Ultrashort optical pulse monitoring using asynchronous optical sampling technique in highly nonlinear fiber

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An asynchronous optical sampling scheme based on four-wave mixing (FWM) in highly nonlinear fiber (HNLF) is experimentally demonstrated. Based on this scheme, 10-GHz input pulse train with 1.8-ps pulse width is successfully sampled in 100-m HNLF. A single pulse at 10 GHz with 2.3-ps pulse width is rebuilt by using a 50-MHz frequency tunable free-running fiber laser as the sampling pulse source (SPS). 40-GHz pulse train is used as the input signal. The rebuilt waveforms, together with the low-jitter eye diagram, are also presented.

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Optical sampling technology has played a key role in ultrahigh-speed optical communication systems[1,2], all-optical analog-to-digital conversion[3], and real-time waveform displays[4]. This technique has been widely studied[5−16]. The reported sampling systems are divided into the synchronous system[6−8] and asynchronous system[9−14]. The synchronous all-optical sampling system accurately rebuilds data waveforms or eye diagrams by adopting clock-recovery circuits[7]; however, this dramatically increases the system cost and volume[6−8]. In recent years, asynchronous optical sampling system has received much attention due to its low cost, compact volume, and avoidance of expensive clock-recovery circuits[9−14].

In reported asynchronous systems, optical sampling is implemented mainly based on the nonlinear phenomena in medium, such as the second-order susceptibility χ^2 and third-order susceptibility χ^3. For the utilization of χ^2, sum-frequency generation (SFG) in nonlinear crystals, such as $KTiOPO_4$ (KTP)[1,15], and periodically poled $LiNBO_3$ (PPLN) crystals[16,17], has been widely studied. However, this scheme requires that the wavelength of the sampling source should precisely meet the phase-matching condition limiting the wavelength range of the input data stream. Such system is sensitive to surrounding vibration and temperature change. These disadvantages are harmful to the stability and application of the system. The cross-phase modulations in nonlinear optical loop mirror[6] or in semiconductor optical amplifiers[18−20] have been demonstrated; however, these schemes are not widely utilized because of their system complexity and low efficiency[6,18]. Recently, the scheme based on four-wave mixing (FWM) in highly nonlinear fiber (HNLF) has been widely studied and reported because of its high efficiency, low cost, compact volume, and stability[7−10].

In this letter, we demonstrate an asynchronous optical sampling system based on FWM in 100-m HNLF by using a free-run passively mode-locked fiber laser as the optical sampling source. For the application of FWM, this scheme is suitable to measure the periodic signal at a single wavelength, satisfying the phase-matching condition. Pulse trains at 10 and 40 GHz with 1.8-ps optical pulse width are accurately rebuilt and displayed by the proposed system, which avoids the expensive clock recovery circuit using software arithmetic. The results show that our system has a stable performance with high-speed bit rate input signal.

The basic principle of the asynchronous sampling system is presented in Fig. 1. Figure 1(a) shows the optical data signal, while Fig. 1(b) represents the optical sampling pulse train. The optical sampling pulse width is much narrower than the data signal. In our experiment, the frequency of the sampling pulse was 50 MHz. To obtain the amplitude information of the data signal at different places in time, the following relationship needs to be satisfied:

$$B = Mf_s + \Delta f, \quad (1)$$

where integer M corresponds to the bit rate reduction factor, which is noted by the omitted pulses ($\cdots$) in Fig. 1; Δf corresponds to the offset frequency between the original signal bit rate B and the sampling frequency f_s, which determines the bit slot scanned in the original pulses at different places in time. This factor was tuned by adjusting the repetition frequency of the sampling pulse source in our experiment for the use of a frequency tunable fiber laser. The sampled pulses generated in the sampling gate are presented in Fig. 1(c). Their frequencies are the same as the sampling pulses, and the amplitudes are proportional to the data signal at the corresponding location. The dashed line indicates that the outline of the sampled pulse is a time-magnified copy of the data signal.

The experimental setup is presented in Fig. 2. The sampling system used a passively mode-locked fiber laser,

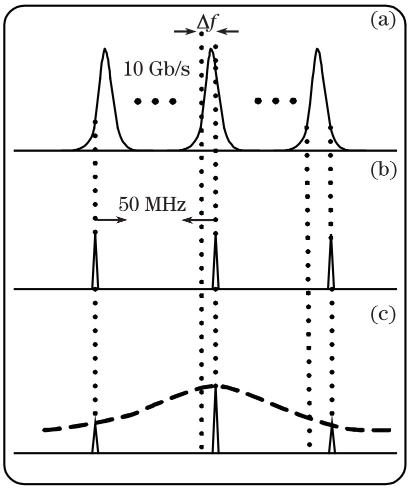

Fig. 1. Principle of optical sampling. (a) Original data pulse train, (b) the first three pulses of the sampling pulse train, and (c) sampled pulses.

which is frequency tunable, generating 50-MHz, 1-ps sampling pulses to make a low-bandwidth (LBD) photodiode detector (PD) available. A semiconductor actively mode-locked laser (U2T Company, TMLL 1550) was used to generate 10- and 40-GHz, 1.8-ps optical pulse trains as the data signals in our experiment. The polarization of the sampling and data light was adjusted by polarization controllers (PCs)1 and 2 (Fig. 2), respectively. The data signal and sampling pulses were combined by a 3-dB fiber coupler and then fed into the HNLF, which refers to the 100-m HNLF in our experiment, to generate the FWM phenomenon. A 1-nm band-pass filter (BPF) was employed to filter the idler component of the FWM generated in the fiber (Fig. 3), which was then detected by a LBD PD. The detected signals were then entered into a personal computer by a data acquisition (DAQ) card with 400-MHz sampling rate. To avoid the conventional clock recovery loop, a software-synchronization method was used to rebuild the data signal and present the eye diagram. The details of this method are described in Ref. [21].

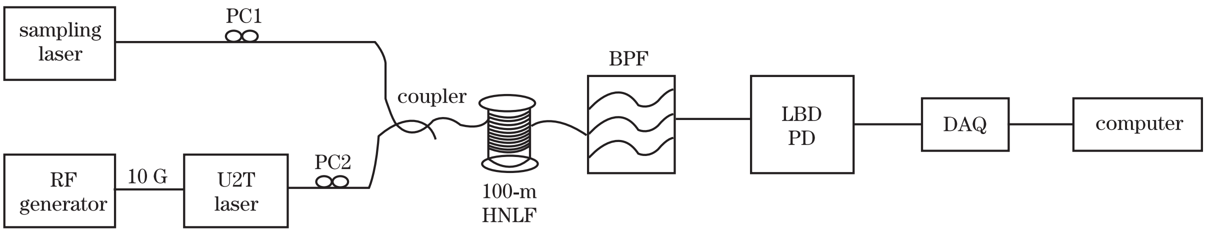

Fig. 2. System setup for fiber-based optical sampling. RF: radio frequency.

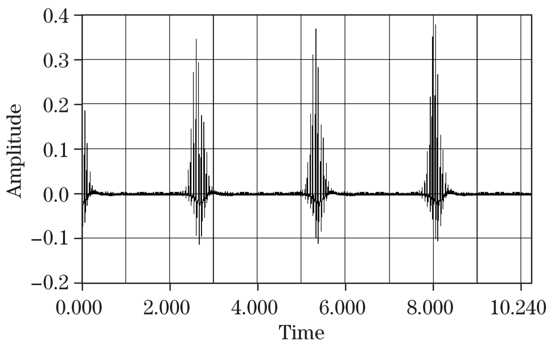

Fig. 3. Signals sampled by the idler. Each comb presents a sampled waveform.

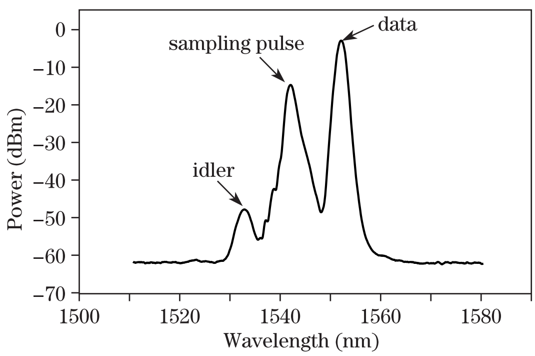

Fig. 4. Spectrogram of the HNLF.

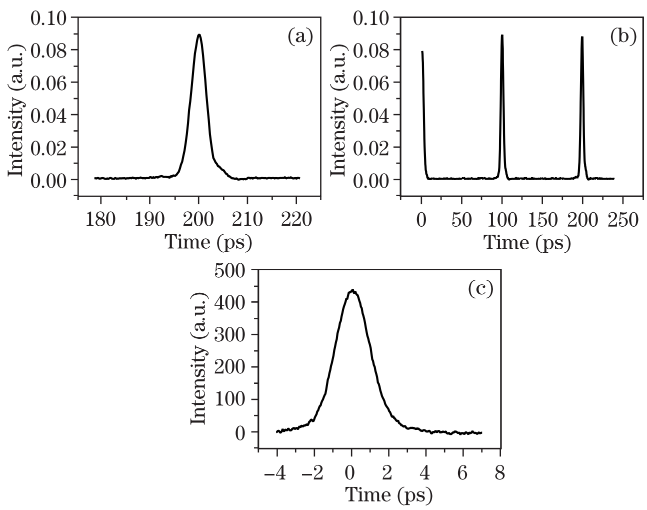

Fig. 5. Rebuilt pulse of 10 GHz. (a) Magnified portion of one pulse, (b) rebuilt pulse train, and (c) autocorrelation curve of the data pulse.

The result of the FWM in the HNLF is presented in Fig. 4. The right peak located at 1554 nm is the original data signal, with a spectrum width of approximately 1.3 nm. The central component at 1543 nm is from the sampling source with 1-nm spectrum width. The left portion is the idler generated by the FWM at 1533 nm. The power of the data signal before injection into the HNLF

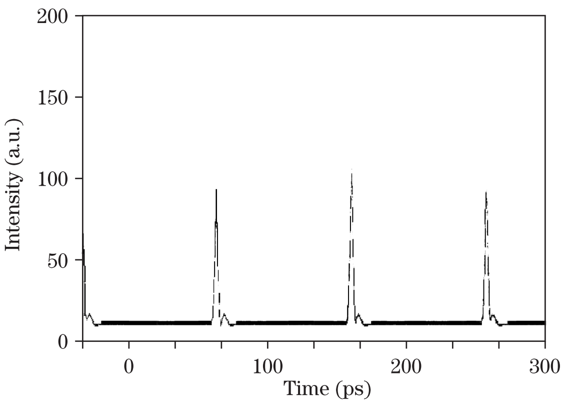

Fig. 6. Dynamic view of the rebuilt signal pulse train.

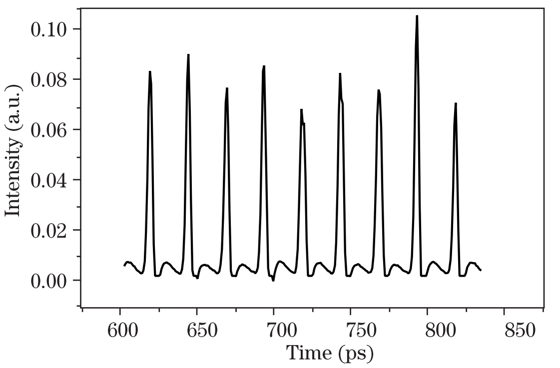

Fig. 7. Rebuilt pulse train of 40 GHz.

was approximately 3 dBm. The phase matching condition was satisfied by simply adjusting the wavelength of the sampling pulse. To increase the FWM efficiency, the power of the sampling pulses and the polarization of the two injected beams were adjusted together. The power of the sampling pulse was set at –8 dBm. The optimized efficiency was obtained with a –42-dBm idler located at 1532 nm.

The raw sampled waveform of the 10-GHz signal is presented in Fig. 3. The comb-like waveforms represent the sampled pulses. The amplitude of each pulse is proportional to the 10-GHz signal at different places. The amplitude data was used to rebuild the original signal together with the corresponding time data. The rebuilt pulse is presented in Fig. 5(a), with a pulse width of 2.3 ps. The system time resolution is computed by $\Delta\tau = \sqrt{\tau^2_{\text{measure}} - \tau^2_{\text{original}}}$. With both the measured width and the original width of the data signal, a 1.43-ps system time resolution was obtained. Figure 6 shows the eye diagram of the rebuilt pulse. The eyelid is thin and the eye opens widely. This proves that a high-quality, low-jitter rebuilt pulse was obtained. Figure 5(b) presents the obtained pulse train measured by the Gage CS12400 DAQ card and displayed by the software designed by Labview. The time distance between two pulses is 100 ps, which means that the bit rate of the pulse train is 10 Gb/s. To observe the details, an amplified portion of a single waveform is presented in Fig. 5(a). For the convenience of comparison, a single data pulse measured by the autocorrelator is presented in Fig. 5(c).

To determine the potential capability of the system, a 40-GHz pulse train from the same U2T laser was injected as the data signal. A 100-m HNLF with nonlinear coefficient of 11 $\text{W}^{-1} \cdot \text{km}^{-1}$ (Denmark Crystal Fiber Company, Nonlinear Photonics Crystal Fiber-NL-1550-POS-1) was used as the sampling gate. The result is presented in Fig. 7. The rebuilt pulse train with a 25-ps time distance between two single pulses is presented, which refers to the bit rate of the rebuilt pulse train at 40 Gb/s. This demonstrates that the system has stable performance even with increasing the bit rate input data strain.

In conclusion, a HNLF-based optical sampling scheme using FWM is demonstrated. Judging from the eye diagram, the time jitter is low, which proves that the entire system is stable and available. The single rebuilt pulse at 10 GHz with 2.3-ps pulse width is presented together with the rebuilt pulse trains of 10 and 40 GHz. When replacing the 10-GHz input signal with the 40-GHz data signal, clear data pulse train is still achieved. This demonstrates that the system runs stably with the increase in data speed. This system could play an important role in future high-speed optical fiber communication and high-speed free space optical communication.

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