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High-frame-rate Spectrum Measurement for Ultrafast Optical Pulses based on Optical Signal Processing

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Abstract

The pulse-by-pulse single-shot spectrum measurement for high-repetition rate optical pulses with femtosecond or picosecond pulse width is important for capturing non-repetitive and rare phenomena of substances. Conventional optical spectrum analyzers cannot acquire the spectrum for each pulse at high-repetition rate without missing due to the low processing speed. Several high-speed optical signal processing techniques can help to acquire pulse-by-pulse single-shot spectrum. The high-speed spectrum measurement using a fiber chromatic dispersion-based time stretch dispersive Fourier Transform (TS-DFT) technique is a powerful tool for such measurements. In this paper, we present a record pulse-by-pulse single-shot spectrum measurement for 1 GHz repetition-rate optical pulses with a less than 67-pm spectral resolution based on the TS-DFT technique.

1. Introduction

Ultra-fast optical pulses with femto- or pico-second pulse width have been widely used for ultra-fast phenomena analysis of substances, manufacturing of fine-structures, precise measurement of object shape, and optical fiber communication [1-5]. The characteristic measurement for ultra-fast optical pulses has become increasingly essential. Especially, the pulse-by-pulse single-shot spectrum measurement for high-repetition rate optical pulses with femtosecond or picosecond pulse width is important for capturing non-repetitive and rare phenomena of substances. However, conventional optical spectrum analyzers (OSA) cannot acquire the all spectra of continuous optical pulses due to the low processing speed. The high-speed spectrum measurement using a fiber chromatic dispersion-based time stretch dispersive Fourier Transform (TS-DFT) method has been proposed and developed for such real-time measurements [6-11]. In this method, by giving a chromatic dispersion (CD) to optical pulses and receiving their chirped optical pulses with a high-speed real-time digital oscilloscope, the spectrum of individual optical pulse can be measured.

In this paper, we present a pulse-by-pulse single-shot spectrum measurement for high-repetition-rate optical pulses by using TS-DFT method. The pulse-by-pulse single-shot spectrum for 1-GHz repetition-rate optical pulses, which is equivalent to one billion frame rate measurement, with a less than 200-pm has been demonstrated [12]. On the other hand, when the spectral resolution or the capturable pulse-repetition-rate is attempted to be improved further, the adjacent chirped optical pulses will be overlapped and unable to be distinguished individually. In order to avoid the overlap between pulses, we have proposed a wavelength demultiplexing (W-DEMUX) technique using a wavelength selective switch (WSS), which can divide a chirped optical pulse into several wavebands [13]. By using the W-DEMUX technique in optical domain and the synthetic processing in electrical domain, we have successfully demonstrated the pulse-by-pulse single-shot spectrum measurement of 1-GHz repetition-rate optical pulses with a less than 67-pm spectral resolution, which is three times higher compared with conventional one [12].

2. Pulse-by-pulse Single-shot Spectrum Measurement based on Time Stretch Dispersive Fourier Transform

We describe the principle of pulse-by-pulse single-shot spectrum measurement based on TS-DFT technique. The TS-DFT is achieved by using a dispersive element with a large CD such as a dispersive fiber or chirped fiber Bragg grating. Figure 1 shows the conceptual diagram of pulse-by-pulse single-shot spectrum measurement using on a fiber chromatic dispersion-based TS-DFT. Here, by giving a linear CD into optical pulse train, optical pulses are chirped. Because the dispersion slope is linear, the spectral information of an optical pulse is mapped to the temporal waveform of the chirped optical pulse. The temporal envelope indicates the spectrum of optical pulses. The spectral-information-mapped chirped optical pulses are received by a high-speed real-time digital oscilloscope. The spectral resolution in this method depends on the amount of CD of the fiber or the bandwidth and the sampling rate of a real-time oscilloscope [9]. A higher amount of dispersion results in a larger stretch factor and better time resolution, as does a larger digitizer bandwidth, and both lead to better spectral resolution. On the other hand, it is necessary to select the appropriate amount of CD to avoid pulse overlap and provide good spectral resolution.

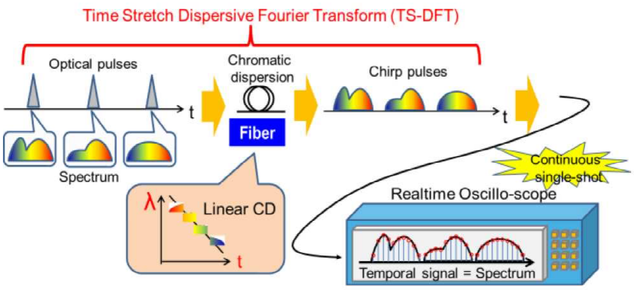

Figure 1. Conceptual diagram of pulse-by-pulse single-shot spectrum measurement based on Time Stretch Dispersive Fourier Transform.

If the higher spectral resolution or the higher capturable pulse-repetition-rate is attempted, chirped optical pulses could overlap each other unless the amount of CD is selected properly, as shown in Figs.2(a) and 2(b). To avoid the overlap between pulses, we proposed a wavelength demultiplexing (W-DEMUX) technique using a wavelength selective switch (WSS), which can divide a chirped optical pulse into several wavebands. Figure 3 shows the conceptual diagram of proposed method. In each waveband, optical pulses do not overlap. The divided chirped optical pulses are received by a multi-channel real-time oscilloscope at the same timing. Finally, the spectrum of a pulse is recovered by the waveform synthesis of the divided pulses. In principle, as the number of W-DEMUX is increased, the spectral resolution or the capturable pulse-repetition-rate can be improved correspondingly.

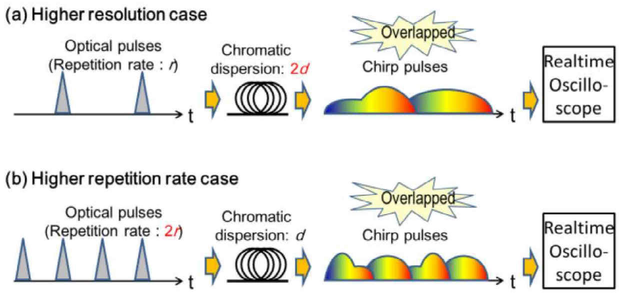

Figure 2. Pulse-by-pulse single-shot spectrum measurement (a) in higher repetition-rate case, and (b) in higher resolution case.

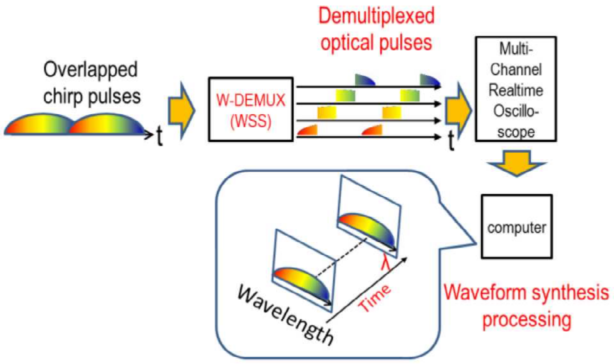

Figure 3. Conceptual diagram of pulse-by-pulse single-shot spectrum measurement with W-DEMUX function to avoid the overlap between pulses.

3. Experimental demonstration of Spectrum Measurement for 1 GHz Optical Pulses

We performed a preliminary experimental demonstration of pulse by pulse single-shot spectrum measurement based on TS-DFT. Figure 4(a) shows the experimental setup. 10-GHz repetition-rate optical pulse train was generated from a 10 GHz semiconductor mode-locked laser diode (MLLD) with a pulse width of 1.6 ps and a center wavelength of 1550 nm. Figure 4(b) shows the average spectrum of optical pulses measured by OSA. Here, the optical pulses of this MLLD were the measurement target, which means that there was no device under test (DUT).

First, the pulse by pulse single-shot spectrum measurement for optical pulses at 1 GHz repetition rate was performed with -100 ps/nm CD without W-DEMUX function. 10 GHz optical pulse train was down-converted to 1 GHz with a Lithium Niobate intensity modulator (LN-MOD) controlled by a pulse pattern generator (PPG). The spectral width was about 2.0 nm. 1 GHz optical pulse train was input into an optical fiber with -100 ps/nm chromatic dispersion. Then, each optical pulse was chirped. As a result, the pulse width was temporally broadened to about 0.2 ns. Chirped optical pulse train was copied by a 3dB coupler. One was directly received by a 4-channel real-time oscilloscope, whose bandwidth and sampling-rate are 16 GHz and 50 Gsample/s respectively. This measured waveform without W-DEMUX was used as a reference. The other was input into a WSS. In first demonstration, the chirped optical pulses were launched only into a reference port and received by the real-time digital oscilloscope. The temporal waveform acquired by the real-time digital oscilloscope was mapped on the frequency axis by a software in a computer.

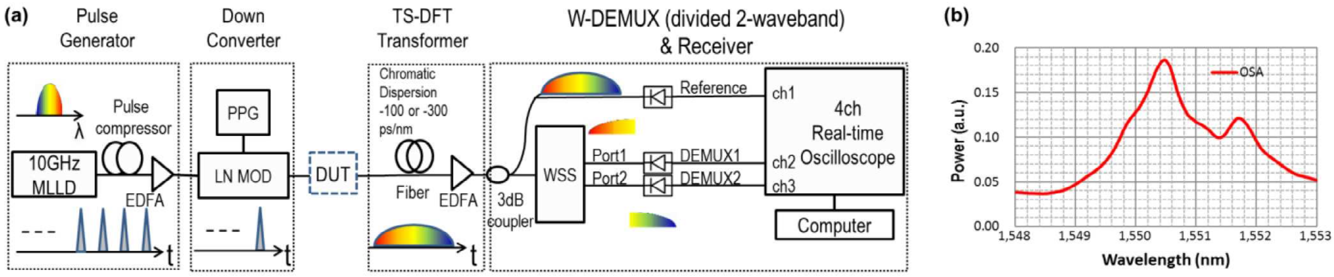

Figure 4. (a) Experimental setup. (b) Average spectrum of 1 GHz optical pulses.

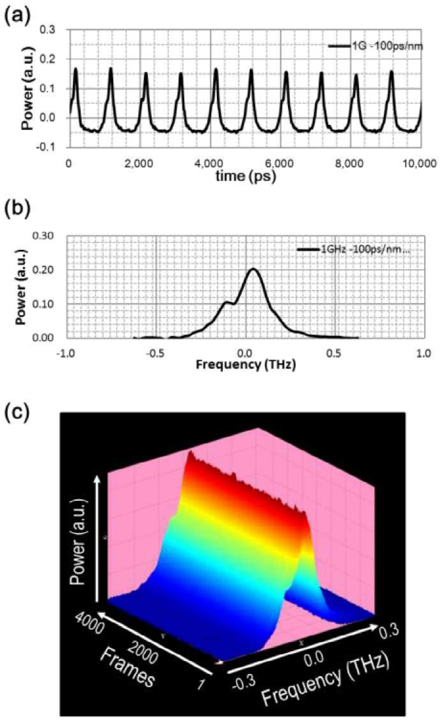

Figure 5. Pulse-by-pulse single-shot spectrum measurement for optical pulses at 1 GHz repetition rate using - 100 ps/nm fiber chromatic dispersion. (a) Temporal waveform of 1 GHz chirped optical pulses. (b) Spectrum of one optical pulse mapped on the frequency axis. (c) Pulse-by-pulse single-shot spectra of 39,997 optical pulses at 1 GHz repetition rate.

Figure 5(a) shows the temporal waveform of 1 GHz chirped optical pulse train received by a real-time digital oscilloscope. Figure 5(b) shows the spectrum of one optical pulse mapped on the frequency axis by a software. The horizontal axis represents the relative frequency. The center frequency corresponds to a wavelength of 1550 nm. Figure 5(c) shows the continuous single-shot spectra of 1 GHz optical pulses, which is equivalent to one billion frame rate measurement. The number of acquired frames at a time was 39,997, which was limited due to the memory size of the real-time digital oscilloscope.

Second, we demonstrated higher spectral resolution of pulse by pulse single-shot spectrum measurement with W-DEMUX function. For higher spectral resolution, we used a fiber with -300 ps/nm CD. The port 1 and 2 of the WSS transmit the waveband of 1547.66-1549.96 nm and 1550.06-1552.37 nm, respectively. The divided chirped optical pulses output from port 1 and 2 were received by the oscilloscope, respectively. These measured waveforms were called as W-DEMUX 1 and W-DEMUX 2 waveforms, respectively. On a computer, the synthesis of W-DEMUX 1 and 2 waveforms was performed. The waveform correction was also performed to compensate the influence of the spectral narrowing due to WSS fileter and the ripple of a photo-detector. Fig 6(a) shows W-DEMUX 1 and 2 waveforms at 1GHz repetition-rate. While adjacent chirped pulses overlapped in the reference waveform, the overlap was resolved by W-DEMUX. Figure 6(b) shows the recovered waveform of one pulse. Figure 6(c) shows the spectrum obtained by mapping the recovered waveform on the wavelength axis. For comparison, the waveform measured by OSA is also shown. In first demonstration, we achieved about 200 ps/nm resolution using -100 ps/nm CD under the same condition. Then, this measurement with -300 ps/nm CD can achieve about 67 ps/nm resolution.

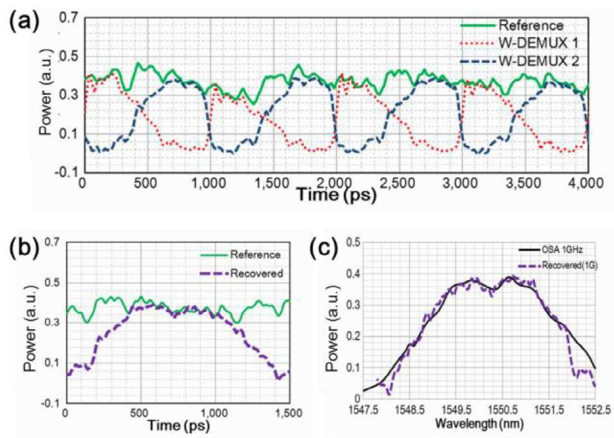

Figure 6. (a) W-DEMUX 1, 2 and reference waveforms, (b) Recovered waveform at 1 GHz repetition rate. (c) Spectrum obtained by mapping recovered waveform on wavelength axis and spectrum measured by OSA.

4. Conclusion

We have presented experimental results of pulse by pulse single-shot spectrum measurement of optical pulse trains with 1 GHz repetition rate based on TS-DFT technique. As a result of applying a chromatic dispersion of -100 ps/nm and receiving stretched optical pulses with a 50 Gsample/s real-time digital oscilloscope of 16 GHz bandwidth, the processing for 1 GHz optical pulse train and one billion frame rate measurement were achieved with the wavelength resolution of approximately 200 pm. In addition, by using W-DEMUX technique, we have achieved a less than 67-pm spectral resolution which is 3-times of conventional one.

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