Nonlinearity detection of laser frequency tuning for improving spatial resolution in OFDR

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Abstract. High spatial resolution is one of the main requirements in Optical Frequency Domain Reflectometry (OFDR) system. Swept tuning in laser system which has been widely used in OFDR system is not linear. This nonlinearity can reduce spatial resolution in OFDR system. In this paper, we present a simple signal processing technique for detecting laser nonlinearity tuning in OFDR system. Information about laser nonlinearity which is previously detected will be used for resampling the reflection data from OFDR. The resampling process is used for compensating the existence of nonlinearity. By using this technique, we obtain fifth times resolution enhancement and 0.02 spatial resolution ratio. Moreover, our system is able to detect nonlinearity in laser tuning which takes around 2 seconds of data processing time.

1. Introduction

Nowadays, optical-based measurement systems are rapidly evolving. General advantages of optical-based measurement system are fast and low in electrical noise. Currently, the development of telecommunication technology cannot be separated from the optical fiber as the communication backbone. When dealing with long distance optical-based communication, we need a reliable instrument with good accuracy and precision. This instrument is needed to gather reliable information regarding power loss location due to occurring damage in optical fiber.

One of the common tools used to analyse loss and damage in optical fiber is called Optical Time Domain Reflectometry (OTDR). OTDR works by sending a pulse of light into optical fiber, then the reflection and back scattering intensity values that occurs over time are detected. The OTDR system has limitation in spatial resolution which is determined by its pulse-width [1]. This limitation is namely as short blindness of the sensor that occur when there is a Fresnel reflection. Fresnel reflection saturates the sensor, it makes the sensor unable to obtain an accurate loss measurement at that time.

There is a technique called Frequency Modulation Continuous Wave (FMCW) that was originally used on radars. FMCW works by sending wave with frequency that changes over time. This wave will be reflected to detector after hitting the object. Then, the received signal will be compared with reference signal. The frequency superposition between reference and received wave generates a beat which indicates the distance of an object. This FMCW technique is adopted in optical fiber based measurement systems called OFDR (Optical Frequency Domain Reflectometry) [2]. Simple OFDR systems consists of a laser with tunable wavelength, an optical fiber coupler as a waveguide for combining lights from reference path and reflection path, and photodetector with data acquisition system to process the signal. Fourier transform is applied on detected signal by data acquisition or PC to obtain the frequency relationship with the corresponding reflection. Typical OFDR has range in
resolution from sub-millimeters [3,4] to even less that makes OFDR systems can be applied for characterising optical components and modules [5], as a distributed sensor system [6–8] and biomedical imaging [9] as in optical coherence tomography when combining OFDR with raster scanning system [10].

One of the problems for developing OFDR systems is to increase the spatial resolution as high as possible. Nonlinearity tuning of the laser causes a decreasing spatial resolution in OFDR [11]. There are some factors that induce nonlinearity in laser tuning e.g. a drift of temperature in gain medium and vibration in laser external cavity mechanical system. A solution has been developed to solve this problem by improving the system design for linearizing the laser tuning over time [12], but this method can be difficult to do. Another method is to add an auxiliary interferometer as the output timer to trigger data acquisition [3, 11], this system is also limited by the length of the additional interferometer which must adjust with the nyquist criterion for sampling optimally. The last method that can be used is by using auxiliary interferometer as a nonlinearity detector in laser tuning [4, 12–15], this information is then used for resampling the interference data to increase spatial resolution in OFDR.

In this paper we present a simple signal processing steps using short time Fourier transform to detect the change in laser tuning frequency from auxiliary interferometer. The measured data from auxiliary interferometer are splitted into subdata with same range. Every subdata is processed with Fourier transforms. Then the maximum frequency spectra of each subdata is averaged. To get a resample ratio, the initial frequency peak from a subdata will be compared with the average of frequency peak. This ratio shows the change of frequency in laser tuning over time. For linearizing the data, ratio between initial frequency and average frequency will be used to resample the raw subdata with the same range that previously used to split the data.

2. Principle of OFDR and Resampling Method
This section describes about OFDR system. To comprehend the detection method in OFDR, a theoretical calculation from two reflections is provided. A common signal processing method for linearizing reflection data is also introduced.

2.1 Basic theory of OFDR
Common OFDR system can be seen in figure 1. It consists of tunable laser, an optical fiber coupler, optical photodetector and data acquisition system. Light from the laser that assumed can be swept linearly over time enters the coupler, and then the light is divided into two paths. First reflection path is used as a local reference/oscillator, and the other reflection path is used as the measurement path.. Two reflections from each path are recombined in fiber coupler and the interference (beating) is detected on photodetector. The detected interference is stored by data acquisition system. By using

Figure 1. Basic configuration of OFDR.
Fourier transform of interference data, the beat frequency of the corresponding reflections can be obtained and distinguished.

Equation of beat intensity that has been captured in photodetector can be expressed as:

\[ I(t, \tau_d) = E_r^2 + E_d^2 + 2E_rE_d\cos\pi\alpha\tau_d t + 2\pi v_0^2\tau_d - \pi\alpha^2 \]  

(1)

where \( \alpha \) is laser tuning rate (Hz.s\(^{-1}\)), \( E_r \) is reference’s electric field (N.m\(^{-1}\)), \( \tau_d \) is time delay (s), \( E_d \) is reflection’s electric field (N.m\(^{-1}\)) and \( v_0 \) is the initial frequency (Hz).

From the equation (1), we can see that the beat frequency information from interference can be calculated as \( \alpha\tau_d \). The value of \( 2\pi v_0\tau_d - \pi\alpha^2 \) is only a phase information and not taken into account. The frequency difference from 2 corresponding reflections can be calculated with:

\[ \Delta f = \alpha\tau_d = \frac{2\alpha\Delta l}{c} n_s \]  

(2)

where \( \Delta l \) is the difference in reflection (m), and \( n_s \) is the refractive index.

2.2 Data resample

Data resample means combining interpolation and decimation in order to change the data sampling rate by a rational factor. The resample process can be seen in figure 2. Interpolation is the process of upsampling followed by filtering. In upsampling, amount of data that already collected are increased by inserting zero-valued between data, hence increase its length by a certain amount. The upsampling data is then convoluted with interpolation filter. The result is as if we have original data with higher sampling rate. Decimation is the process of data reduction by performing an anti-aliasing filter followed by throwing away data samples. This process results in reduction of data length or reduce the sampling rate of the original data.

3. Experimental Methods

In this experiment, we use a tunable light source Santec TSL-510 with 1-100 nm.s\(^{-1}\) tuning range and 500 kHz linewidth which can operate in sweep or ramp mode, Thorlabs photodetector PDA 50-B with 510 kHz maximum bandwidth, and Picoscope 4424 with 20 MHz bandwidth and 80 Msample.s\(^{-1}\) maximum sampling rate. Data is obtained using 2 Megasample.s\(^{-1}\) sampling rate for 5 seconds duration, therefore the total data is 10 million. The Fourier transform process is performed with 4096 FFT bin, so the maximum sensing resolution is 488 Hz or about 4 mm. We use 100 nm.s\(^{-1}\) laser tuning rate with 3 m fiber delay and 70 nm.s\(^{-1}\) laser tuning rate for 10 m fiber delay. These parameters are chosen so that our signal can be detected in our photodetector. Using equation (2), we can estimate the beat frequency. In 3 m fiber delay, the beat frequency will be obtained around 168 KHz and in 10 m fiber delay the beat frequency will be obtained around 390 kHz.

OFDR system set-up with auxiliary interferometer as laser nonlinearity detection can be seen in the following figure. 3. This system consists of two-type interferometers, Mach-Zender and Michelson interferometer. The Mach-Zender interferometer type is used as a detector in frequency tuning difference over time in laser sweep, while Michelson interferomter type is used to measure the reflection of an object being tested. In our system, the output from the photodetector is forwarded to the picoscope as DAQ, then the data from the picoscope is stored and processed in the PC.

![Figure 2. Resample process.](image-url)
Figure 3. OFDR System with auxiliary interferometer as a compensator of laser nonlinearity tuning rate.

Figure 4. Frequency nonlinearity detection process.

The laser nonlinearity detection process with auxiliary interferometers is shown in diagram as shown in figure 4. First, the beat frequency signal from auxiliary interferometer is detected on the photodetector. The detected signal then sampled and collected in data acquisition. After the total data is obtained in DAQ, it will be stored and processed in PC. Data processing is begun by dividing the total data into several subdata with equal length. Shown in step 2 in figure 4 is example of total data with length N which is divided into 1000 subdata. Each subdata were processed with Fourier transform. The next step is detecting the peak frequency of the transformed subdata overtime. To get the resample ratio, the maximum frequency spectra of each initial subdata will be compared with the average of frequency peak from every subdata over time. From this result we obtain the ratio in beat frequency change over time. This ratio is used in data resample process to shift the frequency of subdata, hence linearizing the data in OFDR system. By linearizing the data, we get the same frequency beat signal with equidistant optical frequency grid.

4. Results and Discussion
Based on our measurement in auxiliary interferometer which has processed with short time Fourier transform, we get the shift in optical-frequency swept over time with data enumeration every 0.5 ms. The reflection data of each 0.5 ms will be resampled based on the resample ratio as shown in figure 5 (a). We got the resample ratio by dividing initial frequency with average in frequency change over sweep time (figure 5(b)). It can be seen that the laser tuning is not constant resulting in reduced in spatial resolution due to frequency broadening.
After the data is resampled, Fourier transform is applied to the data. The result is beat frequency without error due to the non-linear frequency sweep. In order to test how much improvement has been made using this resampling method, we apply our system to measure a reflection in a simple OFDR set-up.

An optical fiber with 2.3 m length is added in interferometer’s test arm. The reflection data is taken with variation of delay fiber and the numbers of subdata being resampled. The best results from this variation are used to determine the best possible parameter that can be achieved regarding to highest resolution and fastest processing. The processing time is obtained by using a timer in our software. The OFDR frequency spectrum from this reflection is presented in figure 6. The distance in reflection before resampling cannot be seen clearly because of the nonlinearity tuning of the laser. After resample, the spectrum of reflection data becomes finer with 5 times improvement in Full Width at Half Maximum (FWHM) resolution with a 3-m delay fiber and 5.5 times improvement with a 10-m delay fiber.

![Figure 5](image1.png)

**Figure 5.** (a) Measured ratio of time-varying beat frequency in auxiliary interferometer (b) Measured frequency over time from auxiliary interferometer.

![Figure 6](image2.png)

**Figure 6.** Reflection spectra (a) before and (b) after resample process.

| Resampled subdata (4096 FFT bin) | Processing time (s) every 100,000 data | Resolution after processing (FWHM) (cm) | Resolution before processing (FWHM) (cm) |
|----------------------------------|----------------------------------------|------------------------------------------|------------------------------------------|
| 2000                            | 0.6                                    | 7.6                                      | 31.92 ± 0.35                             |
| 1000                            | 1.05 ± 0.1                             | 6.62 ± 0.23                              | 31.92 ± 0.35                             |
| 500                             | 2.7                                    | 7.3                                      | 31.92 ± 0.35                             |

**Table 1.** Processed data with 10 m delay fiber.
Table 2. Processed data with 3 m delay fiber.

| Resampled subdata (4096 FFT bin) | Processing time (s) every 100,000 data | Resolution after processing (FWHM) (cm) | Resolution before processing (FWHM) (cm) |
|---------------------------------|--------------------------------------|----------------------------------------|------------------------------------------|
| 2000                            | 0.71                                 | 8.41                                   | 40.03 ± 1.09                             |
| 1000                            | 1.35 ± 0.06                          | 7.35 ± 0.27                            | 40.03 ± 1.09                             |
| 500                             | 3.15                                 | 8.28                                   | 40.03 ± 1.09                             |

Based on tables above, we can deduce that the length of delay fiber affects the resolution in OFDR system. Longer delay time in auxiliary interferometer will make the nonlinear spectrum broader. We can understand this phenomenon by assuming laser tuning rate $\alpha$ in equation (1) is nonlinear with:

$$\alpha = \alpha_0 + \alpha_1(t)$$  \hspace{1cm} (3)

where $\alpha_0$ is the initial laser tuning rate and $\alpha_1(t)$ is a nonlinear function of laser tuning rate.

If we apply equation (3) to equation (2), the beat frequency being recorded is

$$\Delta f = (\alpha_0 + \alpha_1(t)) \tau_d$$  \hspace{1cm} (4)

Thus, we can make a better resolution enhancement in our system by increasing the length of the delay fiber. To get a quantitative result we repeat this experiment several times with the same parameters, we get the spatial resolution in this experiment is around 0.02 (5 cm/2.3 m).

5. Conclusions

We have presented a technique to improve spatial resolution in OFDR by detecting nonlinearity tuning in laser. We use Mach-Zender type interferometer as an auxiliary interferometer and a simple signal processing technique to detect nonlinearity in laser tuning. The tuning nonlinearity information is used as a resample ratio for linearizing a reflection data. By implementing this technique, we can detect nonlinearity in laser tuning overtime and successfully suppress the spectrum broadening due to nonlinearity in laser tuning. Our technique demonstrated an improvement in spatial resolution with the best result around 5 times with 1 second data processing. The ratio of spatial resolution from linearized data is 0.02 (5 cm/2.3 m). There are still ways to improve the spatial resolution in our system by using a longer delay fiber, larger sampling rate and higher tuning sweep range. Further investigation will be using a tunable laser with mode hops to test this system performances in high nonlinearity tuning laser.

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