Optical Waveform Monitoring Based on Free-Running Mode-Locked Femtosecond Fiber Laser and Four-Wave Mixing in Highly Nonlinear Fiber

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Abstract

Optical sampling based on ultrafast optical nonlinearities is a useful technique to monitor the waveforms of ultrashort optical pulses. In this paper, we present a new implementation of optical waveform sampling systems by employing our newly constructed free-running mode-locked fiber laser with tunable repetition rate and low timing jitter, an all-optical waveform sampler with highly nonlinear fiber (HNLF), and our developed computer algorithm for optical waveform display and measurement, respectively. Using a femtosecond fiber laser to generate the highly stable optical sampling pulses and exploiting the four-wave mixing effect in a 100m-long HNLF, we successfully demonstrate the all-optical waveform sampling of a 10GHz optical clock pulse sequence with pulse width of 1.8 ps and a 80Gbit/s optical data signal, respectively. The experimental results show that the waveforms of the tested optical pulse signals are accurately reproduced with pulse width of 2.0 ps. This corresponds to a temporal resolution of 0.87 ps for optical waveform measurement. Moreover, the optical eye diagram of a 10Gbit/s optical data signal with 1.8ps pulse width is also accurately measured by employing our developed optical sampling system.

Keywords: Optical sampling, mode-locked fiber laser, four-wave mixing, highly nonlinear fiber, optical waveform monitoring, eye diagram measurement

1. Introduction

Fast and accurate characterization of ultrashort optical pulses is often required by, for example, the study of picosecond/subpicosecond pulsed lasers, ultrahigh-speed optical transmitters, light pulse propagation in various optical media (including optical fibers), and ultrafast all-optical signal processing, respectively. A simple application of pulse evaluation is to monitor the waveforms of ultrashort optical pulses and to measure the full-width at half-maximum, rise and fall times of such a pulse. To achieve this goal, we can use three conventional measurement approaches. One is called the autocorrelation measurement which has a symmetric response function, thus preventing it from the evaluation of rise and fall times for optical pulses and the analyses of asymmetric optical waveforms and/or optical data signals modulated with pseudorandom binary sequence (PRBS) [1,2], respectively. The second scheme is referred to as the "opto-electronic oscilloscope" equipment that consists of a conventional wideband electronic oscilloscope and an ultrafast photodetector connected in series. This approach, however, suffers from the bandwidth limitation imposed by optical-to-electrical conversion and the associated electronic circuits. At present, the bandwidth of state-of-the-art electronic oscilloscopes is restricted to 100 GHz and the commercially available photodetectors can have a bandwidth beyond 100 GHz, thus limiting the measurement bandwidth of the resulting "opto-electronic oscilloscopes" to be about 100 GHz. Moreover, the optical front-end of such an

oscilloscope is based on an ultrafast photodetector which in turn leads to a much poorer optical receiver sensitivity than that based on a low-speed photodetector (e.g., $\leqslant$ 100 MHz). The last approach is to use a streak camera which, however, has a low sensitivity at the wavelength around 1550 nm [1-3], and therefore, precludes the monitoring of optical eye diagrams. Consequently, a new type of optical waveform measurement systems needs to be developed, which should use the all-optical waveform sampling based on ultrafast optical nonlinearities to ensure a very wide measurement bandwidth up to several hundreds of gigahertz or a few terahertz [1,2]. This in turn corresponds to a subpicosecond temporal resolution for the developed waveform measurement system.

All-optical waveform sampling [1,2] is a very useful technique which can be employed to directly measure the waveforms of ultrashort optical pulses generated by ultrafast lasers [1,4,5] or propagating in optical fibers [6] (or waveguides) and the eye diagrams of ultrahigh-speed optical data signals in optical fiber communications [5-7], respectively. This is achieved by using optical signal processing to remove the bandwidth limitation of electronic circuits as encountered in traditional electronic oscilloscopes. According to hardware configurations, optical waveform sampling systems can be generally divided into two major categories [8,9], i.e., synchronous sampling and asynchronous sampling, respectively. The synchronous optical sampling scheme is capable of accurately rebuilding the waveforms or eye diagrams of optical data signals by employing photonic clock-recovery circuits [6,9]. In doing so, this results in the increase of both system complexity and cost. In contrast, asynchronous optical sampling systems do not need the expensive clock-recovery circuits, thus having the advantages of both simple hardware structure and low system cost. However, the latter suffers from the inaccurate measurement of a Q-factor [10,11]. To solve these problems, a software-synchronized optical sampling technique was proposed by Westlund and Andrekson *et al.* [1,10,11], which uses the software algorithm based on the Fourier transform of the sampled data and the eye-diagram timing drift to provide the synchronization information required for accurate Q-factor measurement and waveform/eye-diagram monitoring of ultrahigh-speed optical data signals.

At present, all-optical waveform sampling is normally implemented by exploiting the nonlinear optical effects in optical media such as optical fibers [1,2,7], waveguides [3,12,13] and crystals [4,5]. These include the second-order susceptibility χ^2 in nonlinear crystals (e.g., $KTiOPO_4$ (KTP) [14,15] and periodically poled $LiNbO_3$ (PPLN) crystals [4,5]) and the third-order susceptibility χ^3 (e.g., cross-phase modulation and four-wave mixing) in nonlinear optical fibers [1,2,16], semiconductor optical amplifiers (SOAs) [3,17], and silicon nanowire [12] or chalcogenide planar waveguide [13], respectively. Nevertheless, those schemes can have their individual advantages and respective drawbacks in terms of operational speed, wavelength range, manufacturing cost, complexity and physical size of the resulting optical waveform samplers (also called *sampling gates*). For example, the use of sun-frequency generation (SFG) in nonlinear crystals allows to implement ultrafast optical samplers which are capable of measuring the optical data signals up to 640 Gbit/s [5], while the resulting samplers are normally bulky and their operational wavelength range is also restricted by the phase-matching condition of nonlinear crystals [7,9]. Although a PPLN crystal can be employed to sample optical signal waveforms with higher temporal resolution and larger SFG conversion efficiency than the KTP crystal, a drawback of the former is the requirement for an accurate control of operation temperature [4,13] at the expense of increasing the system complexity and cost. On the other hand, if the SOA-based waveform samplers are used, their operational speed can be ultimately limited by the relatively long gain recovery time in SOAs, and the amplified spontaneous emission noise of a SOA can also cause a degradation of signal-to-noise ratio for the optically sampled signal. Moreover, optical samplers based on advanced silicon nanowire and chalcogenide planar waveguide are promising for optical waveform monitoring, as they are capable of ultrahigh-speed operations and integrated implementation on a single photonic chip [12,13]. However, these chip-scale optical samplers require a sophisticated fabrication process which can prevent them from practical applications nowadays. Moreover, the silicon and chalcogenide waveguides also possess a large coupling loss when they are connected with fiber-based devices in photonic communication systems and networks. For all-optical waveform sampling applications, it is clear that there is a trade-off between optical sampling performance and system cost. Among those reported implementation schemes, fiber-based optical waveform sampling systems are very useful for

engineering design and practical applications nowadays. This is because silica optical fibers enable massive production with mature technology and low cost, besides their high operation reliability. Moreover, optical waveform sampling systems based on silica fibers have a low complexity for implementation and also have a low coupling loss with optical/optoelectronic devices having pigtail fibers which are widely used in optical fiber communication systems/networks. Moreover, silica fibers possess the femtosecond response time of Kerr nonlinearity which in turn allows to realize ultrafast optical waveform samplers for monitoring optical data signals at 640 Gbit/s and beyond [1]. Nevertheless, conventional single-mode fibers are inadequate for optical sampling applications, because the small nonlinear refractive index of such fibers makes a long interactive length or high input power necessary for obtaining sufficient nonlinear effects. To overcome this difficulty, a highly nonlinear fiber (HNLF) can be utilized to effectively shorten the fiber length or lower down input power required by optical waveform samplers [1]. In doing so, this makes fiber-based waveform samplers more attractive for practical applications in terms of physical size, operational stability (affected by environmental disturbances), implementation complexity, optical sampling performance, and manufacture cost of the resulting waveform samplers. Furthermore, the use of HNLF-based ultrafast sampler and free-running femtosecond fiber laser allows the implementation of a cost-effective optical waveform sampling system, as we will report in Section 3 of this paper.

Four-wave mixing (FWM) [1,2,16] and cross-phase modulation (XPM) [7] in HNLFs have been studied for all-optical waveform sampling applications, due to their low cost and easy implementation. Compared to XPM, FWM has the characteristics of phase information preservation and transparency to modulation formats of optical data signals. This in turn makes FWM-based optical sampling systems very suitable for practical applications. However, the reported work on fiber-based optical waveform sampling has mainly focused on HNLF-based optical sampling gates [1,2,7], software-synchronization technique for all-optical sampling of ultrashort optical pulse waveforms [10,11,16], and the associated system performance [1,2,18]. From the viewpoint of engineering applications, there is a need of systematic design for constructing the whole optical waveform sampling system. In particular, its feasible implementation based on commercially available photonic devices is highly desired by optics/optical telecom researchers who plan to self build up cost-effective optical waveform sampling systems at their respective laboratories rather than purchasing such sampling systems which are commercially available only from a few companies worldwide. Moreover, the practical selection of a repetition rate for optical sampling sources also needs to be considered. In this paper, we investigate into the new implementation of a cost-effective optical sampling system with subpicosecond temporal resolution for optical waveform monitoring. This is achieved by using our constructed low-timing-jitter, passively mode-locked femtosecond fiber laser with tunable repetition rate, an all-optical waveform sampler using FWM in a 100m-long HNLF, and our developed computer algorithm for optical waveform display and measurement based on the software-synchronized optical sampling technique [10,11], respectively. The procedure for implementing such a waveform sampling system is also discussed in detail. In the experiments, we successfully demonstrate the all-optical waveform sampling of a 10GHz optical clock pulse sequence with pulse width of 1.8 ps and a 80Gbit/s optical data signal, respectively. The optical pulse waveforms are then reproduced by using digital signal processing and a software-synchronized optical sampling method, with which the associated pulse parameters can be obtained from a computer. We also use this optical sampling system to monitor the eye diagram of a 10Gbit/s optical data signal modulated with a PRBS in the experiment.

2. Optical Waveform Monitoring by Flexible Optical Sampling

A typical optical waveform sampling system consists of an optical sampling pulse source, an all-optical sampling gate (i.e., sampler), an "optical-to-electrical (O/E) and analog-to-digital (A/D) conversion" unit, and an "electronic data processing and waveform display" unit, respectively, as illustrated in Figure 1. Its basic operation principle can be explained with the aid of Figure 2. To properly sample an optical pulse sequence or data signal, the width of optical sampling pulses should be narrower than that of the tested optical pulse signal. Moreover, the jitter of an optical sampling pulse source should be kept as low as possible in order to accurately sample the ultrashort optical

pulses under test. This in turn requires the use of a low-timing-jitter, passively mode-locked femtosecond fiber laser to generate a highly stable train of optical sampling pulses. To correctly acquire the waveform information of the optical signal under test, the repetition frequency f_s of a periodic optical sampling pulse train should be determined according to the following relationship [2,10,11]

$$B = Mf_s + \Delta f \tag{1}$$

where B denotes the repetition rate of the tested periodic optical clock-pulse train or the bit rate of the tested optical data signal, the integer M corresponds to the bit rate reduction factor, and Δf is the offset frequency between B and Mf_s. The parameter Δf determines the bit-slot scanning rate for optical waveform sampling [10,11], which can be properly adjusted to meet the requirement of bit-rate flexible operations. In fact, this requires to appropriately set the repetition frequency of an optical sampling pulse source. Consequently, it is crucial to use a passively mode-locked femtosecond fiber laser with tunable repetition frequency and low timing jitter in the optical waveform sampling system.

FWM in a HNLF can be practically employed to realize the process of ultrafast optical waveform sampling, in which a periodic optical sampling pulse train is used as the intense pump wave to cause the power-dependent refractive index of the optical fiber. When both pump and signal lights of distinct optical frequencies are launched into an optical sampling gate based on the HNLF, under the phase-matching condition, the FWM interaction of pump and signal waves results in the generation of a sampled signal wave, called the idler, at a new optical frequency v_{idler} (see Figures 2b) [1,18], i.e.

$$v_{idler} = 2v_{pump} - v_{signal} \tag{2}$$

where v_{pump} and v_{signal} are optical frequencies of pump and signal lights, respectively. In this way, the idler can be extracted by optical band-pass filtering at the HNLF output of an optical sampling gate, followed by the optical-to-electrical conversion and further data processing, as will be described subsequently. If the parameter Δf in Eq. (1) is nonzero, the sampling time instants would appear in the different time locations with respect to a normalized signal bit period (see Figure 2a). For a repetitive optical waveform, this is equivalent to the creation of sampling time instants having a step ΔT within each signal bit period [1,10,19].

$$\Delta T = \frac{1}{f_s} - \frac{M}{B} \tag{3}$$

At an optical sampling gate, the optical signal waveform is acquired by means of those discrete samples which are carried on top of the uniformly-spaced optical pulses at an interval of $1/f_s$, as shown in Figure 2a(3). After photodetection, the envelope of the detected pulses, which is indicated by the dashed line in Figure 2a(4), is analogous to the waveform of the original optical signal under test except for the time scale. Such electronic pulses at a low pulse rate of f_s must be fed into an A/D converter, so that a computer can be used to efficiently process the electronic data in order to obtain the synchronization information of the acquired samples, time step ΔT of optical waveform sampling, pulse width, rise or fall time, and bit period of an optical signal as well as other time-related signal parameters. In doing so, the computer can reconstruct the complete optical signal waveform for periodic optical pulse trains (or repetitive optical bit patterns) or the eye diagram for the tested optical data signal that is modulated with a pseudorandom bit sequence. In effect, this is achieved by using the software-based synchronization technique (proposed by Westlund et al. [1,10,11]]) with no need of a clock recovery circuit.

For equivalent-time optical sampling with $f_s << B$, the precision in the reconstruction of an optical waveform is mainly dependent on a time step ΔT given by Eq. (3). A higher-precision waveform is reproduced when the value of ΔT is chosen to be smaller at the expense of a longer time for waveform reconstruction or vice versa, as illustrated in Figure 2. This in turn requires the adjustment of f_s based on Eqs. (1) and (3) for a given B. In practice, the optical data signals from a variety of optical fiber communication systems can have the different bit rates. Moreover, for the purpose of laboratory research, various pulsed lasers (e.g., gain-switched or mode-locked lasers) under the test can also generate the periodic optical clock-pulse trains with distinct repetition rates (or

even a tunable repetition rate in the gain-switching operation [20]]). The measurement of such signal or clock-pulse waveforms normally requires to adjust f_s in order to keep a constant ΔT or to achieve a desirable precision which can be needed by users to meet their specific test requirements. To achieve this aim, we should use an optical sampling pulse source with a changeable repetition rate to flexibly generate a train of stable optical sampling pulses in order to obtain the desired ΔT based on Eq. (3). Such a requirement can be satisfied by using our constructed low-timing-jitter, free-running passively mode-locked femtosecond fiber laser with tunable repetition rate and high operation stability [21]. This is regarded as an advantage of our designed optical waveform sampling system.

3. Experimental Setup and Measurements

Based on the above discussions, we can see that the implementation of a high-performance optical waveform sampling system requires the use of (1) highly reliable optical sampling source, (2) low-complexity optical waveform sampling gate, (3) cost-effective photodetection and A/D conversion modules, and (4) efficient computer algorithms for software-based synchronization, optical waveform/eye-diagram display and parameter measurements, respectively. The experimental setup is shown in Figure 3. In the following, we describe the design procedure for a fiber-based waveform sampling system and the experiment results associated with optical waveform/eye-diagram monitoring.

For optical hardware implementation in a cost-effective manner, the constructed optical sampling system uses a free-running passively mode-locked fiber laser (with tunable repetition rate and low timing jitter) as the optical sampling pulse source and a FWM-based optical gate with a 100m-long HNLF as the ultrafast waveform sampler, respectively. In our experiment, the optical signal under test is produced by an optical pulse signal generator which substantially uses an actively mode-locked semiconductor laser (u2t model number TMLL 1550) to provide a stream of original optical clock pulses at a repetition frequency of 10 GHz and a central wavelength of 1554 nm for data modulation and optical time-division multiplexing (OTDM), as shown in Figures 4a and 4b, respectively. The width of the obtained optical clock pulses is 1.8 ps measured by an autocorrelator with resolution $< 5\,\mathrm{fs}$ (see Figure 5). For the purpose of eye diagram monitoring at 10 Gbit/s, a LiNbO$_3$ intensity modulator is employed to on-off modulate the output clock pulse stream of this actively mode-locked semiconductor laser by using the 10Gbit/s electronic PRBS data signal that is obtained from a bit-error-rate (BER) tester. Both actively mode-locked semiconductor laser and BER tester are synchronized with a common RF clock signal source, as shown in Figure 4a. Consequently, a 10Gbit/s optical PRBS data signal is generated with pulse width of 1.8 ps. In the experiment, we also need to measure the waveform of a 80Gbit/s optical pulse signal which can be formed by optically time multiplexing either a 10GHz optical clock pulse sequence or a 10Gbit/s optical data signal. For the sake of simplicity, an OTDM multiplexer is inserted at the output of an actively mode-locked semiconductor laser without employing a LiNbO$_3$ intensity modulator in between, as shown in Figure 4b. To ensure the sufficient power for the generated OTDM signal or optical PRBS data signal, an erbium-doped fiber amplifier (EDFA) is employed at the output of an actively mode-locked semiconductor laser or an optical intensity modulator (see Figure 4). The OTDM multiplexer simply consists of 1×4 and 4×1 optical couplers with single-mode fiber (SMF) pigtails, 3 tunable optical delay lines (T-ODL's) with SMF pigtails, and an optical reference path containing a variable optical attenuator (VOA) with two SMF pigtails of appropriate lengths, respectively. Its operation is based on three steps: (1) split an input 1.8ps optical pulse into four parts, (2) interleave four split pulses through proper optical delays in order to fit into four consecutive time slots of which each has a width of 12.5 ps, and (3) combine those four pulses to form an optical signal pattern containing four successive pulses at 80 Gbit/s. Therefore, a 80Gbit/s optical data signal with the fixed optical pulse pattern of "11110000" and return-to-zero (RZ) format is obtained from this OTDM multiplexer when its input signal is a 10GHz optical clock pulse stream. The waveform of the resulting 80Gbit/s OTDM signal is also monitored by employing a 70GHz electronic sampling oscilloscope (Tektronix TDS8200) connected with a 70GHz photodiode (PD, u2t XPDV3120R) at the output of the OTDM multiplexer, as shown in Figure 6. Note that the pulse waveform of the 80Gbit/s signal with pulse width of about 1.8 ps is not resolved due to the limited bandwidth of ~ 70 GHz of a conventional optoelectronic

measurement system. This problem would be effectively solved if we use an optical waveform sampling system, as will be discussed subsequently.

To accurately sample the waveforms of optical signals under test, we should use an optical sampling pulse source that is capable of producing a stream of ultrashort optical pulses with low timing jitter and high stability. We have recently developed a low-timing-jitter, stretched-pulse passively mode-locked femtosecond fiber laser which has a tunable repetition rate over a range from 49.65 MHz to 50.47 MHz and a timing jitter less than 75 fs over a frequency range of 100 Hz to 100 kHz [21], respectively. The generated stream of femtosecond optical pulses has a central wavelength of 1544 nm. Moreover, this mode-locked fiber laser can keep the mode-locking operation continuously over 10 hours without the adjustment of any optical device in the laser cavity. In our previous experiments, such a fiber laser was able to achieve the self-starting, passive mode locking at a low pump power of 29 mW for stable generation of femtosecond optical pulses [22], when a tunable optical delay line was not used in the laser cavity. A distinguishing feature of tunable repetition rate and low timing jitter for our developed passively mode-locked fiber laser allows the bit-rate flexible operation in a cost-effective manner to meet the requirements of various users for optical waveform monitoring applications. Thus, it is expected that our designed optical waveform sampling system can have a high operational flexibility. In practice, the optical sampling pulse train with repetition rate of about 50 MHz is obtained by using a tunable optical band-pass filter (OBPF) with 3dB bandwidth of 2.5 nm to reduce the spectral width of an original femtosecond optical pulse train at the output of this mode-locked fiber laser, so that the width of the used optical sampling pulses is increased to about 1 ps and is still adequate for measuring the optical signal waveform having a pulse width of 1.8 ps as will be reported subsequently. In doing so, this can substantially alleviate the effect of group-velocity dispersion (GVD) on optical sampling pulses while propagating in the 100m-long HNLF of an optical waveform sampling gate. With a narrower spectrum for the sampling-pulse light, the walk-off (due to the GVD) between a sampling pulse and a signal pulse can be also reduced in a 100m-long HNLF, because a smaller separation between the optical spectra of sampling and signal lights is allowed to use than the case with original optical sampling pulses possessing the pulse width of a few hundred femtoseconds. As a result, the temporal resolution of the designed waveform sampling gate can be improved. Moreover, the use of a wider optical sampling pulse can result in the less effect of self-phase modulation on the optical-nonlinearity-based sampling of optical data signal waveforms in a HNLF [1]. This can also lead to enhancing the performance of an all-optical waveform sampling gate.

At present, the use of highly nonlinear fibers can be treated as a feasible solution to the implementation of ultrafast waveform sampling gates in terms of cost and commercial availability. The 100m-long HNLF used in our experiment has a nonlinear coefficient of 10.5 W^{-1} km^{-1}, a dispersion of 0.04 ps/(nm km) at 1550 nm, a zero dispersion wavelength of 1546 nm, and a total loss of 0.43 dB. A reel of 100m HNLF is relatively compact, as shown in Figure 7 where a normal-size pen is also illustrated in the lower right corner to compare with the outside reel diameter. At the input of a HNLF-based waveform sampling gate, two polarization controllers (PCs) are employed to adjust the polarization states of sampling and data signal lights so as to optimize the FWM conversion efficiency in a HNLF, respectively. Here the sampling pulse light serves as a pump in the FWM process. Then optical sampling pulse train and optical data signal are combined by a 3dB optical coupler before they are fed into a 100m-long HNLF, as illustrated in Figure 3. Clearly, the wavelengths of sampling light at 1544 nm and data signal light at 1554 nm are placed on two sides of a zero dispersion wavelength of the HNLF. This in turn can further alleviate a walk-off between sampling and signal pulses or a phase mismatch due to GVD, and therefore, can improve the temporal resolution of the designed waveform sampling gate. In the experiment, the average powers of sampling and data signal lights are measured to be -4 dBm and 1 dBm at the HNLF input, respectively. When the phase-matching condition is satisfied, the FWM effect happens in the HNLF and leads to the generation of a sampling product (i.e., idler) at a new wavelength $\lambda_{idler} = c / v_{idler}$, where c is the velocity of light in free space and v_{idler} is the optical frequency of an idler wave governed by Eq. (2). In this way, the FWM sampling process generates an idler wave which carries the series of discrete-time optical samples (at rate f_s and wavelength λ_{idler}) of the optical signal under test, as conceptually illustrated in Figure 2a(3). Then a tunable OBPF with 3dB bandwidth of 1 nm is

employed to filter out the idler by tuning the central wavelength of this OBPF to λ_{idler} = 1534 nm. Figure 8 shows the optical spectra measured at the outputs of HNLF and OBPF 2, respectively. Since the filtered idler contains the sampled optical short pulses having a relatively low pulse rate of about 50 MHz and a very low duty cycle, this can result in the impulse response from a low-bandwidth (i.e., 200 MHz), low-noise photodetector (PD) with high linearity when the idler is photodetected. In this case, the amplitudes of output electronic pulses are proportional to the optical peak powers of the corresponding discrete-time optical samples input to the PD, so that the envelope of series of the electronic pulses will be used subsequently to reconstruct the waveform of an original optical signal under test. In practice, the detected signal at the PD output can be weak, which needs to be linearly amplified by a low-noise electronic amplifier in order to facilitate the high-precision signal processing at the electronic A/D converter.

The output of a low-bandwidth photodetector is an analog electronic signal which can not be processed by a conventional personal computer. For the purpose of digital signal processing and waveform/eye-diagram measurement, an A/D converter with sampling rate of 400 MHz and resolution of 12 bits, which is controlled by a personal computer in our designed optical sampling system, is used to sample the analog electronic signal after photodetection. Then the resulting electronic data are fed into a personal computer for further processing. Since the reconstruction of data signal waveform and eye diagram requires the synchronization information on the acquired samples, a conventional approach for achieving this aim is to employ hardware clock recovery and trigger circuit. However, doing so can significantly increase the complexity and cost of an optical waveform sampling system in ultrahigh-speed optical data communications, which also reduces the operation flexibility of such waveform sampling systems due to the bit-rate dependence of a hardware clock recovery circuit. To solve these problems, Westlund *et al.* demonstrated the first software-synchronized all-optical sampling system which can achieve the synchronization of the sampled data in high precision by using only the synchronization algorithm based on the Fourier transform of the sampled data and the eye-diagram timing drift [1,10,11]. Therefore, we adopt this cost-effective software-synchronization method in the design of our optical waveform sampling system to facilitate the use of a free-running mode-locked fiber laser with tunable repetition rate, leading to the reduction of system complexity by avoiding any hardware clock recovery circuit. In this way, the asynchronously acquired sample data after A/D conversion are analyzed by a personal computer using a digital signal processing technique in order to extract the synchronization information and to recover the timebase for equivalent-time optical waveform sampling of ultrashort optical pulses or optical data pulse signals. Consequently, the number of the scanned bit slots, S, is obtained from the truncated sample data of length N by means of appropriate digital signal processing (e.g., Fourier transform of the truncated sample data with suitable length and subsequent determination of accurate time positions corresponding to the transition between mark and space levels of the optical signal eye diagram). For the given bit period $T_b = 1/B$, a time step ΔT for scanning the bit slot is substantially computed according to the relationship $\Delta T = S \cdot T_b / N$. For instance, ΔT can be accurately obtained by employing a high-precision iteration based on the smallest eye-diagram timing drift [10,11].

Based on the software-synchronized optical sampling technique [10,11], we have developed a computer algorithm for use in our constructed optical waveform sampling system to display the optical waveforms/eye diagrams on a computer screen. In this way, the computer can correctly position a series of the asynchronously acquired samples in the time axis according to the computed ΔT and the number of consecutive bit slots required for waveform display. With the software-synchronized timebase, the signal waveform of an optical pulse stream or the eye diagram of an optical data signal under test is thus reproduced by the personal computer with the correct time scale obtained from ΔT. The associated pulse parameters can be also assessed by measuring the reconstructed optical signal waveform (or eye diagram). To demonstrate the waveform sampling of ultrashort optical pulses, we start with the measurement of a 10GHz optical clock pulse sequence in our experiments. After photodetection and A/D conversion, a computer is employed to first reproduce a series of raw samples without correct time scale when the waveform of a 10GHz optical clock pulse sequence is optically sampled at the HNLF-based waveform sampling gate, as shown in Figure 9a.

Clearly, the envelope of those acquired discrete samples contains a certain number of pulse clusters shown on the computer screen, which is analogous to the waveform of the original optical signal except for the time scale. Each cluster consists of multiple pulses with proper peaks corresponding to the impulse response of a low-bandwidth photodetector module, as illustrated in Figure 9b. By using the accurately estimated ΔT, the curve fitting of such a pulse cluster results in the reconstruction of a single pulse waveform with correct time scale for the 10GHz optical clock pulse sequence under test (see Figure 9c). Our designed waveform sampling system shows that the width, $\tau_{measure}$, of the optical pulse under test is 2.0 ps. In this way, the waveform of a 10GHz optical clock pulse sequence is correctly rebuilt and is clearly displayed on the computer screen with 4 optical pulses of very low duty cycle, as shown in Figure 10. Note that both optical clock and data-signal pulses employed in our experiment have an original pulse width, $\tau_{original}$, of 1.8 ps (see Figure 5) measured by a high-resolution autocorrelator. The temporal resolution, t_{re}, of an optical waveform sampling system can be computed by using the following formula [1][2]

$$t_{re} = \sqrt{\tau_{measure}^2 - \tau_{original}^2} \tag{4}$$

Therefore, this results in $t_{re} = \sqrt{2.0^2 - 1.8^2} = 0.87$ ps for our constructed waveform sampling system.

In the experiment, we can use the designed optical waveform sampling system to accurately measure the pulse shapes of a 10Gbit/s optical PRBS data and a 80Gbit/s OTDM signals produced by the optical pulse signal generators (see Figure 4), respectively. The reproduced eye diagram of the 10Gbit/s optical data signal is shown in Figure 11, which opens widely and clearly. Our designed optical waveform sampling system can be used to flexibly display the waveform of the 80Gbit/s OTDM signal with a return-to-zero (RZ) format and a repeated pulse pattern of "11110000" used in the experiment. For example, this may be practically required by some users to characterize the waveform of such an OTDM signal in the relatively long observation duration to meet some of their specific measurement needs, as illustrated in Figures 12a and 12b. Moreover, the displayed optical signal waveform can be easily zoomed in with a correct time scale shown on the computer screen (e.g., see Figures 12b and 12c). In doing so, this allows us to more clearly observe a specific part or pulse pattern of the optical signal under test, as shown in Figure 12c. Due to a high time resolution, our designed waveform sampling system does not cause any problem associated with measurement bandwidth for the 80Gbit/s optical data signal under test, so that the intersymbol interference (ISI) is not observed in the reproduced waveform of such a RZ signal with $\tau_{original} = 1.8$ ps. In fact, the bit period of a 80Gbit/s data signal is 12.5 ps (i.e., the pulse spacing for a data pattern of "1111"). This in turn guarantees a clear separation between two adjacent optical pulses with the measured pulse width of only 2.0 ps in the "1111" pulse pattern, and therefore, the reproduced waveform shows that there is no overlap between neighboring optical pulses. In contrast, if we use a conventional optoelectronic waveform monitoring system consisting of a 70GHz electronic sampling oscilloscope and a 70GHz photodiode, the severe ISI effect would be easily observed from the measured 80Gbit/s signal waveform as illustrated in Figure 6. Moreover, the high resolution of our designed optical waveform sampling system allows us to inspect the detail of each RZ pulse in the measured optical signal waveform with a repeated "11110000" data pattern. For example, we can easily see that the third optical pulse clearly has the lowest peak among four successive pulses and the peak of the first pulse is moderate compared with those of the remaining three pulses as illustrated in Figure 12, whereas it is not easy to find out such pulse details from the 80Gbit/s signal waveform measured by employing a conventional optoelectronic waveform monitoring system due to the limited measurement bandwidth. From both Figures 6 and 12, the uneven pulse amplitudes of this optical "11110000" data pattern are also observed, which is caused by an imperfect OTDM multiplexer having slightly unequal power losses in four optical paths (see Figure 4b). In our experiment, we have used the discrete optical couplers, tunable optical delay lines, a variable optical attenuator, and SMF pigtails to implement a bulk OTDM multiplexer. As a result, it is difficult to keep identical power losses for all the optical paths in such a multiplexer. This problem could be solved if we will be able to use an integrated waveguide OTDM multiplexer in the future. Furthermore, the quality of the displayed waveforms for

both 80Gbit/s and 10Gbit/s optical data signals can be feasibly improved when a high-sensitivity, low-noise optical receiver with appropriate bandwidth is designed and is used in our constructed optical waveform sampling system to optimize the signal-to-noise ratio for an analog electronic signal after photodetection. This topic will need to be studied further and will be reported separately.

3. Conclusions

Optical sampling based on ultrafast optical nonlinearities is a useful technique to measure the waveforms of ultrashort optical pulses and to monitor the eye diagrams of ultrahigh-speed optical data signals. This goal has been achieved by adopting both fiber-based optical hardware implementation and software-synchronized optical sampling technique [10,11]. Using our constructed free-running passively mode-locked femtosecond fiber laser of tunable repetition rate and low timing jitter as a high-performance optical sampling pulse source, we have presented a new implementation of optical waveform sampling systems in this paper. The designed optical sampling system is based on FWM effect in a 100m-long HNLF for ultrafast optical signal waveform sampling and our developed computer algorithm for optical waveform display and measurement based on the software-synchronized optical sampling technique, respectively. We have successfully demonstrated the all-optical waveform sampling of a 10GHz optical clock pulse sequence and a 80Gbit/s optical data signal with pulse width of 1.8 ps. Since the waveforms of the tested optical pulse signals have been accurately reproduced with a pulse width of 2.0 ps, a temporal resolution of 0.87 ps has been achieved for optical waveform measurement in the experiment. We have also used our developed optical sampling system to accurately measure the optical eye diagram of a 10Gbit/s optical data signal which was based on 1.8ps optical pulses and was modulated with a pseudorandom bit sequence. It is expected that optical waveform sampling systems will play an important role in fast and accurate characterization of ultrashort optical pulses as well as future ultrahigh-speed all-optical communication systems and networks.

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Figure Captions

Figure 1. Functional block diagram of a typical optical waveform sampling system.

Figure 2. Illustrations of (a) optical waveform sampling in the time domain and (b) the associated FWM process in the frequency domain, respectively.

Figure 3. Experimental setup of an optical waveform sampling system with a passively mode-locked femtosecond fiber laser and a FWM-based optical waveform sampling gate.

Figure 4. Experimental setup of (a) 10Gbit/s optical PRBS pulse signal generator and (b) 80Gbit/s OTDM pulse signal generator.

Figure 5. Autocorrelation trace of an optical clock pulse generated by a 10GHz actively mode-locked semiconductor laser.

Figure 6. 80Gbit/s signal waveform with 4 adjacent optical pulses measured by a 70GHz electronic oscilloscope cascaded with a 70GHz photodiode at the output of an OTDM multiplexer.

Figure 7. A reel of 100m-long highly nonlinear fiber used in the waveform-sampling experiment.

Figure 8. Optical spectra at the outputs of HNLF and OBPF 2, respectively.

Figure 9. Optical waveform sampling of a 10GHz optical clock pulse sequence. (a) The raw optical samples without correct time scale reproduced by a computer. (b) The detailed structure of a pulse cluster from raw samples. (c) The reconstructed optical pulse with correct time scale.

Figure 10. Dynamic display of the measured waveform for a 10GHz optical clock pulse sequence with an original pulse width of 1.8 ps.

Figure 11. The reproduced eye diagram of a 10Gbit/s optical PRBS data signal.

Figure 12. The measured waveform of a 80Gbit/s OTDM RZ signal with repeated data pattern of "11110000". (a) and (b) Displays of a full pattern "11110000" in relatively long observation durations. (c) Display of a zoom-in pulse pattern "1111".

Optical Waveform Sampling System

Figure 1

Original Optical Data Pulse Signal

(1)

ΔT $2\Delta T$ $3\Delta T$ $4\Delta T$ $5\Delta T$ $6\Delta T$ $7\Delta T$

Time

(2)

Time

Optical Sampling Pulse Train

(3)

Time

Sequence of the Sampled Optical Signal at the Corresponding Time Instants

(4)

Time

Output of a Low-Bandwidth Photodetector

(5)

Time

Reproduced Waveform by a Computer

Figure 2(a)

Power

Pump

v

0

Power

Signal

v

0

Spectra of Input Lights to a HNLF

FWM in a HNLF

Power

Signal   Pump   Idler

v_{signal} v_{pump} v_{idler}

v

0

Spectra of Output Lights from a HNLF

Figure 2(b)

Figure 3

Figure 4(a)
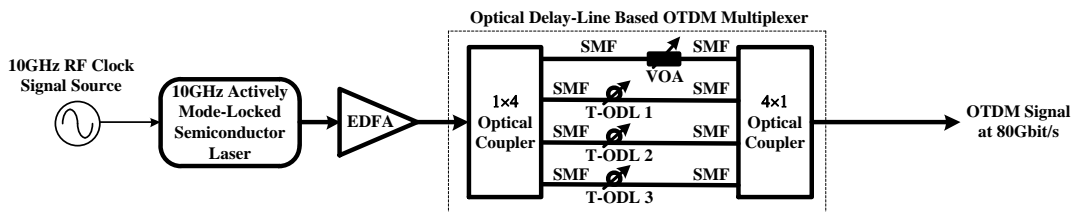
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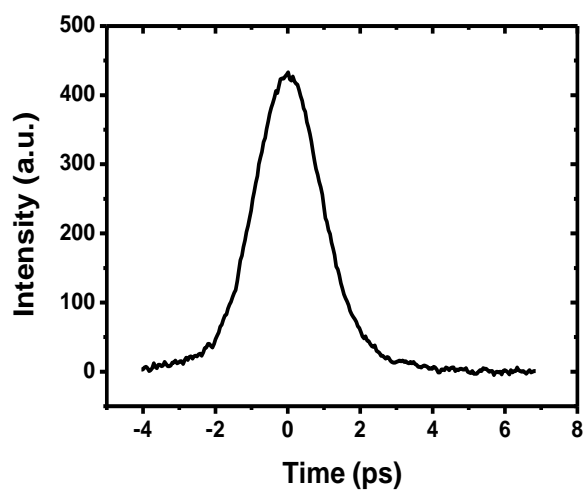
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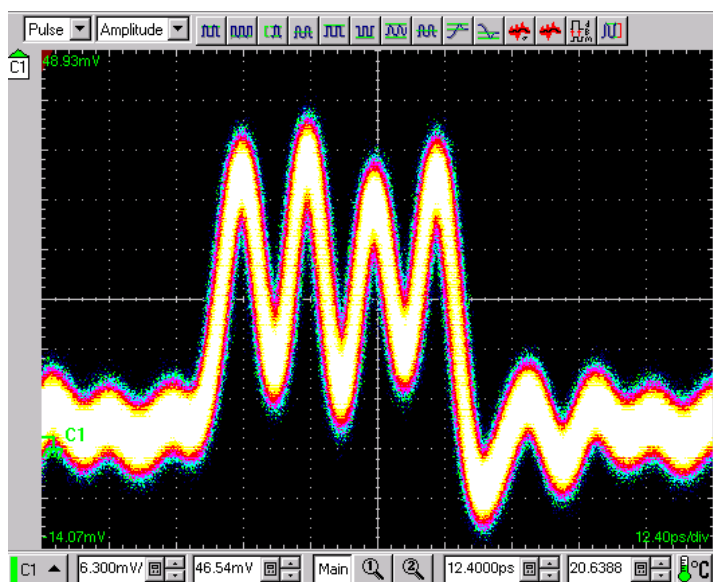
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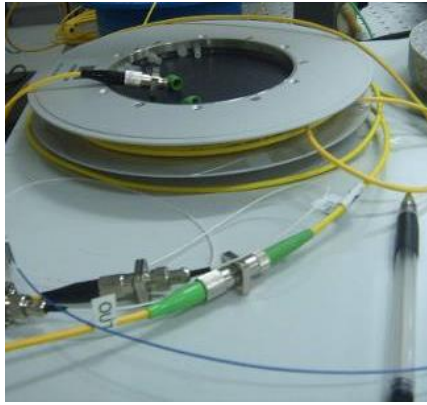
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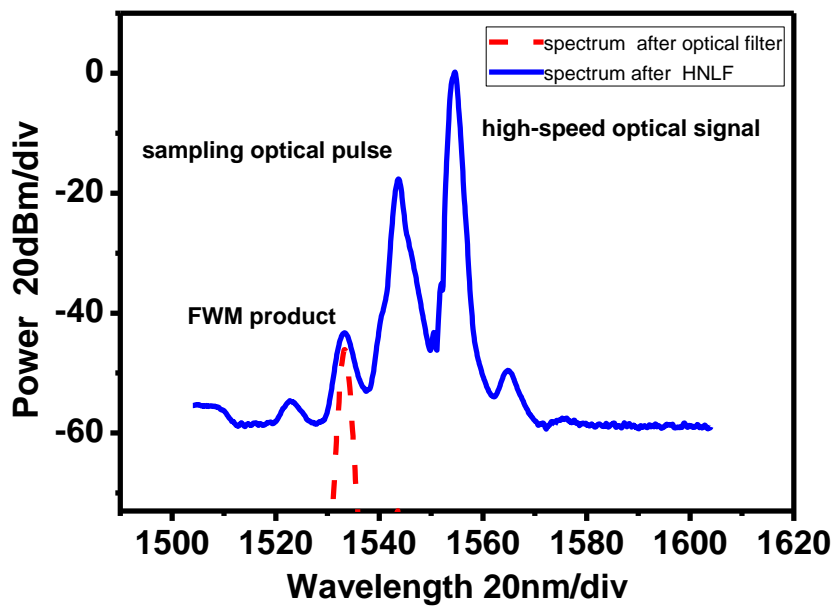
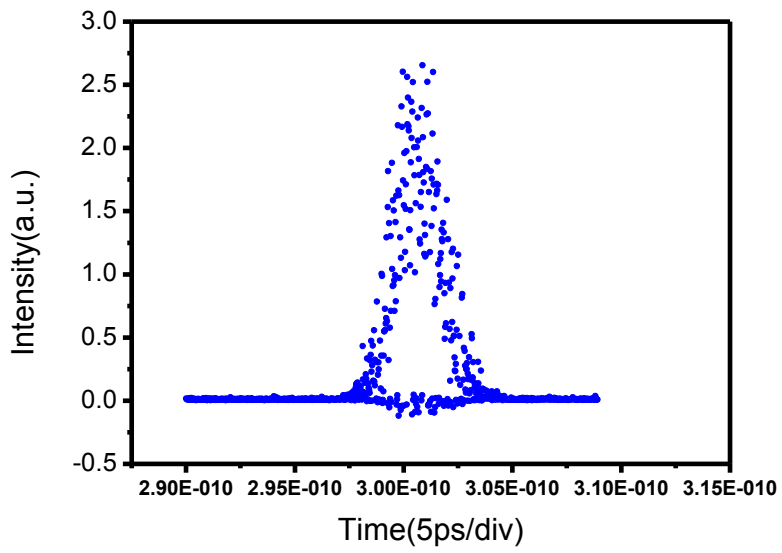**Figure 8**
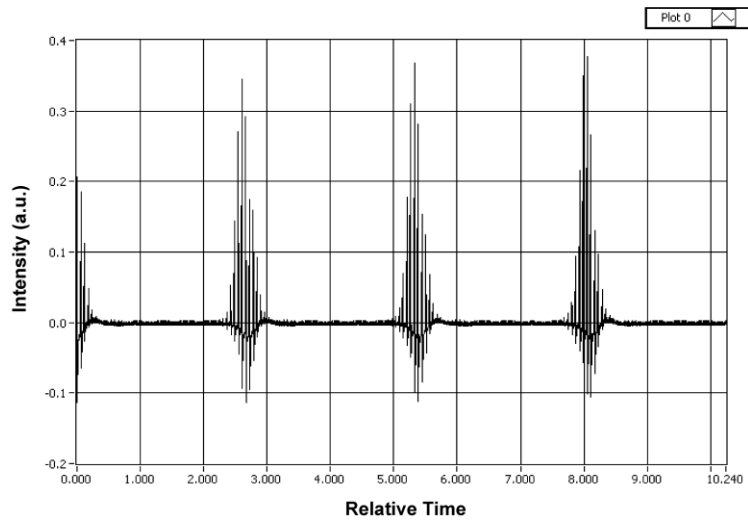
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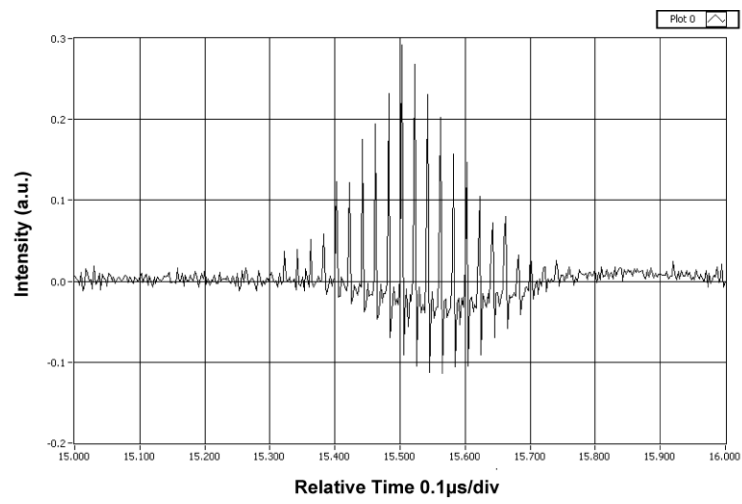
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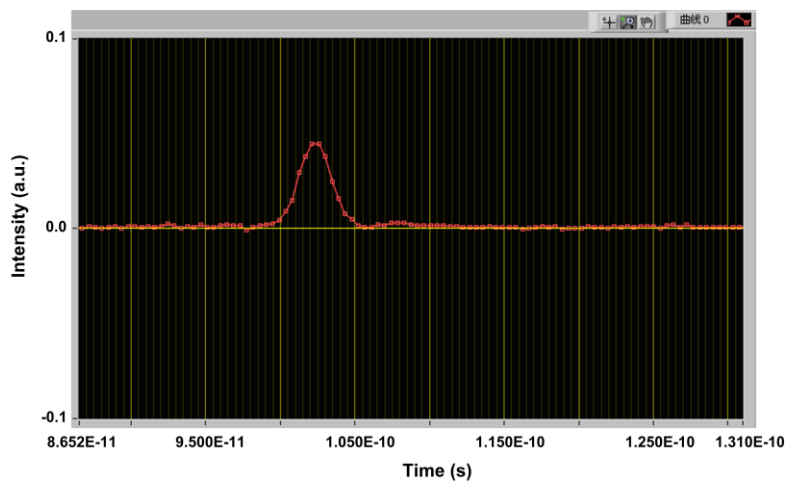
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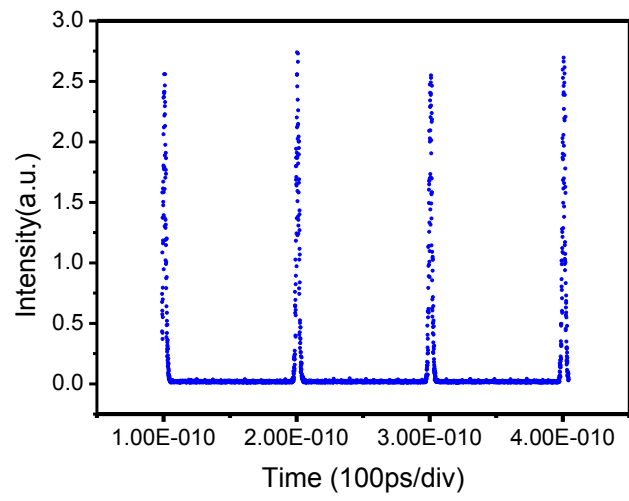
Figure 10

Figure 11
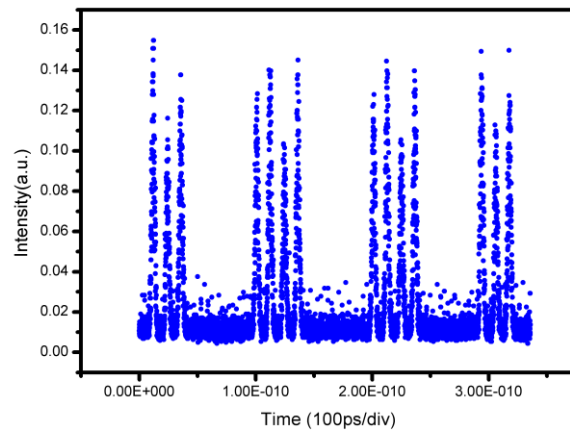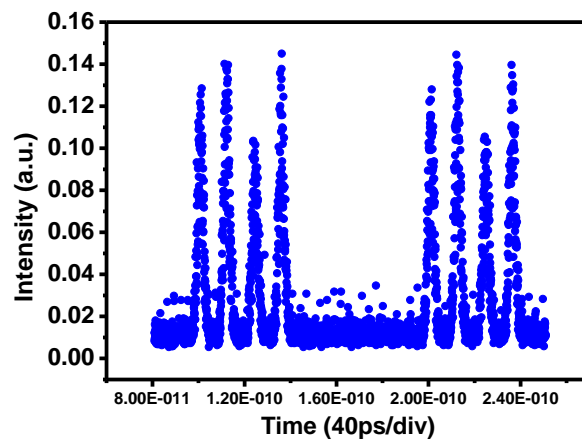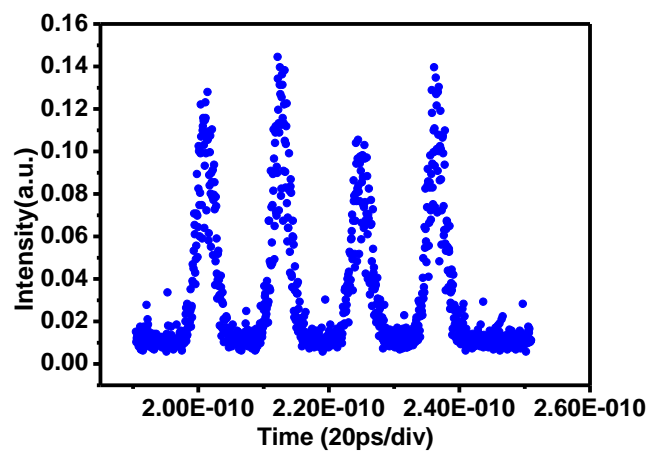
Figure 12(a)

Figure 12(b)

Figure 12(c)