias voltage is tuned to -2.2 V, the two notch frequencies are accordingly changed to 8.665 and 19.305 GHz, respectively, and the associated frequency of the first-order notch is $f_h = 6.127$ GHz

and $H(f_h) = -5.32$ dB. In this case, the fiber dispersion is measured to be $D_T = 418.31$ ps/nm with the double-notch method and $D_T = 419.19$ ps/nm with our method. Agreeable results can also be obtained at other bias voltages, indicating the efficient error correction of the chirp parameter. For a further validation, we adopt a least-squares fitting of the measured transfer function based on Eq. (9), in which the first-order notch frequencies f_1 are set as 6.215 and 8.665 GHz, respectively. The determined dispersions from the curve fitting are 419.7 and 420.3 ps/nm, respectively. The fitted curves are illustrated in the same figure together with the measured transfer functions for comparison, where both agreeable results verify the accuracy of our method.

In order to further verify our method, a 6.1 km length of SMF is chosen to repeat the measurement. As is shown in Fig. 4, the measured transfer function achieves only the first-order notch, and all the higher-order notches are beyond a 20 GHz frequency range even if different chirp parameters are tried by changing the bias voltage of the intensity modulator, which results in difficulty determining the fiber dispersion with the double-notch method according to Eq. (6). With our method, the fiber dispersion can be determined to be $D_T = 98.54$ ps/nm according to the associated frequency $f_h = 10.02$ GHz and $H(f_h) = -5.749$ dB of the first-order notch at 14.168 GHz in the case of a bias voltage of -1.8 V. The measured result in the case of a bias voltage of -2.1 V is $D_T = 98.60$ ps/nm according to the associated

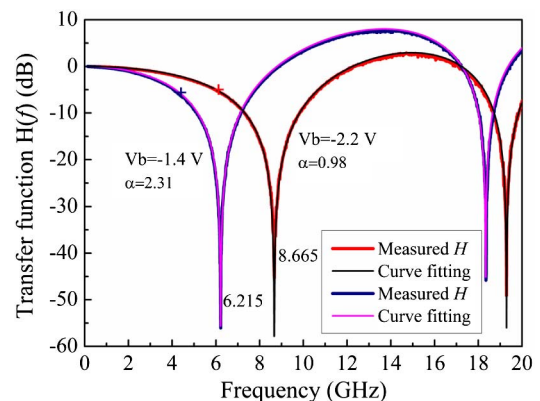


Fig. 3. Measured transfer function for a 25.4 km long SMF at different bias voltages (V_b) of the intensity modulator.

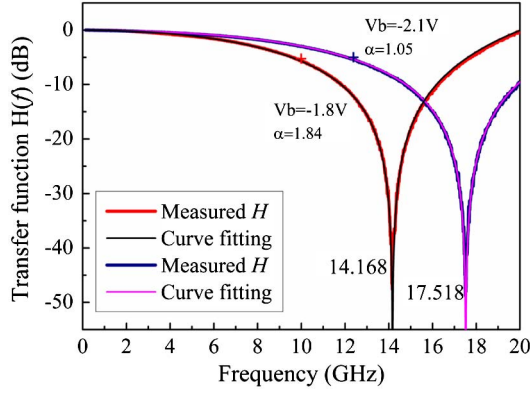


Fig. 4. Measured transfer function of a 6.1 km long SMF at different bias voltages (V_b) of the intensity modulator.

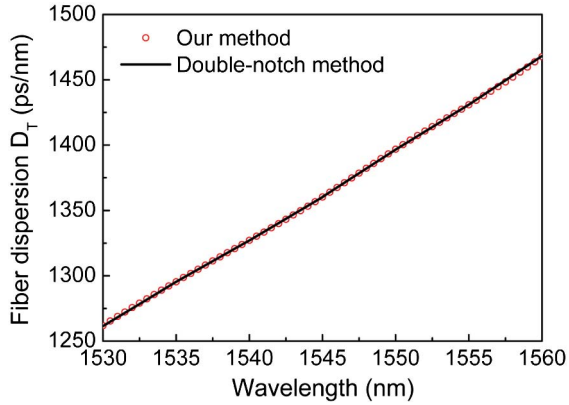


Fig. 5. Measured chromatic dispersion of a 81.5 km long SMF at different operating wavelengths.

frequency $f_h = 12.385$ GHz and $H(f_h) = -5.375$ dB of the first-order notch at 17.518 GHz. For accuracy, we check our results by fitting the measured transfer function using Eq. (9) within 20 GHz, where the first-order notch frequencies f_1 are set as 14.168 and 17.518 GHz, respectively. The least-square curve fittings lead to the determined dispersions 99.55 and 99.83 ps/nm, respectively, which are also included in Fig. 4 for comparison.

Furthermore, we also measure the dispersion of the 81.5 km fiber at different operating wavelengths. Figure 5 shows the measured fiber dispersion as a function of operating wavelength. The measured results with the double-notch method are also included in Fig. 5 for comparison. Both agreeable results verify that our method works over a wide wavelength range with high accuracy.

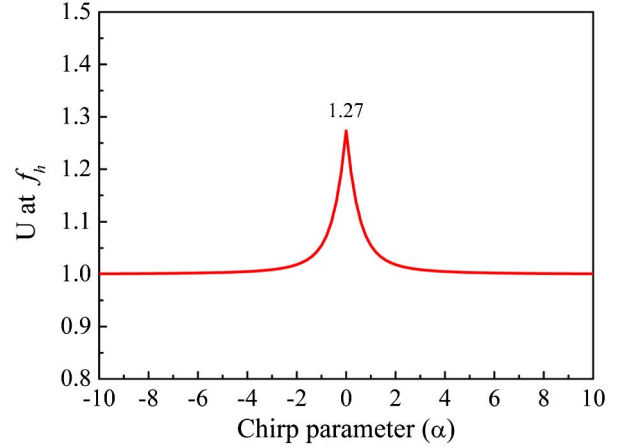


Fig. 6. Error transfer factor at the associated frequency as a function of chirp parameter.

If the sign of the fiber dispersion also needs to be tested, we use a length of standard SMF as the reference fiber to cascade with the fiber under test. If the notch frequencies in the cascade case become larger than those of the reference fiber alone, then the fiber under test will have the same sign of chromatic dispersion as the reference fiber; otherwise, it holds the opposite sign of chromatic dispersion of the reference fiber.

Since both the fiber dispersion and the notch frequency are determined from the transfer function, the uncertainty of the notch frequency will be delivered to the fiber dispersion through the error transfer factor F

$$F = \left| \frac{\Delta D_T}{D_T} / \frac{\Delta f_1}{f_1} \right| = 2, \quad (14)$$

which is deduced from the total differential of Eq. (2). An error factor of 2 means that the relative error of the notch frequency will be transferred to the fiber dispersion two times. In our experiment, the uncertainty of the notch frequency is within 50 MHz, corresponding to a relative error of less than 0.25%, and the maximum uncertainty of 0.5% might be transferred from the notch frequency to the fiber dispersion.

The accuracy of the extracted fiber dispersion will also be impacted by the measured transfer function. The error dependence of fiber dispersion on the uncertainty of the transfer function can be investigated with the help of the total derivative of Eq. (2), given by

$$U = \left| \frac{\Delta D_T}{D_T} / \frac{\Delta H}{H} \right| = \left| \frac{\cos \theta - \alpha \sin \theta}{\theta(\alpha \cos \theta + \sin \theta)} \right|, \quad \theta = \frac{\pi \lambda^2 D_T f^2}{c}. \quad (15)$$

Table 1. Uncertainty of the Fiber Dispersion Resulting from the Measured Transfer Function^a

Fiber Length (km)	V_b (V)	α	f_h (GHz)	f_1 (GHz)	D_T (ps/nm)		Maximum Uncertainty
					Fitted	Measured	
25.4	-1.4	2.31	4.394	6.215	419.7	420.06	2.37%
	-2.2	0.98	6.127	8.665	420.3	419.19	2.47%
6.1	-1.8	1.84	10.02	14.168	99.55	98.54	2.38%
	-2.1	1.05	12.385	17.518	99.83	98.6	2.45%

^a V_b , bias voltage.

According to Eqs. (8) and (10), we have

$$\alpha = \cot\left(\frac{\pi\lambda^2 D_T f_1^2}{c}\right) = \cot\left(\frac{2\pi\lambda^2 D_T f_h^2}{c}\right). \quad (16)$$

Substituting Eq. (16) into Eq. (15), the error transfer factor at the associated frequency can be expressed by

$$U(f_h) = \left| \tan\left(\frac{\text{arccot } \alpha}{2}\right) / \left(\frac{\text{arccot } \alpha}{2}\right) \right|. \quad (17)$$

As is shown in Fig. 6, the error transfer factor at the associated frequency is plotted as a function of chirp parameter. According to the VNA specification, the measurement uncertainty is less than 0.2 dB, corresponding to a relative error of less than $2.33\% = (10^{0.2/20} - 1) * 100\%$. The uncertainties of the fiber dispersion resulting from the measured dispersion are listed in Table 1 for reference. In the worst case, the maximum relative error of the measured dispersion is about $3.46\% (= 1.27 * 2.33\% + 0.5\%)$, which is contributed by both the notch frequency and the transfer function.

4. CONCLUSION

To summarize, we have demonstrated the use of a chirped intensity-modulated signal for accurately extracting the chromatic dispersion of optical fibers based on fiber transfer function measurement with a VNA. Our method allows a wide measurement range with a simple configuration and can achieve fast measurement with high accuracy, which enhances the characteristics of optical fibers, dispersive devices, and optical transmission paths.

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