Chromatic dispersion measurements of long optical fibers by means of optical ranging system using a frequency-shifted feedback laser

Chromatic Dispersion Measurements of Long Optical Fibers by Means of Optical Ranging System Using a Frequency-Shifted Feedback Laser

Koichi Iiyama, *Member, IEEE*, Takahiro Maeda, and Saburo Takamiya

***Abstract*—In this paper, we describe the experimental results on the chromatic dispersion measurement of long optical fibers by means of optical ranging system using a wavelength-tunable frequency-shifted feedback (FSF) laser. The optical ranging system using an FSF laser has high spatial resolution of several centimeter over 10-km measurement range, and then the dependence of the group delay time of the lightwave in the optical fibers on the wavelength can be directly measured. The chromatic dispersion and the zero-dispersion wavelength of an 80-km-long dispersion shifted fiber was estimated, which are in good agreement with the result by the phase method.**

***Index Terms*—Chromatic dispersion, frequency-shifted feedback laser, optical fiber measurements, optical ranging, optical reflectometry.**

I. INTRODUCTION

RECENTLY, a new type of laser, a frequency-shifted feedback (FSF) laser, has been actively studied [1]–[3]. The unique feature of the FSF laser is that an optical frequency shifter is incorporated in the laser cavity as shown in Fig. 1, which means that the lightwave in the laser cavity is frequency-shifted while recirculating in the laser cavity. As a result, the optical frequency of the FSF laser is linearly chirped with high chirp rate. The reported chirp rate is 0.5–100 PHz/s. The FSF laser is applicable to optical ranging system and optical frequency domain reflectometry (OFDR) by utilizing the characteristic feature of the frequency-chirped optical output. In the OFDR, the optical frequency of the laser source has to be linearly chirped with large chirping range to achieve high spatial resolution. In the conventional OFDR using a laser diode as a light source, the optical frequency is chirped by modulating the injection current. However, in such systems, it is difficult to achieve linear optical frequency chirp due to nonlinear optical frequency response with respect to the injection current change caused by thermal resistances of the laser cavity, the submount and the heatsink, and an additional optical and electrical feedback control system is necessary to linearize the optical frequency chirp [4], [5]. On the other hand, the FSF laser is a useful laser source for the OFDR, because the optical frequency of the FSF laser is linearly chirped without any additional optical and electrical circuits. In the reported optical ranging system using an FSF laser, the spatial resolution of about 1 cm is achieved over 1-km measurement range [6].

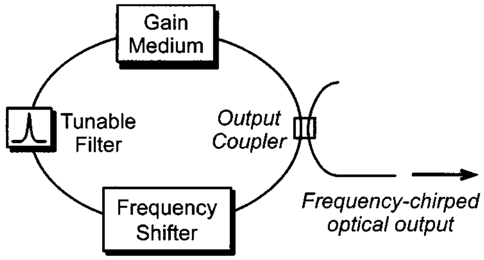

Fig. 1. Basic configuration of a frequency-shifted feedback fiber laser.

In this paper, we describe a novel measurement system of chromatic dispersion of long optical fibers by means of the optical ranging system using a FSF laser. Since the capacity of the high-speed wavelength-division-multiplexed (WDM) optical communication system is limited by the chromatic dispersion and the zero-dispersion wavelength of the optical fiber, the precise determination of the chromatic dispersion of optical fibers is important to design the optical communication networks. The chromatic dispersion has been measured by means of the phase method using an intensity-modulated laser source, and the PM–AM method [7], [8], which utilize the phenomenon that the phase-modulated light is converted to the intensity-modulated light due to the chromatic dispersion. In these systems, high-speed electronics and optics are necessary in the transmitter and the receiver. Other methods based on four wave mixing (FWM) [9] and modulation instability (MI) [10] are proposed to measure the chromatic dispersion. In these systems, high-power optical pulses are required. The advantages of the proposed system in this paper are that no high-power laser source is necessary and no high-speed electronics and optics is required. The required bandwidths in the transmitter and the receiver are only 100 MHz.

In Section II, the principle of measuring the chromatic dispersion is described. The required spatial resolution of the system is discussed. In Section III, the optical ranging system using a FSF laser is described and the experimental results are shown. The experimental results of the chromatic dispersion measurement based on the optical ranging system is described in Section IV, and in Section V, we conclude the paper.

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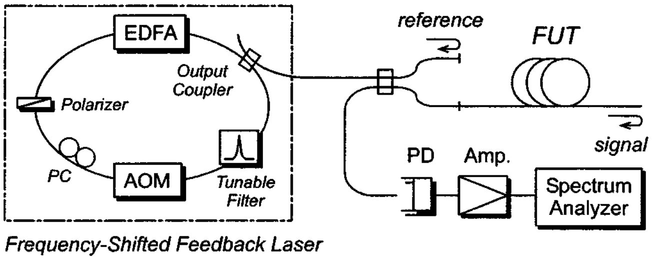

Fig. 2. System configuration for measuring the chromatic dispersion by means of optical ranging system using a FSF laser.

II. Principle

Fig. 2 shows the system configuration for measuring the chromatic dispersion of optical fibers. The FSF laser consists of an erbium-doped optical fiber amplifier (EDFA), a single-cavity-type tunable filter with 3-nm bandwidth, an acoustoptic modulator (AOM) driven by 80 MHz, which was used as an optical frequency shifter, a polarization controller (PC), a polarizer, and an output coupler. The cavity length is about 35 m, and the resultant free spectral range (FSR) is 5.87 MHz. The fibers used in the cavity are ordinary single-mode optical fibers and no polarization preserving fibers and no dispersion-shifted fibers were used. The light from the FSF laser is sent to the Michelson interferometer, in which an optical fiber under test (FUT) is connected in an arm of the interferometer, and the beat signal between the reflected light from the short arm (referred to as the reference light) and the reflected light at the far end of the fiber (referred to as the signal light) is measured by a spectrum analyzer after amplified by an RF amplifier with 40-dB gain. Since the light from the FSF laser is frequency chirped, the beat signal has a beat frequency proportional to the optical path difference between the reference and the signal lights. And the beat frequency changes according to the wavelength of the FSF laser due to the chromatic dispersion of the FUT, because the group velocity in the fiber depends on the wavelength. As a result, the chromatic dispersion can be estimated from the beat frequency change.

Now, we explain how to determine the chromatic dispersion of the FUT. Since the lightwave in the FSF laser cavity experiences frequency shift while travelling in the laser cavity, the optical frequency of the FSF laser $\nu(t)$ is expressed as [1]

$$\nu(t) = \frac{\nu_{\mathrm{FS}}}{\tau_{\mathrm{RT}}} t - \frac{q}{\tau_{\mathrm{RT}}} \tag{1}$$

where

$\nu(t)$	instantaneous optical frequency;
ν_{FS}	intracavity frequency shift caused by the AOM;
τ_{RT}	round-trip time of the laser cavity;
q	integer describing the mode number.

The optical frequency of the FSF laser is schematically shown in Fig. 3. In the FSF laser, many oscillating modes separated by the FSR $(\mathrm{FSR} = 1/\tau_{\mathrm{RT}})$ are simultaneously frequency chirped with equal chirp rate $\nu_{\mathrm{FS}}/\tau_{\mathrm{RT}}$. This is called a chirped frequency comb. The number of the oscillating mode M is given by $\Delta\nu/\mathrm{FSR}$, where $\Delta\nu$ is the chirp range.

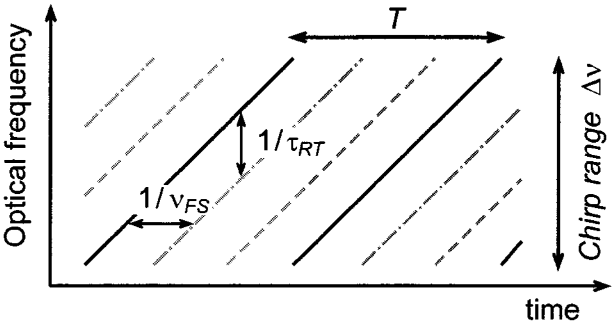

Fig. 3. Schematic drawing of the chirped frequency comb. Three modes are simultaneously frequency chirped in this drawing.

Due to the characteristic feature of the chirped frequency comb, the beat signal between the different oscillating modes can also be measured. The beat frequency f_B is expressed as

$$\begin{aligned} f_B &= \left[\frac{\nu_{\mathrm{FS}}}{\tau_{\mathrm{RT}}} t - \frac{q}{\tau_{\mathrm{RT}}}\right] - \left[\frac{\nu_{\mathrm{FS}}}{\tau_{\mathrm{RT}}}(t - \tau_g) - \frac{q'}{\tau_{\mathrm{RT}}}\right] \\ &= \frac{\nu_{\mathrm{FS}}}{\tau_{\mathrm{RT}}} \tau_g - \frac{m}{\tau_{\mathrm{RT}}} \end{aligned} \tag{2}$$

where τ_g is the delay time between the reference and the signal lights, and is given by $\tau_g = 2n_gL/c$, where n_g is the group index of the fiber and L is the differential length between the signal and the reference arms, which is proportional to the length of the FUT. $m = q - q'$ is a beat order. If $m = 0$, then the beat signal is generated by the two beams in the identical oscillating mode. If $m \neq 0$, then the beat signal is generated by the two beams with a different mode number, whose difference is given by m.

The delay time τ_g is derived by differentiating (2) with respect to ν_{FS} and is given as

$$\tau_g = \tau_{\mathrm{RT}} \frac{df_B}{d\nu_{\mathrm{FS}}} \tag{3}$$

and then the differential length between the signal and the reference arms L is obtained as

$$L = \frac{c}{2n_g} \tau_g = \frac{c\tau_{\mathrm{RT}}}{2n_g} \frac{df_B}{d\nu_{\mathrm{FS}}}. \tag{4}$$

If the length of the reference arms is much shorter than the length of the signal arms, L gives the length of the FUT. Equation (4) shows that L can be obtained from the beat frequency change when the driving frequency of the AOM ν_{FS} is slightly changed.

The chromatic dispersion is determined from the delay time difference between two lights with 1-nm wavelength separation in an 1-km-long optical fiber, and is obtained by differentiating the wavelength dependence of the delay time in an 1-km-long optical fiber with respect to the wavelength. If the wavelength dependence of the delay time in the fiber is given by $\tau_g(\lambda)$, then the wavelength dependence of the chromatic dispersion $D(\lambda)$ is given as

$$D(\lambda) = \frac{1}{L} \frac{d\tau_g(\lambda)}{d\lambda}. \tag{5}$$

Therefore, we can determine the chromatic dispersion of the FUT in our system as follows.

1) First measure the beat frequency change Δf_B as a fuction of the wavelength of the FSF laser. The dependence is expressed as $\Delta f_B(\lambda)$.
2) Next calculate the wavelength dependence of the delay time change $\Delta\tau_g(\lambda)$. The dependence $\Delta\tau_g(\lambda)$ is easily given from (2) as

$$\Delta\tau_g(\lambda) = \frac{\tau_{\mathrm{RT}}}{\nu_{\mathrm{FS}}}\Delta f_B(\lambda). \tag{6}$$

3) Fitting $\Delta\tau_g(\lambda)$ with a suitable function such as a quadratic function.
4) Differentiate the fitting curve with respect to the wavelength, which is expressed as $d\Delta\tau_g(\lambda)/d\lambda$.
5) Finally, the chromatic dispersion can be obtained by normalizing the length of the FUT in kilometers. The chromatic dispersion as a fuction of the wavelength $D(\lambda)$ is then given as follows

$$D(\lambda) = \frac{1}{L}\frac{d\Delta\tau_g(\lambda)}{d\lambda} = \frac{2n_g}{c\nu_{\mathrm{FS}}}\left(\frac{df_B}{d\nu_{\mathrm{FS}}}\right)^{-1}\frac{d\Delta f_B(\lambda)}{d\lambda}. \tag{7}$$

From the above procedure, the chromatic dispersion $D(\lambda)$ can be estimated from the measured wavelength dependence of the beat frequency change $\Delta f_B(t)$. The refractive index of the FUT n_g is required for precise determination of the chromatic dispersion $D(\lambda)$.

The estimated total chromatic dispersion $L \times D(\lambda)$ is actually the differential total chromatic disperion between the FUT and the fiber in the reference arm. Now, letting the length of the FUT, the chromatic disperion of the FUT, the length of the fiber in the reference arm, and the chromatic dispersion of the fiber in the reference arm to be $L_{\mathrm{FUT}}, D_{\mathrm{FUT}}(\lambda), L_R$, and $D_R(\lambda)$, respectively, then the estimated total chromatic dispersion is given as

$$L \times D(\lambda) = [L_{\mathrm{FUT}} \times D_{\mathrm{FUT}}(\lambda)] - [L_R \times D_R(\lambda)]. \tag{8}$$

If $[L_{\mathrm{FUT}} \times D_{\mathrm{FUT}}(\lambda)] \gg [L_R \times D_R(\lambda)]$ is satisfied in the measurements, the estimated total dispersion is regarded as the total dispersion of the FUT. Such a condition is easily satisfied by using a short fiber in the reference arm. Even if $D_{\mathrm{FUT}}(\lambda) = 0$ over the measurement range, the influence of the total chromatic dispersion of the fiber in the reference arm $L_R \times D_R(\lambda)$ can be neglected, because $L_R \times D_R(\lambda)$ is so small that its dependence on the wavelength cannot be measured due to the spatial resolution limitation described below.

Next, we estimate the required spatial resolution in the proposed system. Since the chromatic disperion $D(\lambda)$ is given by the first-order derivative of the delay time with respect to the wavelength, the delay time difference $\delta\tau_g$ between two lights, whose wavelengths are λ_1 and λ_2 is given by

$$\delta\tau_g = L\int_{\lambda_1}^{\lambda_2} D(\lambda)\,d\lambda. \tag{9}$$

TABLE I

REQUIRED SPATIAL RESOLUTION IN THE PROPOSED SYSTEM. $D = 1$ ps/nm/km IS ASSUMED

L	$\Delta\lambda$	δz
100 km	0.1 nm	< 2.06 mm
	1 nm	< 20.6 mm
10 km	0.1 nm	< 0.206 mm
	1 nm	< 2.056 mm

If $\Delta\lambda = |\lambda_2 - \lambda_1|$ is so small that $D(\lambda_1) \approx D(\lambda_2)$, the integral in (9) becomes $D \times \Delta\lambda$, and then $\delta\tau_g$ is given as

$$\delta\tau_g = L \times \Delta\lambda \times D. \tag{10}$$

The spatial resolution δz must be smaller than $v_g \times \delta\tau_g$ to measure the delay time difference between λ_1 and λ_2, where $v_g = c/n_g, c$ is the light speed in vacuum and n_g is the group refractive index of the FUT.

As a result, if the fiber length, the dispersion value, and the group velocity in the fiber are denoted by L (km), D (ps/nm/km), and v_g (m/s), respectively, then the required spatial resolution δz is given by

$$\delta z < D \times L \times \Delta\lambda \times v_g \times 10^{-12}. \tag{11}$$

The estimated spatial resolution for $D = 1$ ps/nm/km (a dispersion-shifted fiber (DSF) is assumed), $c = 3 \times 10^8$ m/s, and $n_g = 1.46$ is tabulated in Table I. If the spatial resolution of 1 cm is achieved, we can measure the chromatic dispersion of 100-km-long DSFs with the wavelength interval of less than 1 nm. The wavelength interval can be decreased with enhancing the spatial resolution, which results in accurate determination of the chromatic dispersion. Hence, the spatial resolution of several centimeters or several millimeters is preferable. Such a spatial resolution over 10-km measurement range cannot be achieved in the conventional optical time-domain reflectometry (OTDR) and OFDR. As can be seen in the next section, such a spatial resolution can be achieved in the optical ranging system using a FSF laser.

III. OPTICAL RANGING USING A FSF LASER

The spatial resolution δL is given by differentiating (2) as

$$\delta L = \frac{c}{2n_g}\frac{\tau_{\mathrm{RT}}}{\nu_{\mathrm{FS}}}\delta f_B \tag{12}$$

and δf_B is given by

$$\delta f_B = \frac{1}{T} = \frac{\nu_{\mathrm{FS}}}{\tau_{\mathrm{RT}}\Delta\nu} \tag{13}$$

where T is the repetition period of the optical frequency chirp as shown in Fig. 3. The δf_B is estimated by 30 kHz in our experiments. By substituting (13) into (12), the spatial resolution is calculated as

$$\delta L = \frac{c}{2n_g\Delta\nu}. \tag{14}$$

The above expression is the same with that for conventional OFDR. The spatial resolution can be enhanced with increasing the chirp range of the FSF laser.

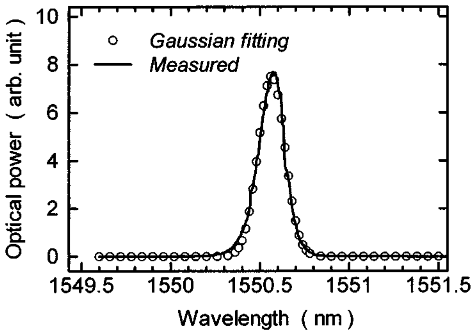

Fig. 4. Measured optical spectrum of the FSF laser. The solid line is the measured spectrum and circles are the fitted data with a Gaussian function.

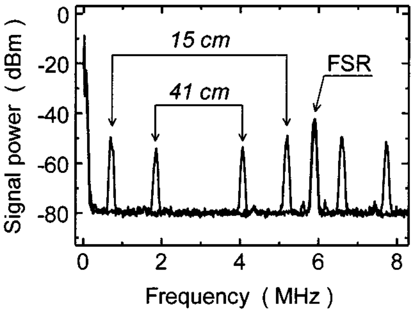

Fig. 5. Measured beat spectrum when the differential fiber length is 15 and 41 cm.

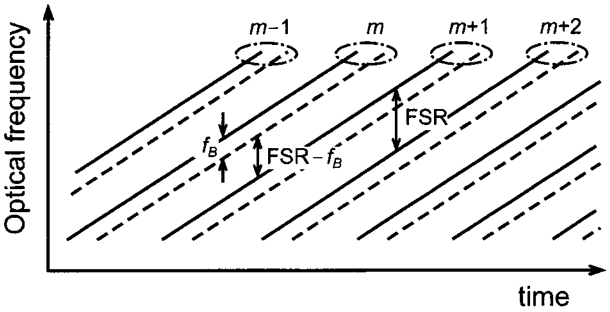

Fig. 6. Schematic drawing of the instantaneous optial frequencies of the reference beam (solid line) and the signal beam (dashed line) with the mode number labeled with $(m-1)$–$(m+2)$.

TABLE II
MEASUREMENT CONDITION OF THE SPECTRUM ANALYZER FOR MEASURING THE BEAT SPECTRUM.

item	value
Resolution bandwidth	3 kHz
Video bandwidth	100 kHz
Sweep time	5 sec
Average number	1

Fig. 4 shows the measured optical spectrum of the FSF laser. The resolution bandwidth of the optical spectrum analyzer was 0.1 nm, and the sweep time was 3 s. The optical spectrum is broad, and is well approximated with a Gaussian function. The broad optical spectrum means that the optical frequency is chirped in high chirp rate, and the envelop is observed. The full-width at half-maximum (FWHM) of the optical spectrum is about 0.17 nm, and therefore, the chirp range $\Delta\nu$ is estimated to be about 20 GHz. As a result, the theoretical spatial resolution is estimated to be $\delta L = 5.1$ mm for $n_g = 1.46$. The chirp range is determined by the uniformity of the optical gain of the EDFA within the bandwidth of the tunable filter. The larger chirp range can be obtained by using a tunable filter with wider bandwidth. Since $\Delta\nu \approx$ 20 GHz in our experiment, and $M = 3400$ in our system.

Fig. 5 shows the measured beat spectrum when the differential fiber length between the signal and the reference arms are 15 and 41 cm. The measurement condition of the spectrum analyzer is shown in Table II. The resolution bandwidth is determined to be much smaller than δf_B given in (13). The beat signals generated by the Fresnel reflection at the far end of the fiber were clearly measured. It is also found that the beat spectrum consists of two beat signals within the FSR of the laser cavity, and the two beat signals approach each other with increasing the differential fiber length. The two beat signals appear at the same frequency when the beat frequency $f_B = \mathrm{FSR}/2$, and then the distributively measurable range L_c is given by substituting $f_B = \mathrm{FSR}/2 = 1/2\tau_{\mathrm{RT}}$ and $m = 0$ into (2) as

$$L_c = \frac{c}{n_g \nu_{\mathrm{FS}}}. \tag{15}$$

In our experimental condition ($n_g = 1.46, \nu_{\mathrm{FS}} = 80$ MHz), $L_c = 1.28$ m is obtained.

Here, we explain the reason why two beat signals appear within the FSR. Fig. 6 shows the instanteneous optical frequencies for the reference beam (solid line) and the signal beam (dashed line) with the mode number labeled with $(m-1)$–$(m+2)$. It can be obvious that two beat signals appear within the FSR, whose frequencies are f_B and $(\mathrm{FSR} - f_B)$. The beat signal appeared at f_B is gererated by the reference and signal beams with the same mode number (mth reference and the mth signal beams), and the beat signal appeared at $(\mathrm{FSR} - f_B)$ is gererated by the mth signal and the $(m+1)$th reference beams in this figure.

The experimental spatial resolution defined by the FWHM of the beat spectrum is about 1 cm from Fig. 5. Since the chirp range $\Delta\nu$ is estimated from the envelop of the optical spectrum shown in Fig. 4, and is not directly measured, the difference between the theoretical and the experimental spatial resolutions is insignificant.

The signal-to-noise ratio (SNR) in Fig. 5 is about 30 dB. The SNR is an insignificant factor in our system, because it only limits the length of the FUT. If the loss of the FUT is assumed to be 0.2 dB/km, the maximum length of the FUT can be estimated to be $30/2/0.2 = 75$ km for a Michelson interferometer system. The measurable length can be easiliy expanded by using an optical amplifier or by using a Mach–Zehnder interferometer (MZI) instead of a Michelson interferometer.

Fig. 7 shows the measured beat spectrum when a 5-km-long optical fiber is used as the FUT. The fiber length of the reference arm is negligible because it is about 1 m. In this case, we can obtain the beat spectrum similar to that for short optical fibers, and the spatial resolution is also 1 cm. The beat order of the beat spectrum is $m \approx$2000. This means that the beat spectrum between the two beams, whose mode numbers are different by about 2000, can be observed in the low frequency region.

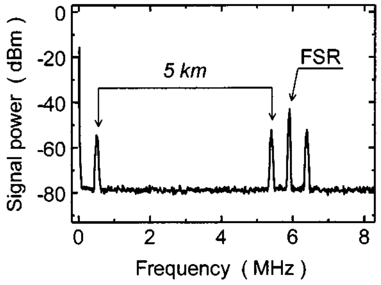

Fig. 7. Measured beat spectrum for a 5-km-long optical fiber.

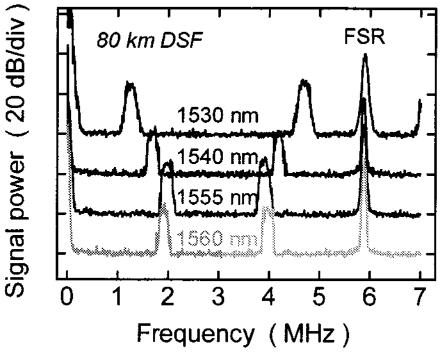

Fig. 8. Measured beat spectrum for an 80-km-long DSF for various wavelength of the FSF laser.

IV. Chromatic Dispersion Measurements

In this section, we describe the experimental results on the chromatic dispersion for long optical fibers. An 80-km-long DSF was used as the FUT. In the measurement, an MZI was used instead of a Michelson interferometer because of the loss of the DSF (0.2 dB/km $\times$ 80 km $=$ 16 dB). Fig. 8 shows the measured beat spectrum for different lasing wavelength of the FSF laser. The measurement condition of the spectrum analyzer is shown in Table II. Although the vertical axis is relatively scaled because four traces are intentionally separated, the noise level for four traces are -80 dBm, which are the same with Figs. 5 and 7. In the experiment, the effect of the fiber length of the reference arm is negligible, because its length is short (typically, 1 m), and the delay time change of the lightwave in the reference arm with the wavelength change is negligible. No polarization controller was used in the interferometer to maximize the beat signal level. The beat frequency changes according to the wavelength of the FSF laser. The beat spectrum shown in Fig. 8 is broader than that of Fig. 7, and as a result, the spatial resolution is degraded to be about 4.5 cm. This is due to the fluctuation of the beat spectrum caused by an accoustic noise and environmental fluctuation in our laboratory. The beat spectum is stable for several minutes regardless of multimode oscillation of the FSF laser. We believe that this stability is due to high-speed optical frequency chirping of the FSF laser. In the usual interferometer using a free-running multimode fiber laser, the beat signal is generally unstable because of fluctuation and mode hopping of the optical frequency. On the other hand, the optical frequency of the FSF laser is chirped with high chirp rate as shown in (1). The repetition period of the optical frequency chirp T is given by (13), and is about 33 μs in our system. The oscillating mode of the FSF laser is considered to be stable during the period T, because the fluctuation of the lasing modes are slower than the repetition period T, and therefore, stable beat spectrum can be measured.

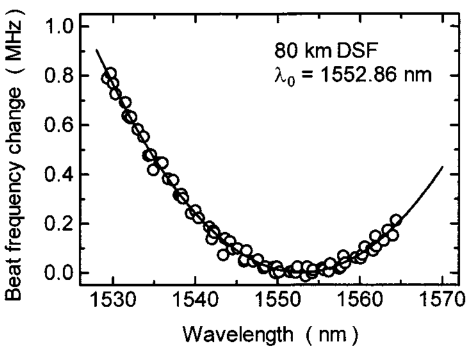

Fig. 9. Measured beat frequency change for an 80-km-long DSF. The open circles are the measured data and the solid curve is the fitting curve with a quadratic function.

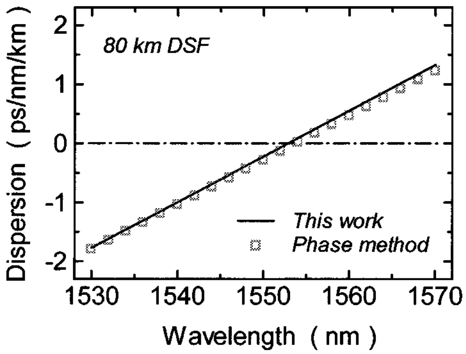

Fig. 10. Estimated chromatic dispersion for an 80-km-long DSF. The solid line is the result by this work and the squares are the results by the phase method.

The beat frequency change against the wavelength of the FSF laser is plotted in Fig. 9. In the figure, the open circles are the measured results, and the solid line is the fitting curve using a quadratic function. The measured beat frequency change is well fitted with the quadratic function. The zero-dispersion wavelength λ_0 is the wavelength at which the beat frequency change is bottom (or peak) and is determined to be $\lambda_0 = 1552.86$ nm. Fig. 10 shows the estimated chromatic dispersion against the wavelength. The solid line is the result by this work and the squares are the result by the phase method. The chromatic dispersion can be well estimated by the proposed system. The small difference between the two methods is caused by the uncertainity of reading the beat frequency in the beat spectrum. If a frequency counter is used to read the beat frequency with proper averaging times, then the difference is reduced.

V. Conclusion

We have proposed a novel method for measuring the chromatic dispersion of long optical fibers by means of optical ranging system using a FSF laser. The advantage of this system is that no high-speed electronics and optics are required. The principle is the direct measurement of the dependence of the propagation time in the optical fiber on the wavelength. This can be carried out by using the optical ranging system using a FSF laser, because the spatial resolution of several centimeter can be easily achieved over 10-km measurement range. The chromatic dispersion for an 80-km-long DSF was estimated and the estimated result agrees well with the conventional method. The proposed method is very useful technique for measuring the chromatic dispersion of the fibers, as well as its length.

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