Japanese Journal of Applied Physics

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Japanese Journal of Applied Physics
Vol. 47, No. 8, 2008, pp. 6809–6811

Non-synchronous Optical Sampling and Data-Pattern Recovery Using a Repetition-Rate-Tunable Carbon-Nanotube Pulsed Laser

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(Received January 13, 2008; accepted April 23, 2008; published online August 22, 2008)

We demonstrate a non-synchronous all-optical sampling system using a carbon-nanotube mode-locked laser with a tunable repetition-rate. This allows a stable and unambiguous waveform reconstruction without the inherent limitation encountered in conventional non-synchronous optical sampling such as the time-direction ambiguity and the frequency-hole or sparse-sampling phenomena. Real-time eye-diagram reconstruction of 160 Gbit/s return-to-zero (RZ) signals with sub-picosecond resolution and data-pattern recovery with sequence length up to $2^{17} - 4$ has be realized. [DOI: 10.1143/JJAP.47.6809]

KEYWORDS: Optical sampling oscilloscope, non-synchronous sampling, carbon-nanotube pulsed laser, mode-locked laser, eye-diagram reconstruction, data-pattern recovery, software clock recovery, high bit-rate optical communication

1. Introduction

Electrical sampling oscilloscopes and high-speed photo-detectors are currently bandwidth limited to 100 GHz. They also suffer from the imperfect photo-detector impulse response. The evaluation of high bit-rates data signals of 160 Gbit/s and beyond therefore requires optical sampling oscilloscopes, which offer a bandwidth beyond 500 GHz and allow the visualization of true optical waveforms without the photo-detector limitation. The conventional all-optical sampling oscilloscope[1,2] requires an external clock to synchronize the internal sampling pulsed laser through a complex clock-recovery and offset-frequency generation circuit. It has a limited flexibility due to the strict requirement of a stable external clock at a limited lockable frequency range.

The proposal of a non-synchronous sampling scheme using a software algorithm for clock recovery and eye-diagram reconstruction[3)] was an attractive method for clock-free operation. However, the relatively long computing time makes it impractical for real-time application. The introduction of a fast software eye-diagram reconstruction algorithm[4,5)] finally makes the non-synchronous optical sampling oscilloscope a practical real-time measurement tool.

The key performance index of a non-synchronous optical sampling oscilloscope lies on the free-running sampling pulsed laser, which has to be very stable with an ultralow timing jitter. This is usually a stabilized mode-locked fiber laser with a fixed free-running repetition rate. Previously demonstrated non-synchronous optical sampling oscilloscopes[3–5)] only allow the reconstruction of eye-diagram, but not data pattern due to the limited sampling points. Additionally, they suffer from fatal problems such as time-axis direction ambiguity and an occasional sparse-sampling or frequency-hole phenomenon. That means the time axis could be reverse and full waveforms sometimes can not be visualized when the input signal frequency is at some integer- or rational-integer-multiple of the sampling frequency.

In this paper, we solve the above problems with a repetition-rate-tunable carbon-nanotube (CNT) mode-locked laser. The ultralow timing jitter of this laser also enables the acquisition of a long sampling series upto >500,000 samples. We developed a real-time algorithm to recover not only the eye-diagram but also the data pattern. We have demonstrated, to the best of our knowledge, the longest data-pattern recovery of an equivalent of $(2^{17} - 4)$ bits or 131,068 bits with a 40 Gbit/s return-to-zero (RZ) signal, using non-synchronous sampling method.

2. Experiment

The configuration of the sampling pulsed laser is shown in Fig. 1. The laser is a polarization-maintaining (PM) version of the CNT mode-locked laser similar to the one reported in ref. 6.

The mode-locked laser is in a ring configuration, constructed with PM fibers and PM components throughout. A length of erbium-doped fiber is pumped by a 978 nm single mode laser diode through a 980/1550 wavelength multiplexer. Optical isolators are used to force single directional lasing operation. Another length of single-mode fiber is inserted for pulse shaping. The light is free-space coupled in and out of the CNT mode-locker through a pair of fiber collimators, which is fined tuned with polarization extinction ratio >30 dB. The fiber collimators pairs are also placed on a motorized translational stage, which serve to allow control of the cavity length, and therefore making the laser repetition-rate tunable. The optical alignment is crucial for stable operation of the laser throughout the repetition tuning range. The laser nominal repetition rate is close to 50 MHz, and can be tuned within ±0.5 MHz. The laser pulse width is around 1 ps, with a center wavelength at 1570 nm, and the average power is around 5 mW.

The sampling configuration is shown in Fig. 2. A polarization diversified fiber four-wave mixing gate is used as the ultrafast sampling gate. The input signal is sampled by the free-running CNT mode-locked laser pulses via four-wave mixing (FWM), and since the sampling laser wavelength is at 1570 nm, input signals in the C-band region from 1525 nm to 1565 nm can be converted over to the L-band region from 1575 nm to 1615 nm. The converted signal is filtered and detected using a photo-detector with 125 MHz bandwidth and analog-to-digital (A/D) converted at 14 bit into a long memory buffer. A fast algorithm similar to the one reported in ref. 5 is used to recover the sampling internal for eye-diagram reconstruction.

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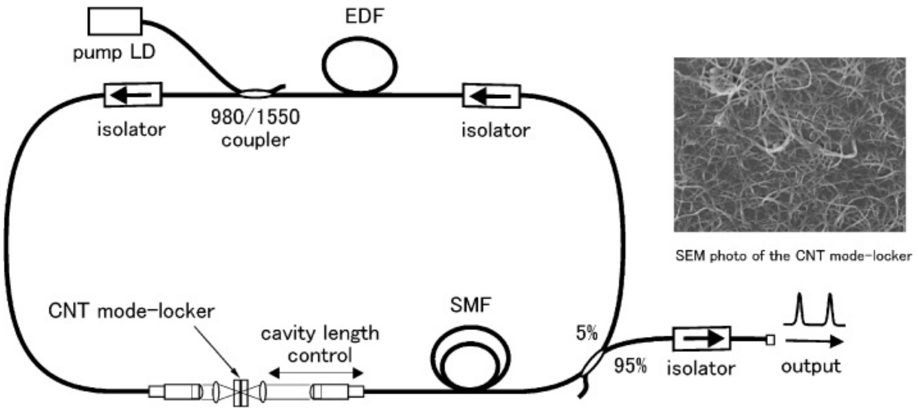

Fig. 1. Schematic of the CNT mode-locked laser.

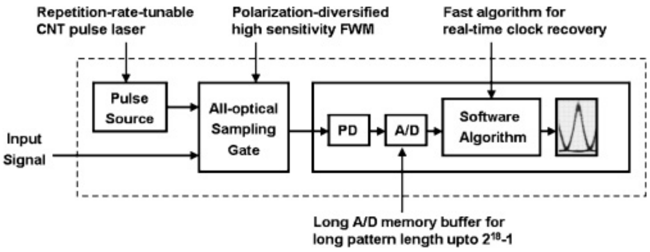

Fig. 2. All-optical sampling configuration.

In the software synchronization scheme as described in ref. 5, the sampling step size Δt is defined by

$$\Delta t = \frac{ET}{N},$$

where T is the signal period, N is the number sampling point, and E is the number of envelop in the sampled data. This fast algorithm, allows real-time calculation of the number of envelop E, thereby determine the sampling interval Δt which is required for the waveform reconstruction in non-synchronous sampling scheme.

The number of envelop E (which is related to the sampling interval Δt) is determined by the frequency beating between the input signal frequency ($F_{sig} = 1/T$), and the repetition rate of the sampling laser F_{sam}. The sparse-sampling or frequency-hole phenomenon will occur when F_{sig} is at integer multiple, or some rational fractions of F_{sam}. This condition can be determined by monitoring the number of envelop, and to make sure that E will not be close to an integer or some rational fractions.

In order to avoid the sparse-sampling or frequency-hole phenomenon, the laser repetition rate F_{sam} is adjusted whilst the E is monitored. The laser repetition rate is then tuned to achieve a predefined optimum value of the envelop number, and in the correct direction to allow non-ambiguous time-axis, as well as preventing the sparse-sampling or frequency hole problem (Fig. 3) from occurring. The time-axis ambiguity problem can also be solved by monitoring the directional changes in E when varying F_{sam} in one direction.

3. Results and Discussion

The optical sampling system is used to measure (a) 40 and (b) 160 Gbit/s RZ signals. Both signals are optical time-domain multiplexed signals of 10 Gbit/s pseudo-random bit-sequence (PRBS) de-correlated data streams. The real-time reconstructed eye-diagrams are shown in Fig. 4.

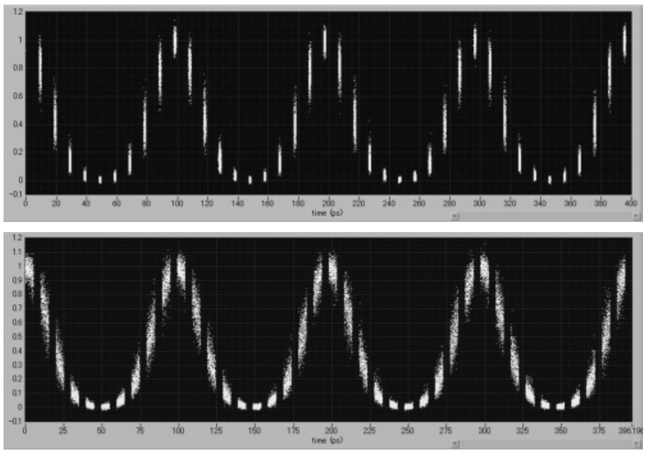

Fig. 3. Sparse-sampling/frequency-hole phenomena.

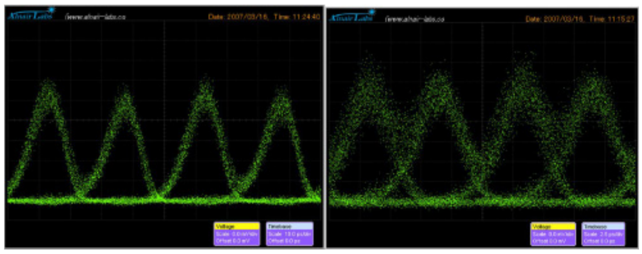

Fig. 4. (Color online) Eye-diagram of (left) 40 Gbit/s, and (right) 160 Gbit/s signals.

The reconstructed data pattern of the 40 Gbit/s signal is shown in Fig. 5. The signal is the de-correlated multiplex of four channels of 10 Gbit/s PRBS with $2^{15}-1$ pattern length each. This gives us an effective multiplexed pattern length of $2^{17}-4$. Figure 5 shows only a fraction of the full data pattern (40 bits out of the total pattern length of 131,068 bits). The acquired 512 K sample points are all stored in the memory, and all of the bit patterns can be viewed by simply dragging the scroll bar below the graph. Although more data samples (32 M samples) can be acquired for even longer data pattern, we are currently limited by the timing jitter of the data source. Longer pattern lengths are possible with more stable data source.

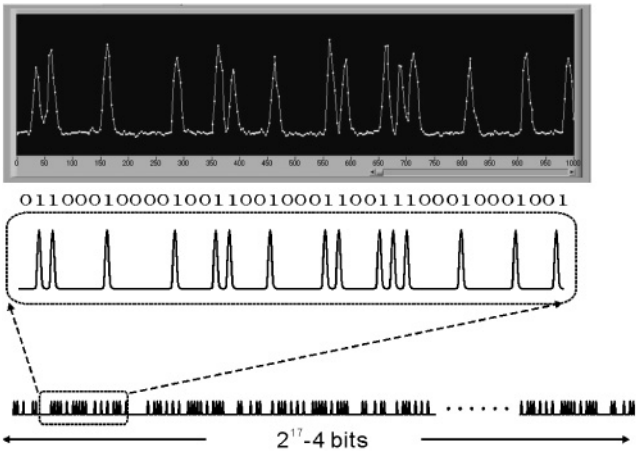

Fig. 5. Data-pattern of 40 Gbit/s RZ signal ($2^{17} - 4$ bits).

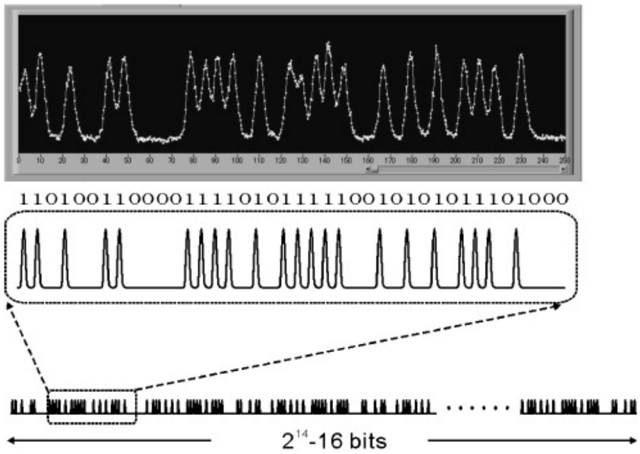

Fig. 6. Measured data-pattern of 160 Gbit/s RZ signal ($2^{14} - 16$ bits), only a section of the full data sequence is displayed.

We have also reconstructed the 160 Gbit/s data pattern (Fig. 6), of which 16 channels of 10 Gb/s PRBS with $2^{10} - 1$ pattern length was multiplexed, giving an effective pattern length of $2^{14} - 16$ bits. Again, the graph in Fig. 6 only displayed 40 bits from the total available 16,368 bits stores in the memory. Note that both Figs. 5 and 6 are one-shot, single-scan data. There graphs can be intensified with more data points by overlaying multiple scans on top of each other.

4. Conclusions

We have demonstrated a non-synchronous all-optical sampling oscilloscope for real-time eye-diagram and data-pattern reconstruction without the need for external clock. The common problems associated with non-synchronous sampling, such as time-axis ambiguity and sparse sampling/frequency-holes, are solved using a repetition-rate tunable CNT-based mode-locked laser, and a monitor-and-feedback control system. The ultra-stable feature of the CNT pulsed laser also enables the acquisition of long sample points, together with a newly developed algorithm for data-pattern recovery, we have successfully demonstrated full data pattern reconstruction of 160 and 40 Gbit/s RZ signals with pattern length as long as $2^{17} - 4$ bits (131,068 bits).

Acknowledgement

This work was supported by Strategic Information and Communications R&D Promotion Programme (SCOPE) of the Ministry of Internal Affairs and Communications (MIC), Japan.

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