Fiber Dispersion Measurement With a Swept-Wavelength Pulse Light Source

Siao-Shan Jyu, Shiou-Fong Liu, Wei-Wei Hsiang, and Yinchieh Lai

***Abstract*—A new fiber dispersion measurement method by utilizing a periodically swept-wavelength pulse light source is proposed and demonstrated. The periodic pulse timing variation of the pulse train induced by wavelength sweeping can be directly detected by a radio-frequency spectrum analyzer. Experiments by using an asynchronous mode-locked fiber soliton laser as the swept-wavelength pulse source have been successfully carried out to demonstrate the feasibility.**

***Index Terms*—Chromatic dispersion, group velocity dispersion, mode-locked fiber laser, swept-wavelength light source.**

I. Introduction

FIBER dispersion originates from the combined effects of fiber material/waveguide dispersion and can cause the linear optical pulse broadening effects through the wavelength-dependent group time delay. Fiber dispersion also plays an important role in many applications of nonlinear fiber optics and ultrafast fiber optics. In the literature, many dispersion measurement methods have been demonstrated. They can be roughly classified into two main categories: noninterferometric and interferometric. The time of flight (TOF) technique and the modulation phase-shift (MPS) technique are the most well-known noninterferometric methods [1]. Some recent schemes using supercontinuum pulse light sources for broadband measurement are also under this category [2]. The interferometric category also includes many subcategories. Temporal interferometry methods and various spectral interferometry methods with continuous-wave (CW) narrowband or broadband lights are the most well known approaches [1], [3]. Some special techniques based on the cavity resonance effects like the self-seeding laser oscillation method [4] can also be listed under this category. In general, the noninterferometric methods will have the advantages of setup simplicity and measurement stability, while the interferometric methods have the main advantage of higher sensitivity.

Among the above-mentioned approaches, the standard MPS technique is probably the most commonly used method due to its simplicity. However, since it will typically require the precise phase measurement of the radio-frequency (RF) modulation signals through an expensive RF network analyzer, the equipment cost is higher. In the present work, we propose and demonstrate a new method of fiber dispersion measurement based on a periodically swept-wavelength pulse light source. Only the RF spectral measurement capability is required. The measurement principles are based on two concepts: 1) Periodic wavelength sweeping of a pulse train will induce periodic pulse timing variation; 2) the periodic pulse timing variation of a pulse train can be directly measured by an RF spectrum analyzer. In this way, we are able to construct an economic new noninterferometric method for fiber dispersion measurement.

In order to demonstrate the feasibility of the proposal, a 10-GHz asynchronously mode-locked (ASM) Er-fiber soliton laser we previously developed has been utilized as the wavelength-swept pulse source [5]–[7]. Such a mode-locked fiber laser system can produce slow sinusoidal center wavelength sweeping with the half peak-to-peak amplitude around 1 nm at the oscillating frequency of several tens of kilohertz (kHz). Preliminary dispersion measurements have been performed on two types of test fibers, i.e., large-effective-area fiber (LEAF) and dispersion-compensating fiber (DCF), and comparable results to commercial equipment have been obtained. Directions for further improvement on measurement sensitivity will also be given.

II. Principle

Let us consider a delta function pulse train with slow periodic timing and amplitude oscillation

$$I(t) = \sum_{m=-\infty}^{\infty} a(mT_p)\delta(t - mT_p - s(mT_p)). \qquad (1)$$

The Fourier transform of $I(t)$ can be derived in the following way. First, (1) can be rewritten as:

$$I(t)=\sum_{m=-\infty}^{\infty}\int_{f=-\infty}^{\infty} e^{j2\pi ft}e^{-j2\pi fmT_p}a(mT_p)e^{-j2\pi fs(mT_p)}df. \qquad (2)$$

Since the functions $a(t)$ and $s(t)$ are slow periodic functions (with the fundamental frequency f_d), the final two terms in the integral can be expanded in Fourier series to obtain

$$I(t) = \sum_{m=-\infty}^{\infty}\int_{f=-\infty}^{\infty} e^{j2\pi ft}e^{-j2\pi fmT_p} \times \sum_{k=-\infty}^{\infty} c_k(f)e^{j2\pi kf_d mT_p}df$$

Manuscript received October 19, 2009; revised January 20, 2010; accepted February 01, 2010. Date of publication February 22, 2010; date of current version March 31, 2010. This work was supported in part by the National Science Council of the Republic of China under Contract NSC 96-2628-E-009-154-MY3.

S.-S. Jyu and S.-F. Liu are with the Department of Photonics, National Chiao-Tung University, Hsinchu 300, Taiwan (e-mail: hillg8023@gmail.com; tinana2001@hotmail.com).

W.-W. Hsiang is with the Department of Physics, Fu Jen Catholic University, Taipei 24205, Taiwan (e-mail: 069179@ mail.fju.edu.tw).

Y. Lai is with the Department of Photonics, National Chiao-Tung University, Hsinchu 300, Taiwan, and also with the Research Center for Applied Sciences, Academia Sinica, Taipei 10617, Taiwan (e-mail: yclai@mail.nctu.edu.tw).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2010.2043248

$$= \int_{f=-\infty}^{\infty} e^{j2\pi ft} \sum_{k=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} c_k \left(\frac{m}{T_p} + kf_d \right) \times \delta \left(f - kf_d - \frac{m}{T_p} \right) df. \quad (3)$$

This proves that the Fourier spectrum of a pulse train with slow periodic oscillation will exhibit subharmonic side-peaks. Moreover, the power ratio of the zeroth and first spectral side-peaks can be written as

$$\Delta = \frac{\left| c_0 \left(\frac{m}{T_p} \right) \right|^2}{\left| c_1 \left(\frac{m}{T_p + f_d} \right) \right|^2} \approx \frac{\left| c_0 \left(\frac{m}{T_p} \right) \right|^2}{\left| c_1 \left(\frac{m}{T_p} \right) \right|^2}. \quad (4)$$

Here the coefficients $c_0(f)$ and $c_1(f)$ are the zeroth- and first-order Fourier coefficients of the function $a(t) \exp[-j2\pi fs(t)]$. For the particular case when there is no amplitude oscillation, $a(t) = a_0$, and the slow timing oscillation is sinusoidal

$$s(t) = \Delta s \cos(2\pi f_d t + \theta) \quad (5)$$

it is not difficult to show that the power ratio can be formulated by using the Bessel functions

$$\Delta \approx \frac{\left| J_0 \left(\frac{2m\pi \Delta s}{T_p} \right) \right|^2}{\left| J_1 \left(\frac{2m\pi \Delta s}{T_p} \right) \right|^2}. \quad (6)$$

From (6), the half peak-to-peak timing oscillation amplitude Δs can be determined. For different implementation schemes with more general swept-wavelength formats and/or nonflat amplitude responses, (4) can also to be used to compute the timing oscillation amplitude. If the timing oscillation is induced by the wavelength oscillation through dispersion, then $\Delta s = DL\Delta\lambda$. Thus the dispersion parameter D can also be determined from the measurement. Since the Bessel functions are oscillating functions, for measuring large dispersion one may need to dynamically reduce the wavelength sweeping amplitude.

III. Experiment

The above theory is correct for general swept-wavelength pulse light sources. To demonstrate the idea experimentally, an ASM Er-fiber soliton laser system with the center wavelength at 1560 nm has been used in the present work, with its schematic setup illustrated in Fig. 1 [5]–[7]. The mode-locking principle and lasing dynamics of this laser system have been studied carefully in our previous works and will not be repeated here. To summarize, we have shown that such a mode-locked fiber laser system can produce 10-GHz sub-picosecond (sub-ps) pulse trains with slow sinusoidal center wavelength sweeping. The half peak-to-peak wavelength sweeping amplitude can be as large as 1 nm at the oscillating frequency of several tens kHz. However, one important point needs to be explained more here. The pulse train from the ASM Er-fiber soliton laser will also have a certain amount of slow pulse timing oscillation and such original timing oscillation is exactly 90° out-of-phase with the wavelength oscillation. This property will change the relation between the timing and wavelength oscillation amplitudes to be

$$\Delta s = \sqrt{\Delta s_0^2 + (DL\Delta\lambda)^2}. \quad (7)$$

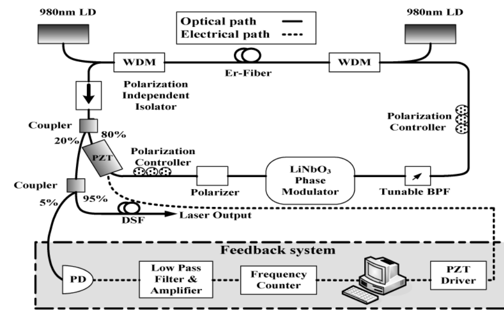

Fig. 1. Experimental setup of the 10-GHz ASM Er-fiber soliton laser. BPF: bandpass filter. PD: photodiode. LD: laser diode. WDM: wavelength-division-multiplexing couplers. DSF: dispersion-shifted fiber. PZT: piezoelectric transducer.

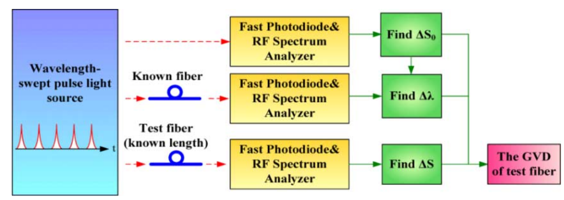

Fig. 2. Schematic setup of the dispersion measurement procedure.

Here ΔS_0 is the original timing oscillation amplitude and ΔS is the timing oscillation amplitude after propagation. Form (7), the fiber dispersion can then be calculated by

$$D = \frac{\sqrt{\Delta s^2 - \Delta s_0^2}}{(\Delta\lambda L)}. \quad (8)$$

We have actually utilized this mode-locked laser system to measure the dispersion of two test fibers: LEAF and DCF fibers. The whole measurement procedures are illustrated in Fig. 2. The standard single-mode fiber (SMF) with known length is used to calibrate $\Delta\lambda$ based on (7). With this information, the dispersion of the test fibers can then be determined by (8) with measurements before and after propagation.

IV. Result

The typical RF spectra of the pulse trains before and after propagating are illustrated in Fig. 3. One can see that indeed there are subharmonic side-peaks with frequency separation around 19 kHz. Only the zero- and first-order peaks will be utilized for measurement since the higher order peaks are much smaller and may be more distorted by the ASM laser dynamics and the noises [6]. The pulse energy of the ASM fiber laser will also exhibit small slow periodic oscillation which is not pure sinusoidal. This is why the higher order side peaks do not obey the Bessel function formula. The first-order side peaks are less affected but some measurement uncertainties are expected. Fig. 4(a) shows the measured timing oscillation as a function of the fiber length when the SMF is used. One obtains the expected dependence predicted in (7) and the wavelength variation can then be determined. It should be emphasized that the wavelength variation is the only fitting parameter here, which strongly validates our theoretical analyses experimentally. Fig. 4(b) shows the measured power ratios as a function of the fiber length when the SMF is used. The values for the first (10 GHz) and second (20 GHz) main harmonic components are plotted for illustration. The final

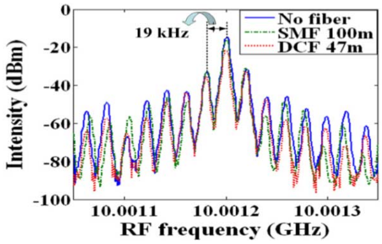

Fig. 3. RF spectra of the pulse trains.

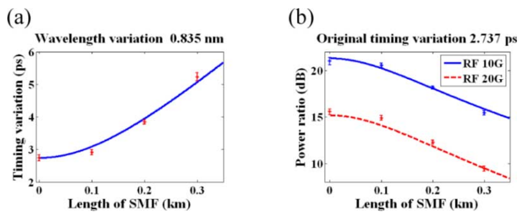

Fig. 4. (a) Timing variation versus fiber length. The SMF is used here for calibration. (b) Power ratio versus fiber length.

TABLE I
MEASUREMENT RESULTS

Fiber type	Fiber length (m)	$\Delta\lambda$ (nm)	Δs_0 (ps)	Δs (ps)	|D| (ps/nm/km)
LEAF	380	0.835	2.74	3.05	4.21
DCF	47	0.835	2.74	5.15	111

results of our dispersion measurement are listed in Table I. The absolute values of the dispersion parameters for the LEAF and DCF fibers are estimated to be 4.21 and 111 ps/nm/km, respectively. The wavelength variation $\Delta\lambda$ is 0.835 nm and the original timing variation is 2.74 ps. The timing variations after the test fibers are 3.05 and 5.16 ps for the LEAF and DCF fibers. Most importantly, the used fiber lengths are only 380 and 47 m for the two cases. The accuracy of these measurement values has been checked by comparing with the data from a commercial equipment (Advantest Q7760). The deviations for the LEAF and DCF fibers are 9.2% and 6.0%, respectively. This indicates that the proposed method indeed can measure the fiber dispersion with good accuracy and sensitivity.

Further improvement on the measurement sensitivity can be achieved either by further increasing the wavelength oscillation $\Delta\lambda$ or by reducing the original timing oscillation Δs_0. As has been analyzed in [6], the wavelength variation can be increased by increasing the modulation depth. For the ASM fiber laser, we have observed more than 1.0-nm wavelength variation and expect that several nanometers (nm) may be possible. The original timing variation can be reduced by reducing the cavity dispersion and it may also be possible to reach the sub-ps level.

We have confirmed that the group time delay measurement uncertainties of our present measurement is in the sub-ps level ($\pm$0.2 ps), comparable to the commercial equipments based on the MPS method. Since the wavelength variation is 0.835 nm, this corresponds to the dispersion measurement uncertainty of $\pm$0.24 ps/nm. However, the wavelength resolution of the present experiment will be less than that of the commercial equipments (typically around 0.1 nm) due to the larger optical bandwidth of the ASM laser (2–3 nm). Amplitude variation due to nonflat spectral responses of the tested devices may also be taken into account with the general formula developed here. Another limiting factor for measuring large dispersion is the pulse overlapping effect. When the adjacent pulses are broadened to strongly overlap, the measured RF harmonic signals will also be strongly degraded. This effect can be reduced by using longer ps pulses. On the other hand the minimum detectable group delay is right now limited by the original timing variation of the ASM laser to the ps level. From Fig. 4(a), the minimum detectable dispersion-induced group delay is roughly the group delay of a 100-m SMF with 0.8-nm wavelength sweeping, which corresponds to the 2.0-ps/nm minimum detectable dispersion. The value of the minimum detectable dispersion should be approximately the same between the tunable wavelength range (from 1545 to 1565 nm) of the ASM laser, and this lower limit may be more easily overcome by using different implementation schemes. For example, the pulse train can be generated by a CW wavelength-scanning laser with an electrooptic (EO) modulator. This kind of implementation scheme may provide ways to reduce the setup complexity and to measure the dispersion over a wide wavelength range.

V. CONCLUSION

We have proposed and demonstrated a new method of fiber dispersion measurement based only on simple RF spectral measurement with a swept-wavelength pulse light source. By measuring the periodic pulse timing variation before and after the test fiber with an RF spectrum analyzer, the fiber dispersion can be determined. This new method should provide an economic way for measuring fiber dispersion noninterferometrically and should be potentially useful for fiber communication and ultrafast fiber optics applications.

REFERENCES

[1] L. G. Cohen, "Comparison of single-mode fiber dispersion measurement techniques," *J. Lightw. Technol.*, vol. LT-3, no. 5, pp. 958–966, May 1985.

[2] L. J. Hult, R. S. Watt, and C. F. Kaminski, "Dispersion measurement in optical fibers using supercontinuum pulses," *J. Lightw. Technol.*, vol. 25, no. 3, pp. 820–824, Mar. 2007.

[3] J. Y. Lee and D. Y. Kim, "Versatile chromatic dispersion measurement of a single mode fiber using spectral white light interferometry," *Opt. Express*, vol. 14, pp. 11608–11615, 2006.

[4] K.-H. Yoon, J.-W. Song, and H. D. Kim, "Simultaneous measurements of dispersion parameter and fiber length using the self-seeding laser oscillation of a fabry-pérot laser diode," *IEEE Photon. Technol. Lett.*, vol. 19, no. 14, pp. 1036–1038, Jul. 15, 2007.

[5] W.-W. Hsiang, C.-Y. Lin, M.-F. Tien, and Y. Lai, "Direct generation of 10 GHZ 816 fs pulse train from an erbium-fiber soliton laser with asynchronous phase modulation," *Opt. Lett.*, vol. 30, pp. 2493–2495, 2005.

[6] W.-W. Hsiang, H.-C. Chang, and Y. Lai, "Laser dynamics of a 10 GHZ 0.55 ps asynchronously harmonic modelocked Er-doped fiber soliton laser," *IEEE J. Quantum Electron.*, vol. 46, no. 3, pp. 292–299, Mar. 2010.

[7] S.-F. Liu, S.-S. Jyu, H.-C. Chang, W.-W. Hsiang, and Y. Lai, "A simple group velocity dispersion measurement method by RF spectral periodic pulse timing variation characterization," in *Proc. Optical Fiber Communication (OFC) Conf.*, San Diego, CA, 2009, Paper JWA1.