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Chromatic Dispersion Measurements of Single-Mode Fibers, Polarization-Maintaining Fibers, and Few-Mode Fibers Using a Frequency Domain Method

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Abstract: Chromatic dispersion is an important fiber attribute affecting transmission performance over optical fibers. Various chromatic dispersion measurement methods have been developed primarily for single-mode fibers. In the literature, measurement techniques were also developed to characterize few-mode fibers and multi-mode fibers. These methods are often subject to some limitations. In this paper, a simple and robust measurement method for chromatic dispersion measurement of single-mode fibers, polarization–maintaining fibers, and few-mode fibers is presented using a frequency domain instrument and a vector network analyzer. The method is applied to all three types of fibers through one measurement methodology uniformly. Using a vector network analyzer, the measurement instrument obtains the complex transfer function of fiber transmission. The inverse Fourier transform of the measured complex transfer function is used to determine the group delays for each mode of the fiber. Although the sampling is highly under-sampled for the whole fiber link, through proper treatment of the data, we can de-alias the signals and obtain accurate values of the group delays of each mode. By measuring the group delays over different wavelengths, the data can yield the chromatic dispersion of each mode over the wavelength window.

Keywords: chromatic dispersion measurement; single-mode fiber; few-mode fiber; polarization-maintaining fiber; multi-mode fiber; multicore fiber; frequency domain measurement method

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1. Introduction

Chromatic dispersion is an important fiber attribute affecting the transmission performance over optical fibers. Due to chromatic dispersion, different frequency or wavelength components within an optical signal may travel at different speeds that cause pulse broadening. The amount of chromatic dispersion is a main factor in today's high-speed optical communications, limiting the distance that the optical signals transmit. For standard single-mode fibers, the chromatic dispersion is specified to meet certain values. As a result, the chromatic dispersion measurement is important for single-mode fibers.

Various chromatic dispersion measurement methods have been developed primarily for single-mode fibers. Since for a standard single-mode fiber, the chromatic dispersion is around 17 ps/(nm·km) at 1550 nm, for a time domain measurement, it would require a picosecond-level pulse width and an optical bandwidth greater than 100 GHz for the receiver in order to detect the pulse broadening at 1 km length, which is challenging. As a result, more sensitive measurement techniques have been developed. One method is modulation phase shift method [1,2]. When an optical source is modulated by a sinusoidal wave, the propagation delay can be evaluated by the relative phase retardation of the received radio frequency (RF) signal and the chromatic dispersion can be calculated from the derivative of the group delay over wavelength. Another method is called baseband amplitude modulation response. As the chromatic dispersion changes the relative phase of the sidebands of modulated signals, with an intensity modulated signal, the chromatic dispersion converts AM to frequency modulation (FM). The effect gives the AM response a characteristic shape which can be analyzed to determine the chromatic dispersion at a particular wavelength [3,4]. Such a measurement requires a very long fiber length with significantly cumulated chromatic dispersion to see a series of nulls in the frequency modulations to retrieve the chromatic dispersion information. Another method for measuring chromatic dispersion is the interferometric method using a Mach–Zehnder interferometer with a fiber under test in one arm and a reference fiber in the other arm [4,5]. By sweeping the wavelength, the wavelength-dependent arm length difference can be obtained, from which the chromatic dispersion can be calculated.

A chromatic dispersion measurement for single-mode fibers is often carried out using well-established methods as described above, some of which are available from commercial instruments. The methods require that the fiber under test be strictly single-mode for the measurement technique to work. In the case of polarization-maintaining fibers (PMFs), which are single-mode fibers, the above-mentioned methods would not work. Because of high birefringence, the two polarization modes have well-separated group delays, and the fiber behaves as a two-mode fiber. Therefore, it breaks the single-mode requirement. In recent years, space division multiplexing (SDM) has been an active research topic for increasing the system capacity beyond the single-mode fiber. SDM requires new types of fibers with more spatial modes for parallel signal transmission, such as few-mode fibers (FMFs) or multi-core fibers (MCFs). For FMF and MCF, new methods need to be developed for accurate and low-cost chromatic dispersion measurements for different spatial modes. In spite of the various dispersion measurement techniques developed in the past to characterize FMF and multi-mode fibers (MMFs), such as time domain methods [5], optical low-coherence reflectometry [6], and interferometric techniques [7,8], these methods have some limitations, such as using only a short fiber [6] or obtaining only relative dispersion between modes unless a reference fiber with known chromatic dispersion is used [7,8].

In this paper, we present a chromatic dispersion measurement based on using a vector network analyzer (VNA) to measure the complex transfer function (CTF) of the light traveled through the fiber under test. We report on the measurements of chromatic dispersion that is applied to single-mode fibers, PMFs, and FMFs using one measurement methodology uniformly applied to all three fiber types. The measurement method used in the current work is extended from our previous work measuring group delays for FMF [9], the differential mode delay and modal bandwidth for MMF [10], and groups delays, chromatic dispersion, and skews for MCF [11]. Even though MCF has been used to study group delay and chromatic dispersion in more complex fibers, its applications to more common types of fibers have not been reported before. Using a VNA, the measurement instrument obtained the CTF of the fiber transmission. The inverse Fourier transform of the measured CTF is used to determine the group delays for each mode of the fiber. Although the sampling is highly under-sampled for the whole fiber link, through proper treatment of the data, we can de-alias the signals and obtain the accurate values of the group delays of each mode. By measuring the group delays over different wavelengths, the data can yield the chromatic dispersion of each mode over the wavelength window. In this paper, we present the measurement principle in Section 2 and show the measurements of chromatic dispersion for several types of fibers of interest in Section 3. Section 4 presents a discussion of the measurement techniques used as compared to those in the literature. The conclusions are presented in Section 5.

2. Frequency Domain Measurement Method

In this section, we present the details of the experimental setup and measurement principle. The experimental setup is shown in Figure 1. The main measurement instrument is a VNA, an RF instrument measuring the electrical response of a device under test over a range of driving frequencies. In our experiments, we used an Agilent N5230C PNA-L Network Analyzer. For our measurements, we are primarily interested in the transmission property of the fiber under test, which is also known as the S_{21} parameter or

CTF. Considering that the purpose of the measurement is to determine the optical properties of the fiber under test, we added an electrical-to-optical conversion at the launching end using a CW laser, followed by an intensity modulator (IM) to convert sweeping frequency electrical signals into optical signals into the fiber under test, and an optical-to-electrical conversion at the receiving end using a photodetector (PD) or linear optical receiver to convert the optical signals back to electrical signals. For launching the light into the fiber under test, we added a polarization controller and a fiber alignment stage. For single-mode fiber measurement, the launched single-mode fiber just needs to be coupled with the fiber under test center to center. For PMF, the polarization controller is used to control the state of polarization excited so that both states of polarization are present. For FMF, some offset between the launched single-mode fiber and the fiber under test needs to be set so that all propagation modes are present. Light source and intensity modulator are chosen so that they function at the corresponding wavelengths of measurements, which include measurements in wavelength ranges from 800 to 880 nm, and in the O-band covering 1260–1360 nm and 1520–1570 nm.

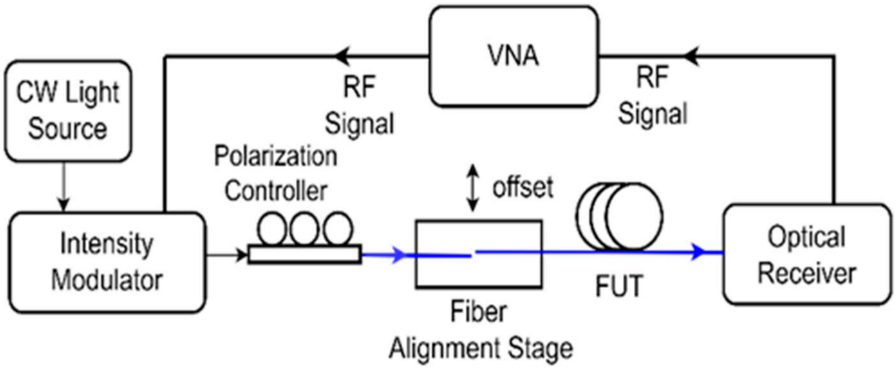

Figure 1. The schematic of the measurement setup.

Through proper calibration in the back-to-back condition without the fiber under test using a short fiber, we can take out the contribution of the baseline system and obtain the CTF for the fiber under test only. The CTF takes the form,

$$CTF(f) = S_{21}(f) = \sum_{j=1}^{n} a_j \cdot \exp(-i \cdot 2\pi f \tau_j), \tag{1}$$

where a_j is the relative optical power in mode j, and τ_j is the group delay of mode j. The CTF is directly related to the time domain picture. When one input pulse, $P_{in}(t)$, is launched into the fiber under test with n modes, the output pulse consists of n pulses resulting from the different group delays, τ_j, of the n modes:

$$P_{out}(t) = \sum_{j=1}^{n} a_j \cdot P_{in}(t - \tau_j) \tag{2}$$

One can perform an inverse Fourier transform of $CTF(f)$ on either the real or imaginary part to extract the time domain information from the frequency domain measurement in order to obtain the group delay of each mode, $\tau_{j.}$ To fully resolve the time domain information without causing aliasing or ambiguity of the group delay time τ_j, the sampling frequency step, df, needs to meet the condition as set by Nyquist theorem, $df \leq 1/(2 \cdot \max(\tau_1, \ldots \tau_n))$, which results in unreasonably large numbers of points that need to be sampled. However, this problem can be solved if we apply a de-aliasing procedure to link the time of the peak location in the inversion Fourier transform to the actual group delay of each mode, τ_j by a simple equation,

$$\tau_j = k/df \pm t_j \tag{3}$$

where k is an integer. Depending on the sign before t_j, the time sequence from inverse Fourier transform can either be the same time sequence or the opposite one compared to the actual propagation times for each core.

Detailed procedures have been described in Ref. [10] on how to obtain de-aliased signals, which would recover the true group delays of each mode, τ_j. For the whole fiber, typically with a length of many kilometers, a large group delay results in a rapid oscillation of the actual CTF. By knowing the approximate group delay of the fiber under test using Equation (2), one can transform the CTF to cancel the fast-oscillating term that arises from the large group delay of the modes and obtain a modified or transformed CTF that is slowly varying. The modified CTF, labeled as CTF', is related to the original CTF by a phase term,

$$CTF'(f) = e^{i2\pi\tau_0 f} \cdot CTF(f), \quad (4)$$

where τ_0 is determined by the following equation,

$$\tau_0 = \frac{k}{df} \pm t_p. \quad (5)$$

t_p can be chosen at the peak location of the inverse Fourier spectrum of the CTF. In the case of FMF when there are several peaks, t_p can be chosen at one of the peak locations. With the transform, in the local time frame, the time at the t_p is set to zero. The time in the local time frame to the full delay is linked by Equation (5). One can obtain the output pulses of the transmission link by performing an inverse Fourier transform of the product of the modified CTF (CTF′) and the Fourier transform of the input pulse so that,

$$P_{out}(t) = \mathcal{F}^{-1}(CTF'(f) * \mathcal{F}(P_{in}(t))) \quad (6)$$

where $P_{in}(t)$ is the assumed input pulse as if we have a system with an optical pulse launched into the fiber under test. When τ_0 in Equation (4) is added to the output pulse in the local time frame, we can see the output pulses after traveling through the whole fiber length.

Because the sampling is under-sampled, the frequency content of the CTF can be 'folded' differently based on the frequency step of sampling [12], as shown in Equation (3). The transform in Equation (6) is sensitive to the sampling choice on frequency. When the proper value of k and sign in Equation (3) are chosen, well-behaved output pulses corresponding to the de-aliased condition can be identified [10]. Since the fiber length information is typically known to close accuracy, around 1 m, and as the group delay over 1 km of fiber is typically between 4900 and 4950 ns, the initially estimated k value is typically accurate within ± 1 so that the de-aliasing to recover the true group delay of each mode can be executed relatively easily. Even if the information of the fiber length is not precisely known—for example, someone takes some lengths of the fiber from the reel without recording the length change—one can still recover the correct k value and sign in Equation (3) by searching in a wider range. Moreover, the frequency parameters, i.e., the range of frequency and the number of points (NOPs) of sampling used by VNA for measuring CTF, can be chosen to further remove the ambiguity of identifying the de-aliased condition. In Ref. [10], since the interest there was to measure the differential group delay of MMF, not the absolute group delays over a long length of the fiber, the frequency parameters can be chosen so that the de-aliasing choice is independent of the k value in Equation (3). In the case of the current work, the main interest is to obtain the total group delay to calculate the chromatic dispersion. The parameters in Equation (5) including both the k value and the sign must be chosen properly to obtain the de-aliased CTF that yields the correct group delays.

After the group delays are obtained over a wavelength range, the chromatic dispersion, $D(\lambda)$ can be calculated as the first-order derivative of the group delay,

$$D(\lambda) = \frac{1}{L}\frac{d\tau}{d\lambda}, \quad (7)$$

where L is the length of the fiber and τ is the total group delay of a particular mode at the length L.

3. Chromatic Dispersion Measurements of Single-Mode Fiber, PMF, and FMF

Now that we have established the measurement principle in Section 2, we can show detailed measurements of single-mode fibers, PMFs, and FMFs in the three subsections below. All three fibers are glass optical fibers with Germania-doped core and pure silica cladding.

3.1. Measurements of a Single-Mode Fiber

The first fiber to measure is a commercial single-mode fiber, Hi780 [13]. It is a single-mode fiber at 780 nm and a range of wavelengths above 780 nm, including 850 nm, which is well below the wavelength range of commercial instruments for chromatic dispersion measurement. For example, the PerkinElmer CD500 measures chromatic dispersion from 1250 nm to 1630 nm, so that the chromatic dispersion value of Hi780 fiber at 850 nm is not commonly available. We measured a reel of Hi780 with a length of 10.095 km. The frequency range for the VNA sampling was from 10 MHz to 10 GHz with NOP of 850. For the length of 10.095 km, it would have required at least 1 million data points to meet the Nyquist sampling requirement, which far exceeds the maximum number of sample points used by some VNAs at around 25,000. With only 850 sample points, the sampling is highly aliased. Following the procedure in Ref. [10], we obtained the CTF of the fiber using the setup in Figure 1 with the real part shown in Figure 2a. Real and imaginary parts are fast-oscillating, so what is visible is mostly the envelope. Through an inverse Fourier transform, we obtained the spectrum shown in Figure 2b. We further transformed the CTF into a slowly varying form, i.e., CTF'(f), following Equations (4) and (5), as shown in Figure 2c. Using a k value of 584 and t_p of 36.3971 ns, associated with a negative sign in Equation (5), we can obtain the well-behaved output pulse shown in Figure 2d showing the total group delay of the fiber at 850 nm to be 49,594.83 ns.

The measurements were conducted over a wavelength range of 815 nm to 875 nm with a 5 nm increment. Following the same procedures as above, we obtained the group delays for each wavelength and normalized them to 1 km, as shown in Figure 3a. We have also conducted a fitting using the second-order polynomial, as shown by the solid line. Such fitting can help us to overcome minor errors associated with each individual measurement. Using the fitted curve, we calculated the chromatic dispersion using Equation (7), as shown in Figure 3b. In the wavelength window, the chromatic dispersion of the fiber has a high negative value around −100 ps/(km·nm), consistent with our knowledge of the fiber. At 850 nm, the chromatic dispersion value is −100.6 ps/(km·nm). This value is essentially the same as the chromatic dispersion value measured on another reel of Hi780 fiber, which is −100.3 ps/(km·nm), as reported in [14] using the method in [4] and Chapter 3.2 of Ref. [15].

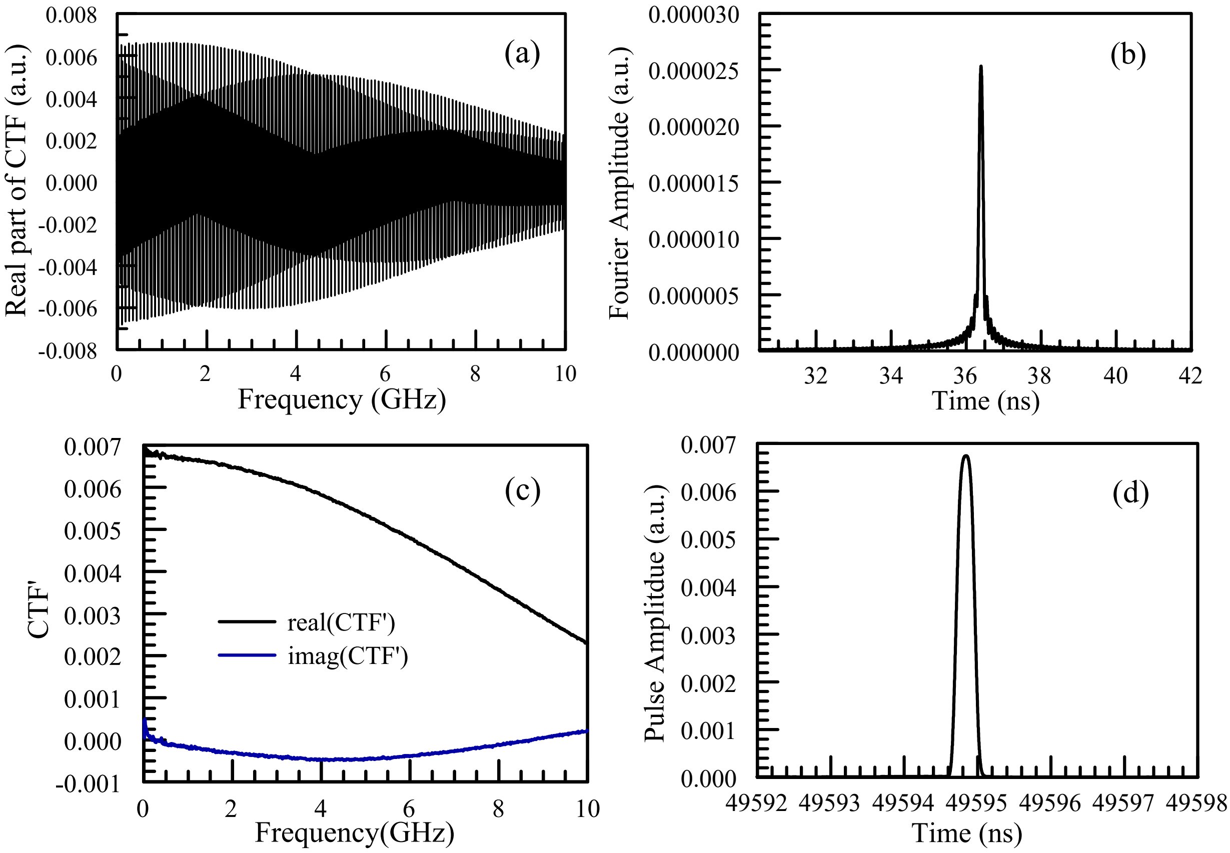

Figure 2. (**a**) The real part of CTF measured by VNA; (**b**) the inverse Fourier transform of the real part of the measured CTF; (**c**) CTF′; (**d**) the calculated output pulse.

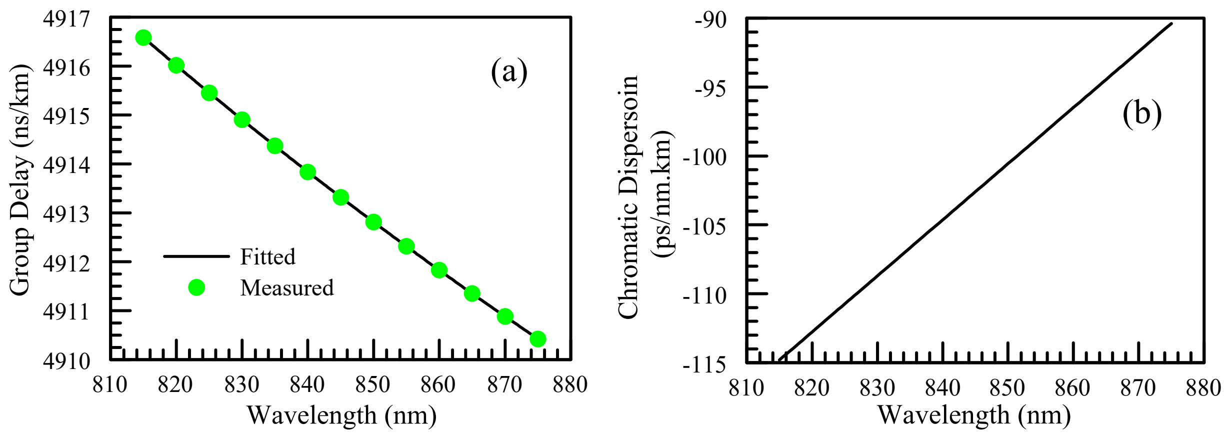

Figure 3. (**a**) The group delay vs. wavelength for a Hi780 fiber. (**b**) The chromatic dispersion vs. wavelength for a Hi780 fiber.

We note here that one benefit of the frequency domain measurement technique is that it can measure the fiber chromatic dispersion with very low optical power. The optical power launched into the fiber under test is around −4 dBm. Over a distance of 10 km, the total attenuation of the fiber under test is well above 20 dB. Optical power reaching the optical receiver is below −25 dBm. Using this capability, we can measure fibers of very long lengths as well as fibers as short as a few hundred meters, as shown in the next measurement example.

3.2. Measurements of a PMF

Here we show detailed measurements of a 500 m PMF that is commercially available, called PM 1550 [16]. Because of the use of Panda-type stress rods, the core of the fiber has anisotropic indices, resulting in high birefringence. Even though PMF is a single-mode fiber, due to the high birefringence of the fiber, the two polarization modes have significant different group delays so that the fiber practically behaves like a two-mode fiber. Since the measurement principle is strictly designed for single-mode fibers, a commercial chromatic dispersion measurement instrument cannot directly measure the fiber unless only one polarization mode is launched. In the current case, we show that the same frequency domain measurement setup can be used to measure the chromatic dispersion of PMF in a straightforward way.

First, we acquired a series of CTF from 1525 nm to 1570 nm with a 5 nm wavelength increment using the setup in Figure 1. The frequencies used for the measurement are from 10 MHz to 10 GHz with 2000 data points. The polarization controller was adjusted so that both polarization modes were excited. The inverse Fourier transform of the measured CTF at 1550 nm is shown in Figure 4a. It can be observed that there are two peaks in the inverse Fourier spectrum, which correspond to the two polarization modes of the PMF. They are separated due to high birefringence of the fiber t_p. is picked at the location of the higher peak with the value of 4.7234 ns. With a k value of 33 and a negative sign for Equation (5), we can see the slowly varying CTF′ in Figure 4b. The $CTF\prime$ shows periodic modulations over frequency, which is a typical behavior for a two-mode fiber, whose transfer function was studied in detail in Ref. [17]. The $CTF\prime$ also yields the well-behaved output pulses shown in Figure 4c using Equation (6) with τ_0 added to the local time to show the full group delay. According to the peak locations of the two pulses, the full group delays for the two polarization modes over 500 m length at 1550 nm are 2468.755055 ns and 2469.450814 ns. We can calculate the group beatlength of the fiber at 1550 nm using the following equation:

$$L_B = \frac{\lambda \cdot L}{c \cdot \Delta\tau}, \quad (8)$$

where λ is the wavelength of interest, L is the length of the fiber, c is the speed of light in vacuum, and $\Delta\tau$ is the group delay difference between the two polarization modes [18]. The group beatlength at 1550 nm for this PMF is 3.72 mm, which agrees well with the value provided by the factory upon its inspection of this fiber with the 3.8 mm value.

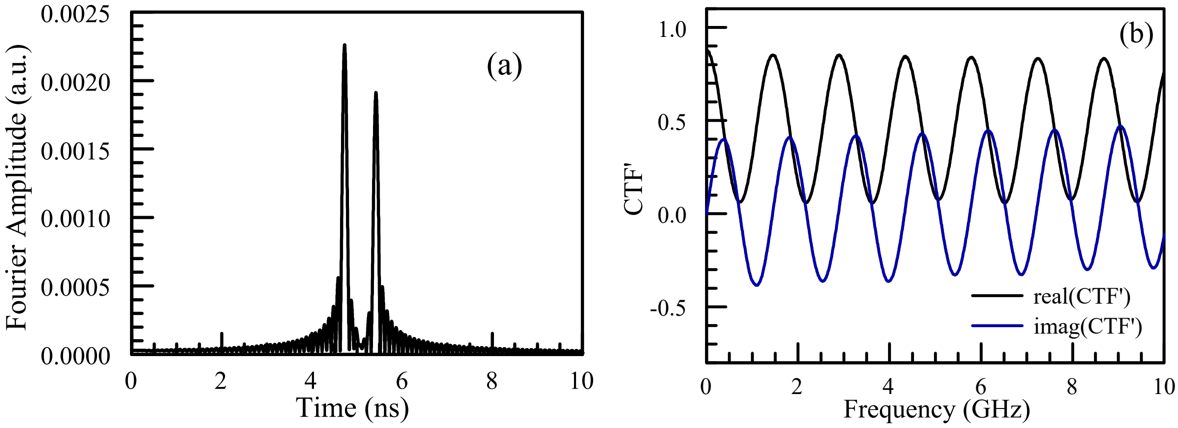

Figure 4. *Cont*

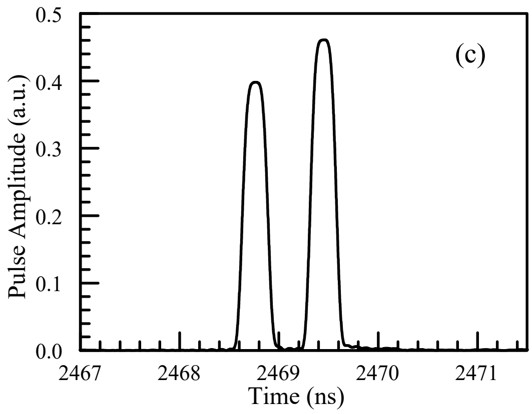

Figure 4. (**a**) The inverse Fourier transform of the real part of CTF measured at 1550 nm; (**b**) the modified CTF defined in Equation (4), CTF′; (**c**) the calculated output pulses for the 500 m PMF.

We measured the fiber over a wavelength range, similarly to the procedure for the first fiber in Section 3.1. We show the normalized group delay for each polarization mode in Figure 5a. In Figure 5b, we show the calculated chromatic dispersion value based on the fitted group delay using Equation (7). The measurement is sensitive enough to tell the difference between the two polarizations in terms of group delay and chromatic dispersion at 500 m. In addition, the overall chromatic dispersion value is consistent with a fiber with a step-index core.

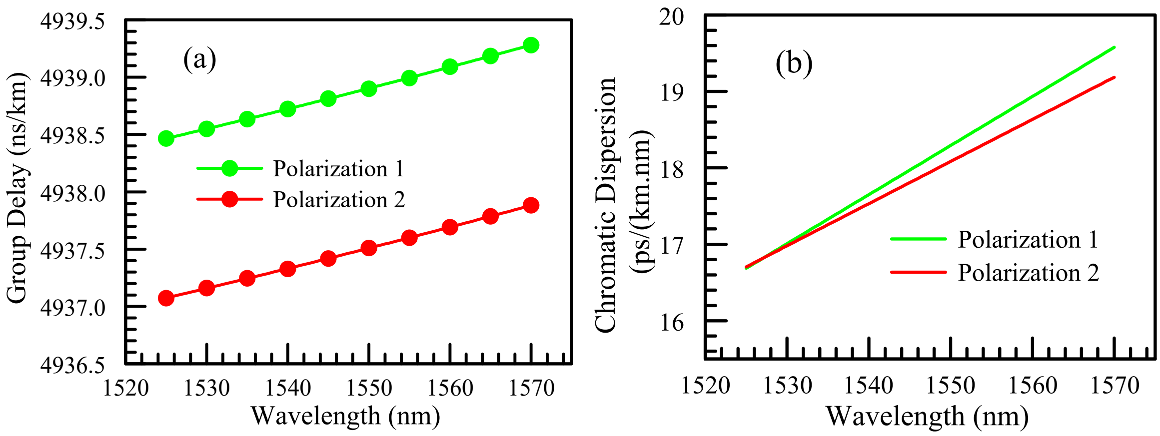

Figure 5. (**a**) Group delay as a function of wavelength for PMF around 1550 nm; (**b**) chromatic dispersion as a function of wavelength for PMF around 1550 nm.

In addition to measuring the PMF at wavelengths around 1550 nm, we also measured the PMF in the O-band, from 1260 nm to 1360 nm, with a 5 nm wavelength increment. The measurement results are shown in Figure 6. The two polarization modes of the PMF have slightly different group delays in the O-band. At 1310 nm, such a difference is translated into a group beatlength of 3.19 mm. The polarization modes have similar chromatic dispersion values across the O-band wavelength range. Worth noting is that the chromatic dispersion value crosses the zero point at 1311.5 nm, which is consistent with our knowledge of single-mode fibers with a step-index refractive index for the core. At the zero-dispersion wavelength, the slopes of chromatic dispersion for 'Polarization 1' and 'Polarization 2' are 0.0928 ps/(km·nm^2) and 0.0926 ps/(km·nm^2), respectively.

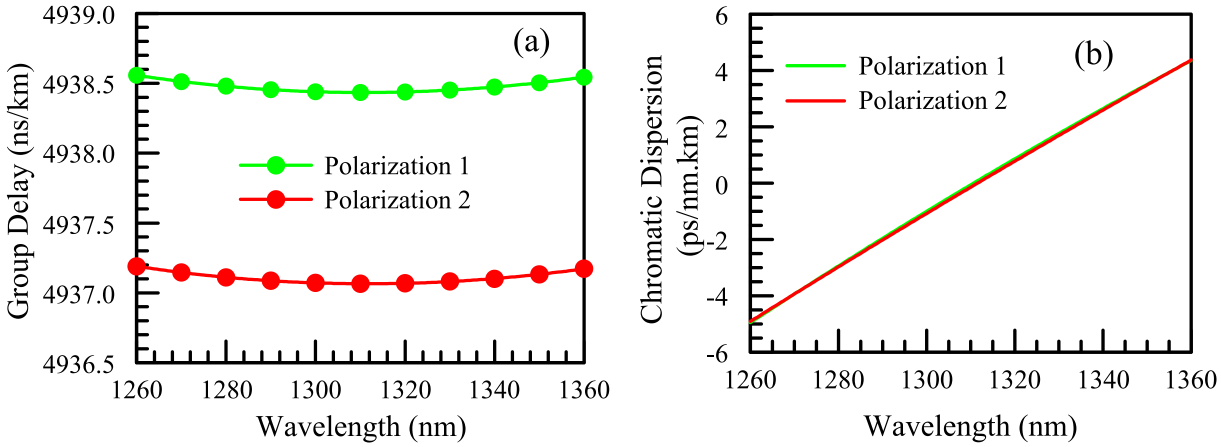

Figure 6. (**a**) Group delay as a function of wavelength for PMF around 1310 nm; (**b**) Chromatic dispersion as a function of wavelength for PMF around 1310 nm.

3.3. Measurements of an FMF

In this subsection, we study an FMF for its chromatic dispersion property. This fiber has four modes in the O-band from 1260 nm to 1360 nm. Its group delay properties were investigated when the frequency domain measurement method was first developed [9]. With a 5 nm wavelength increment, the CTFs over the O-band wavelength window were measured using the procedures described in Section 2. The fiber alignment stage introduced some offset between the launched single-mode fiber and the fiber under test so that all four modes of the FMF can be excited. The VNA uses the frequency range from 10 MHz to 12 GHz with 2001 sampling points. The inverse Fourier transform for the real part of the CTF is shown in Figure 7a. This fiber has four peaks reflecting its nature as a four-mode fiber. t_p was chosen to be the time location at the highest peak, 64.066 ns. For Equation (5), k is 29 and the sign is positive. With these, the CTF$'$ is shown in Figure 7b with more complex behavior than the two-mode situation for PMF. The output pulse after traveling 1 km is shown in Figure 7c. The four modes, i.e., LP_{01}, LP_{02}, LP_{11}, and LP_{12}, show distinct group delays at 1270 nm wavelength.

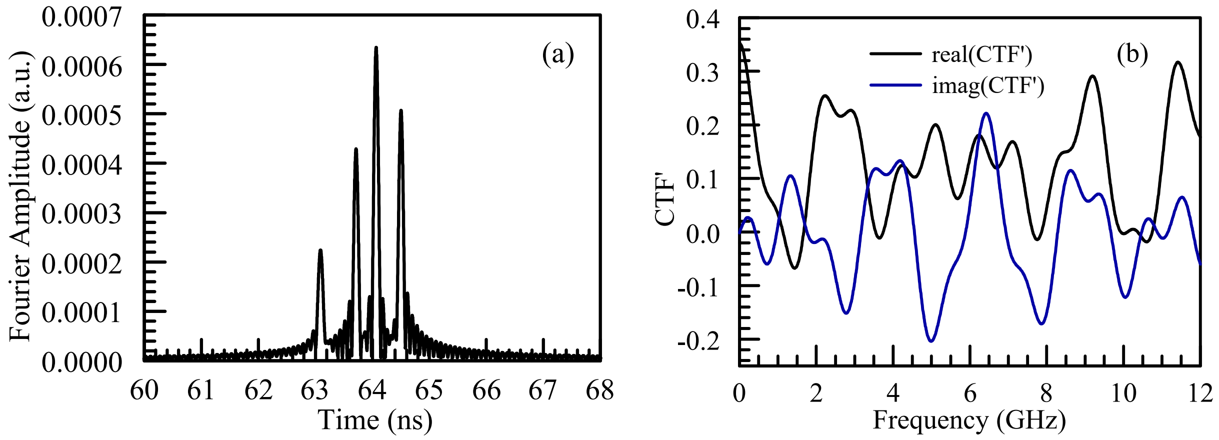

Figure 7. *Cont.*

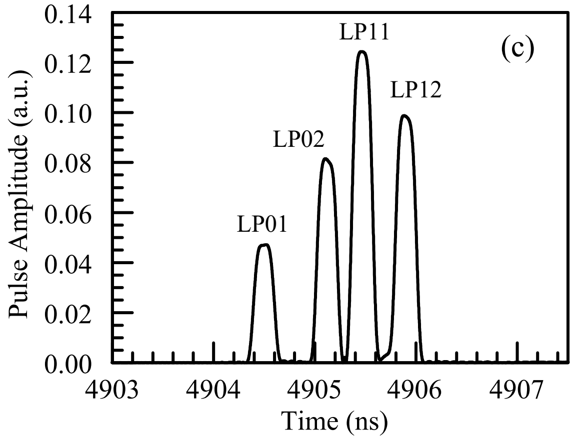

Figure 7. (**a**) The inverse Fourier transform of the real part of CTF measured at 1270 nm; (**b**) modified CTF defined in Equation (4), CTF′; (**c**) the calculated output pulses for the 4-mode FMF.

We subsequently processed all the data over the O-band wavelength window and show the group delay and chromatic dispersion for each mode in Figure 8a and Figure 8b, respectively. It should be noted here that we conducted numerical modeling of the group delays of each mode vs. the wavelength using the fiber refractive index profile, which illustrates the trending of each mode consistent with the measurement results. Using the information, we can associate each group delay curve with a specific LP mode as labeled in Figure 7. This FMF shows an interesting behavior for the group delays between the four modes. A cross-over of LP_{01} and LP_{02} group delays occurs around 1332 nm, whereas the group delays for LP_{11} and LP_{21} modes are expected to cross each other slightly over 1360 nm. Measurements in the frequency domain can capture the features. When the group delays for two modes are too close, the output pulse from each mode is overlapped. For processing the group delay curve, we excluded the data points near the crossing point. The overall group delay curve for each mode can be obtained using polynomial fitting up to the third order, as shown by the solid curve in Figure 8a. The chromatic dispersion for each mode as a function of wavelength was calculated using Equation (7) and is shown in Figure 8b. LP_{01} and LP_{11} modes have similar chromatic dispersion values over the entire O-band window, and the chromatic dispersion moved from a negative value to a positive value as the wavelength increased. The chromatic dispersion values of two other modes, LP_{02} and LP_{21}, are negative for most of the O-band, but the chromatic dispersion for LP_{21} turns positive when approaching 1360 nm.

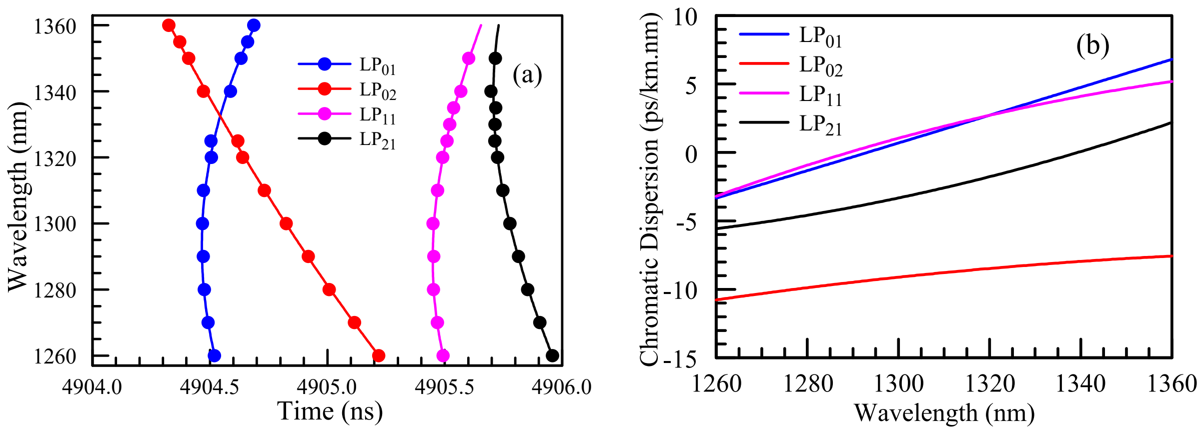

Figure 8. (**a**) Group delay as a function of wavelength. (**b**) Chromatic dispersion as a function of wavelength for the 4-mode FMF over O-band wavelength window.

4. Discussions

Three types of optical fibers have been measured and the results are presented in Section 3. We note that the measurements were performed with a uniform method consistently applied to all three fibers. To our knowledge, there has not been a method that can measure the chromatic dispersion across single-mode fibers, PMFs, and FMFs under a single principle. Below, we discuss the capabilities of existing methods or tools as relevant to the three measurements we have conducted.

- Single-mode fiber case: The most mature measurement methods were developed for single-mode fibers as shown in Refs. [1,2]. They were available from commercial instruments. However, one limitation of commercial instruments is the wavelength coverage, which is typically from 1250 nm to 1630 nm. In Section 3.1, we showed that we can conveniently work in wavelengths outside commercial instrument limits at around 850 nm. Another important feature of the measurement is its ability to handle lower optical power. With high fiber attenuation at wavelengths around 850 nm, fiber attenuation is high over 2 dB/km. The frequency domain measurement method can handle long lengths of fiber without requiring high power optical sources, which can be difficult to find.
- PMF case: The mature measurement methods for single-mode fibers require that the fiber under test be strictly single-mode for the measurement technique to work. Even though PMF is a single-mode fiber, due to its high birefringence, the two polarization modes have significant different group delays so that the fiber practically behaves like a two-mode fiber. Since the measurement principles in [1,2] are strictly designed for single-mode fibers, the commercial chromatic dispersion measurement instrument cannot directly measure the fiber unless only one polarization mode is launched. Indeed, it is difficult to find the chromatic dispersion measurement results of PMF. The measurements with results in Section 3.2 are useful additions to the literature.
- FMF case: The chromatic dispersion measurement for FMF remains an evolving subject. To our knowledge, there has been no well-developed method of measuring chromatic dispersion for FMF that can simultaneously measure group delays and chromatic dispersion for all modes. Some existing methods [7,8] rely on a reference fiber with a known chromatic dispersion value and therefore are not flexible in measuring fibers with different lengths. In our measurements, the group delays and chromatic dispersion values for all four modes of the fibers were measured and obtained simultaneously.

5. Conclusions

In this paper, we present a frequency domain method for measuring the chromatic dispersion of several types of fibers, including single-mode fibers, PMFs, and a four-mode FMF. The frequency domain measurement instrument measures the CTF of fiber transmission. The inverse Fourier transform of the measured CTF is used to determine the group delays for each mode of the fiber. Although the sampling is highly under-sampled for the whole fiber link, through proper treatment of the data, we can de-alias the signals and obtain accurate values of the group delays of each mode. By measuring the group delays over different wavelengths, the data can yield the chromatic dispersion of each mode over the wavelength window. The measurement method has been applied to three types of optical fibers uniformly, which illustrates the robustness of the method. It is important to note that most of the existing chromatic dispersion measurement methods were mainly designed for single-mode fibers, and they would not work once the fiber became few-mode or multi-mode. On the other hand, the measurement methods shown in the research literature for FMF often suffer from various limitations. The presented method handles the measurement from single-mode fiber to FMF using a uniform method and is relatively simple to conduct. We note here that the measurement method can handle very low optical power, making it possible to measure very long fibers up to tens of kilometers in length. This is particularly helpful when the fiber attenuation is high in certain wavelengths.

On the other hand, the method can also be applied to short lengths of 500 m or less. We expect that the presented method would be useful to address group delay and chromatic dispersion measurements for many types of optical fiber without the need to develop a specific method for a specific fiber type.

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