Ultra-high-accuracy chromatic dispersion measurement in optical fibers

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ABSTRACT

The chromatic dispersion in optical fibers is a key property for applications where a broadband light source is used and the timing of each individual wavelength is crucial. Counteracting the timing offset introduced by the fiber is a challenge in many applications especially in mode locked lasers. The dispersion parameters need to be measured with high precision. The length of the fiber, the temperature, and the used wavelength will highly impact the amount of dispersion and the accuracy of the measurement. We developed an ultra-high-accuracy dispersion measurement setup at 1080 ± 50 nm considering all the parameters that may influence the measurement. It is based on a home-built wavelength tunable laser where the output is modulated by an electro-optical modulator connected to a 24 GSamples/s arbitrary waveform generator to a complex pattern consisting of pulses and a 4 GHz sine wave. After passing through the fiber the signal is measured with an 80 GSamples/s real time oscilloscope. The fiber’s temperature is controlled to allow for reproducible measurements over several days and we achieve timing measurement accuracies down to ~200 fs. We also present the performance of the setup at ~850 nm. We will discuss and quantify all effects which can negatively impact the system accuracy and we will report on more cost-effective options using lower performance equipment.

Keywords: Dispersion measurement, chromatic dispersion, fiber dispersion measurement, optical component characterization, tunable laser, FDML

1. INTRODUCTION

Optical fibers are subject to chromatic dispersion which leads to different propagation times depending on the wavelength. If a light pulse propagates through an optical fiber, it gets broadened depending for instance on the amount of the dispersion or the length of the fiber. This broadening can lead to major issues in applications like data transmission in telecommunications [1], fiber-based mode locked lasers or for instance in Fourier domain mode locked (FDML) lasers [2].

FDML lasers are ultra-rapidly wavelength swept lasers based on a long fiber ring cavity where the frequency of the periodic signal of the filter driver has to be synchronized with the optical round-trip time of light in the cavity. If the chromatic dispersion is well known it can be compensated which leads to improved noise characteristics and increased coherence properties [3].

Four fundamental methods are often used to measure the chromatic dispersion of optical fiber [4]. Temporal or spectral interferometric methods can be used, such as a Mach-Zehnder [5][6] or other interferometers [7]. They are used for short fibers of interest (FOI) of a few meters. The Chromatis\textsuperscript{TM} Dispersion Measurement System commercialized by Thorlabs is using a white light interferometer that achieves a group delay dispersion resolution of ± 5 fs\textsuperscript{2}. On the other hand, the time-of-flight of pulses can be measured, with either supercontinuum lasers to cover a very broad spectrum [8] or with a simple tunable light source [9][10][11] to determine the group delay. For instance, FDML lasers can be used to measure the dispersion of optical fibers at high speed [12]. The latest method requires a relatively long FOI, about 1 km, to add a long enough delay to differentiate between a reference and sample. Lastly, the time delay can be determined from the phase-shift between two signals. However, this method is time consuming due to the fact that a full interference spectrum must be measured repeatedly [13]. The company Viavi is achieving a dispersion uncertainty of ± 0.3 ps/nm/km with a 10 km FOI in a few 10\textsuperscript{th} of a second in their system T-BERD/MTS around 1550 nm.

Here we present a precise method to measure the group velocity dispersion (GVD) and the group delay of optical fibers with an ultra-high accuracy system combining a time-of-flight and a phase-shift measurement. Our reference and sample arm are being separated to enable the measurement of the time shift in short fiber. Thus, the delay between the reference and sample arm is measured at each wavelength to retrieve the group velocity slope and finally obtain the dispersion of...
our FOI. We show that our system can have improved accuracy compared to other methods and can be easily adapted to different wavelengths.

2. EXPERIMENTAL SETUP

The optical setup presented in Figure 1 consists of a self-built wavelength tunable laser. A broadband semiconductor optical amplifier (SOA) (Innolume, SOA-1070-70-HI-24dB) emits a broad spectrum (ASE, amplified spontaneous emission) being subsequently spread spatially by a ruled diffraction grating (Thorlabs, GR25-0610). Only a small fraction of the light is then coupled back into a fiber achieving a wavelength bandpass filtering. The measured linewidth of the laser is 5 GHz or 20 pm which is limited by the resolution of the optical spectrum analyzer (OSA) (Yokogawa, AQ6370). The filtered light propagates back to the SOA where it is amplified. The laser has an optical output power of 9.5 mW at 1090 nm. 30% of the laser light is coupled out and split again by a 90:10 coupler. The 10% output is used to monitor the emitted wavelength of the ring laser with the OSA. The light coupled out at the 90% output is used for the dispersion measurement. It is propagating through a polarization controller and a polarizer until it gets modulated by an electro-optic modulator (EOM) (iXblue, NIR-MX-LN-40). The light is split again in a 70:30 ratio where the 70% output is used for the FOI path to compensate any losses in the long fiber spool. The other 30% are used for the reference measurement. Each signal is detected by a fast photodiode (PD). In the case of the reference light a 35 GHz photodiode (PD1) (Discovery Semiconductors Inc., DSC20H) is used and in the case of the sample light a 30 GHz photodiode (PD2) (Thorlabs, DXM30AF) is used as shown in Figure 1. Both PDs are connected to an 80 GSamples/s real time oscilloscope (DSO) (Keysight, DSOZ634A) to acquire the data. All the dispersion measurements in the range of 1080 ± 50 nm are realized with a 307 m long fiber spool of Hi1060. The spool is placed inside a thermal insulated housing where the temperature is kept constant at 27°C or 30°C.

![Figure 1. Dispersion measurement setup based on a tunable ring laser on the left followed by the modulation and dispersion measurement part on the right. (SOA, semiconductor optical amplifier; FC, fiber collimator; OSA, optical spectrum analyzer; EOM, electro-optic modulator; AWG, arbitrary waveform generator; DC, direct current; DSO, digital storage oscilloscope).](image)

The modulation is realized by a 24 GSamples/s arbitrary waveform generator (AWG) (Tektronix, AWG7122B). It consists of a 4 GHz sine burst with 1000 cycles including a pulse type marker at the beginning and the end of the burst. The output power of the reference and the sample arm is 1.1 mW and 1.4 mW respectively at 1080 nm.

The optical setup has been adapted to realize measurements at 850 ± 15 nm. A 610 m long 780-OCT fiber spool (Nufern) is used as FOI, and all components were specifically designed for 810 ± 50 nm with 780-HP (Nufern) single-mode fiber. This fiber spool is placed inside the thermal insulated housing likewise.

3. DISPERSION MEASUREMENT

The ring laser is tuned over a bandwidth of 100 nm centered around 1080 nm by rotating the diffraction grating. For each wavelength, a reference measurement and a measurement of the FOI is acquired in parallel as shown in Figure 2.
A low pass filter is used to clean up the signal and a 10-times spline interpolation is used to increase the number of data points. A first coarse estimation of the time delay is determined by placing two markers on the first pulses of both signals as shown in Figure 2. The sine burst is then cropped out of both signals. A cross-correlation algorithm is applied afterwards for a precise calculation of the coarse alignment error. Finally, both values are added to give the total delay. This processing is realized for every wavelength and for all upcoming datasets.

![Figure 2. Acquired data after low pass filtering, 10 times interpolation, and mean subtraction at 27°C with 307 m of Hi1060 fiber at 1094.78 nm. The red and blue datasets represent respectively the reference (red) and the sample path (blue). The green and dark red markers are placed at the beginning of each signal, on the first pulse, as shown in the bottom right zoomed area.](image)

Since a time delay measurement at one wavelength is taking about one minute, the temperature of the FOI may shift during a set of measurements. In order to observe the behavior of the temperature, the time delay is first measured in forward direction, from short to long wavelengths, and then backwards. These results are then fitted by a 2nd order polynomial and the slope of the polynomial is determined with a 3rd order Taylor expansion. Once the slope and the intercept are determined, the 1st order dispersion $D_1$ and the 2nd order dispersion $D_2$ can be calculated with equation 1 and 2 respectively where $k$ is the wavenumber, $\omega$ the angular frequency, and $v_g$ the group velocity.

$$D_1 = \frac{\partial k}{\partial \omega} = \frac{1}{v_g}$$

$$D_2 = \frac{\partial^2 k}{\partial^2 \omega}$$

The standard deviation (STD) of a series of values is calculated after removing the 1st, 2nd and 3rd order. This value will give an information on the quality of the last series of measurements - forward and backward. A short 1 m fiber and a long 307 m fiber are used to evaluate the limits of the measurement technique.

For a 1 m Hi1060 fiber as FOI the group delay’s standard deviation for a set of 14 measurements between 1036 nm to 1121 nm goes down to 54 fs. For a set of 18 measurements between 1038 nm and 1127 nm a 307 m Hi1060 fiber spool induces a group delay’s standard deviation of 414 fs. The higher STD can be explained by an increased influence of temperature and lower signal to noise ratio when using longer fibers. However, with longer fibers, the effect of chromatic dispersion has a greater impact on the delay, which increases the accuracy of the measurement. Nevertheless, a shift of 0.01 nm in wavelength will impact the time delay by 104 fs with a fiber spool of 307 m while with a 1 m FOI the impact is in the order of 0.1 fs. Thus, the longer the fiber is the more accurately the wavelength should be measured. It is confirming that the accuracy of the measurement of long fiber length is limited by the resolution of the wavelength measurement and not the time delay measurement.
This time delay performance enables an accurate chromatic dispersion measurement in optical fibers. The GVD measured at 1080 ± 50 nm equals 20.98 ± 0.35 fs²/nm and the group delay dispersion (GDD), also called 2nd order dispersion, equals 0.076 ± 0.003 ps/nm²/km. The results obtained at 850 ± 15 nm can be seen in Table 1. The 610 m of 780-OCT fiber induces a group delay’s STD of 320 fs, that is comparable with the standard deviation obtained around 1080 nm. However, the low signal to noise ratio due to less performant components is limiting the quality of the measurements.

Table 1: (A) Group delay’s standard deviation and time delay caused by a measurement error in wavelength, (B) chromatic dispersion of different fibers at several wavelengths.

| Wavelength nm | 1st order dispersion ps/nm/km | STD | 2nd order dispersion ps/nm²/km | STD | 3rd order dispersion ps/nm³/km | STD |
|---------------|-------------------------------|------|-------------------------------|------|-------------------------------|------|
| 1190 ± 45     | -0.2606                      | 0.789 | 0.052                        | 0.002 | -1.14.10^-4                  | -    |
| 1080 ± 50     | -0.33697                     | 0.698 | 0.075                        | 0.0026 | -2.4.10^-3                   | 5.44.10^-5 |
| 850 ± 15      | -1.00.186                    | 0.526 | 0.209                        | 0.031 | -2.4.10^-3                   | 654.10^-6 |

In addition, we noted that the chromatic dispersion cannot be measured in a 1 m fiber. Indeed, the linear dispersion in Hi1060 fiber at 1080nm is according to our data processing, -33.697 ps/nm/km. Thus, to be able to measure the dispersion in a 1 m fiber length, a system with a minimum resolution of 30 fs/nm should be sufficient. Having in a 1 m fiber length a group delay’s STD of 54 fs with a 100 nm tunable laser should allow us to measure this resolution. However, we were not able to achieve reliable measurements for 1 m and 2 m fiber length. We measured a wrong dispersion value $D_1$ of -26.614 ps/nm/km and a dispersion slope $D_2$ of 0.326 ps/nm²/km for a length of 2 m. For 1 m we measured the incorrect value $D_1 = -7.512$ ps/nm/km and $D_2 = 0.088$ ps/nm²/km. We are currently investigating possible sources of this systematic error.

The time delay measurements around 1190 nm and 1080 nm have been realized with the same fiber spool but with two different setups. However, a comparison can be realized between these two graphs, see Figure 3 (A). The setup used in this study can be adapted to any wavelength. Furthermore, a broader tunable source would enable the dispersion analysis of an optical fiber over a wider range.

4. INFLUENCE OF TEMPERATURE

The FOI is placed in a thermally insulated box in order to control its temperature. Depending on the experiments, the temperature is set either to 27°C or 30°C. All measurements are taken 1 hour after the stabilization of the temperature in the insulated box to make sure that the entire FOI is at the same temperature. All other components are not placed in this box due to impracticability. In order to study the reliability of the setup, five measurements were taken at 2 minute intervals. Several measurements were taken at 27°C and 30°C in order to compare the influences of the temperature on $D_1$ and $D_2$.

According to Yang & al. [14] the refractive index of Hi1060 fiber changes by 1.178.10^-3°C^-1. Thus, for a shift of 3°C a fiber spool of 306.789 m a time shift of 53.162 ps will be observed. The experiment at 30°C and 27°C shown in Figure 3 (B) led to a result of 66.479 ps. Both values are in the same order of magnitude within a factor of 1.25. Nevertheless, a change of 1°C in 1 m of fiber will impact the time delay by 131 fs. Thus, some uncertainty remains because of the inability of controlling all components’ temperature. Indeed, thanks to the forward and backward measurement technique, a slight shift of temperature during each series can be observed with the second order dispersion. Some examples are circled in red in Figure 3 (B).

A total of 177-time delay measurements were taken around 1080 nm on 7 different days at 27°C. The accuracy of the data is 590 ± 155 fs. We observed a standard deviation of 461 fs on 5 measurements taken at 2 minutes intervals. The wavelength drifting and the temperature changes can decrease the accuracy of each measurement, as well as the data processing. Nonetheless, this result remains accurate enough to precisely determine the chromatic dispersion of optical fibers.
Figure 3. (A) Dispersion measurement realized with a 1080 nm and a 1190 nm system. (B) Representation of the 1st and 2nd order dispersion at 27°C and 30°C – backward and forward measurements. The red circles indicate a temperature shift during each series of measurements.

5. COST EFFECTIVE SOLUTION

In view of a more cost-effective setup, a lower frequency modulation has been used as well as lower performant equipment. The analog bandwidth of the DSO was reduced to 1 GHz and the sampling rate to 20 GSamples/s for this purpose (mimicking a more affordable oscilloscope). It has been observed that a modulation of 1 GHz is precise enough to obtain the same standard deviation in regard to the 1st and 2nd order dispersion with a group delay standard deviation of ± 1.227 ps. However, the accuracy is not high enough to recognize any 3rd order dispersion. At 400 MHz even the 2nd order cannot be determined accurately, however the precision of the time delay measurement is enough to have an approximation of the group delay with an accuracy of ± 15.262 ps. Regarding a 40 MHz sinewave modulation, in Figure 4 we can observe a shift of the time delay on three different linear fits (green dotted line) having almost the same slope. Each fit is separated by about 4.5 ns. Furthermore, the same experiment has been realized at 40 MHz but with slower PDs (150 MHz PDB150C and the 350 MHz PDB130C from Thorlabs). We can see while comparing the black datapoints (slow PD) and the red and blue (fast PDs) in Figure 4 that the measurement’s STD is worse compared to the fast diodes, 353 ps and 43.6 ps respectively. These differences are most likely introduced during the processing step of the cross-correlation.

Figure 4. Three series of dispersion measurements were realized at 40 MHz with a 307 m FOI. The blue and red series were realized with the fast PDs. These two series show a shift of the time delay which can be separated by three different green dotted linear lines. The black series were measured with the slow PDs. Each series includes forward and backward measurements.

6. DATA PROCESSING ROBUSTNESS

Lastly, the robustness of the processing steps is evaluated. Therefore the FOI is replaced by a free space beam path to exclude the effects of chromatic dispersion and have an accurate method to change time delay values. The length of the free space was changed in steps of 0.1 mm to see if the algorithm was able to detect them. An accuracy down to 385 fs is achieved with a slope of 3.238 ps/mm. A change of 0.1 mm in air should increase the time delay by 333 fs, here it is
increasing by 323.8 fs. Thus, the software enables us to detect this time shift with a femto-second accuracy. Another phase-shift algorithm such as the Hilbert function, may be tried to confirm the results. On the other hand, the cross-correlation is highly impacted by the position of the cursor. If the same data are processed twice with different marker position, the results will not be identical. The behavior of the cross-correlation is even more interesting since the position of each cursor is not impacting the data processing on the same way. Regarding the left cursor of the reference signal, when moving it forward or backward, for all wavelengths the same positive or negative shift of a few femto-seconds respectively, is observed. For the two other markers, the shift is randomly positive or negative and does not have a unique value. This confirms the fact that our modulation composed of two pulses and the sine wave is well thought out as the markers can be precisely positioned.

7. CONCLUSION

Combining a time-of-flight measurement with a cross-correlation algorithm allows us to achieve a high accuracy measurement of the chromatic dispersion for optical fiber longer than 2 m. One of the most limiting factors is the wavelength measurement. Also, the temperature of the fiber must be controlled and stabilized precisely to exclude any impacts on the group delay measurements. Furthermore, the data processing is currently in an early stage but is already yielding promising results. Each of these mentioned issues does not have a major impact on the 1st and 2nd order dispersion directly, but the combination of all may distort the results. An automatization of the entire process could speed up the measurement reducing the temperature impact and lead to a less time-consuming measurement.

Moreover, depending on the accuracy required, the frequency of the modulation can be adapted until a certain point. A frequency of 400 MHz will provide enough accuracy to obtain a reliable 1st order dispersion. Thus, more cost-effective equipment can be used. However, for an accurate group delay measurement, a 1 GHz modulation is the lower limit. With increasing modulation frequency a more precise estimation of the chromatic dispersion can be achieved.

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