APPLIED PHYSICS LETTERS **94**, 041105 (2009)

Time stretch enhanced recording oscilloscope

Shalabh Gupta[a)] and Bahram Jalali[b)]
Department of Electrical Engineering, University of California, Los Angeles, 420 Westwood Boulevard, Los Angeles, California 90095, USA

(Received 5 November 2008; accepted 6 January 2009; published online 26 January 2009)

Recording analog signals using photonic time-stretch technique in a mode which combines advantages of continuous signal capture, as in real-time analog-to-digital converters (ADCs), and very high bandwidth capability of (equivalent-time) sampling oscilloscopes, is proposed. It is shown that the eye diagrams of high speed serial data can be acquired at least 100 times faster than the fastest capture rates today. Unlike conventional sampling scopes, this technique can capture ultrafast dynamics of repetitive signals, nonrepetitive signals, and rare events. Experimentally, 45 Gbit/s data eye diagram measurement is demonstrated. © *2009 American Institute of Physics*.

[DOI: 10.1063/1.3075057]

With ever increasing speeds of electronic circuits and data rates in communications systems, the demand for higher performance digitizers has become paramount. High bandwidth digitizers are needed in defense applications such as radars and in detection of electromagnetic pulses.[1] In science, such digitizers are central tools in particle accelerator or x-ray free electron laser systems,[2] as well as in time resolved fluorescence microscopy. In telecommunications, fast digitizers are used for measuring eye diagrams to characterize impairments in high speed serial links. Availability of high speed digitizers for fault diagnostic techniques, such as time-domain reflectometry (TDR),[3] obviate the necessity of network analyzers that require slow frequency domain sweeping. TDR simplifies the measurement techniques and improves speeds many times. However, all such applications require very high resolution in time making the high bandwidth digitizers invaluable.

Digitizers are broadly categorized into two classes. Equivalent-time digitizers (or sampling oscilloscopes) rely on repetitive or clock synchronous nature of the signals to reconstruct them in time. In a sampling oscilloscope, the signal is sampled at megahertz frequencies (typically 100 kHz to 10 MHz) and then reconstructed digitally, requiring a long time to obtain the original signal with high fidelity [Fig. 1(a)]. While they can reach equivalent time bandwidths of up to 100 GHz, they are not capable of capturing nonrepetitive waveforms. Even for repetitive signals, they cannot provide real-time information about the dynamics that occur at rates faster than a few MHz. Equivalent-time sampling is similar to the strobe light technique used for measuring cyclical events, which are much faster than the speed of the detector. For example, flashing strobe light on a vibrating tuning fork periodically can make it look stationary or very slowly vibrating. The second type of digitizers, called real-time digitizers [Fig. 1(b)], continually sample the signals as they change, but have input bandwidths limited to only a few gigahertz. Currently, the fastest available real-time digitizer has a bandwidth of 18 GHz (LeCroy model SDA-18000).

In this letter, we introduce the equivalent time operation of the photonic time-stretch (TS) analog-to-digital converter (ADC).[4–6] In contrast with a sampling scope, which captures only a single sample at a time, this instrument records segments in real time, each consisting of many samples [Fig. 1(c)]. It then displays them on an equivalent time scale. Because it captures an entire segment in real time, the Time-Stretch Enhanced Recording (TiSER) scope can record ultrafast nonrepetitive dynamics that occur within the segment period. Such fast events cannot be observed by a sampling scope because it has no real-time capability, or by a real time digitizer because of its limited bandwidth. Therefore, the TiSER scope fills the performance and functional gap between sampling scopes and real-time digitizers. Figure 2 shows the comparison of the real-time bandwidth of the TiSER scope relative to the incumbent sampling scopes and a real-time digitizer. The example assumes a real-time digitizer with 1.5 GHz bandwidth (BW_{ADC}) used alone [Fig. 2(a)] and used as the backend digitizer in the TiSER scope [Fig. 2(b)]. Here, segments (snap shots) of the input signal, each spanning several samples, are captured asynchronously with respect to the signal, as shown in Fig. 1(c).

In a TS system, the effective bandwidth of the rf signal is compressed prior to digitization by stretching the waveform

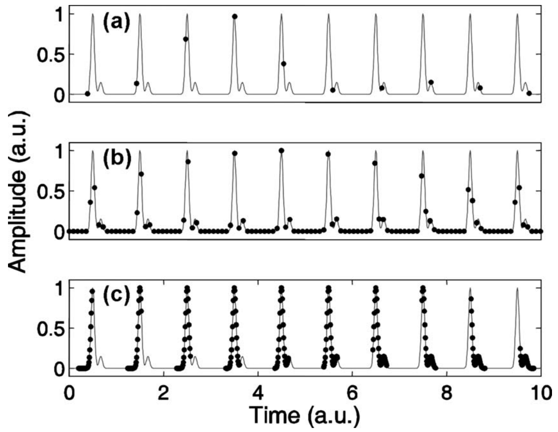

FIG. 1. Different sampling techniques are shown. (a) An equivalent-time oscilloscope samples signals at very slow rates and can reproduce signals only of repetitive nature. (b) A real-time digitizer samples signals continuously but has limited bandwidth. (c) The TiSER scope can capture very high bandwidth signal segments in real-time and quickly reproduce them on equivalent time scales.

[a)] Electronic mail: shalabh@ee.ucla.edu.
[b)] Electronic mail: jalali@ucla.edu.

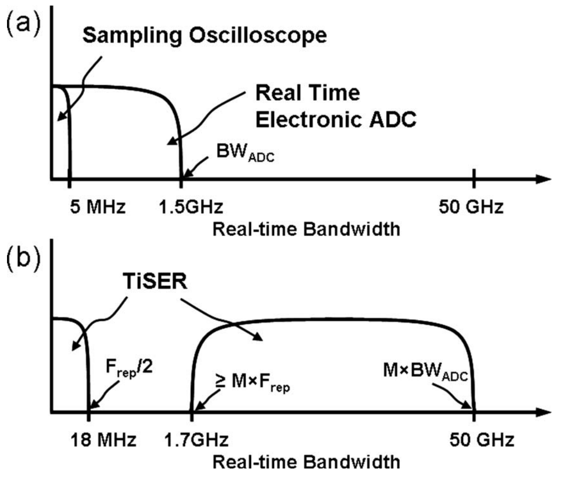

FIG. 2. Bandwidth limitations in different sampling technologies. (a) Typical real-time bandwidths of a real-time and an equivalent-time digitizer are shown. (b) Bandwidth coverage of segments captured by TiSER (which uses the real-time backend digitizer in (a). M: stretch factor. F_{rep}: laser repetition frequency.

in time, as shown in Fig. 3. The resultant signal can be recorded by a slow real-time electronic ADC. To accomplish this, the rf signal is modulated over a pulse of linearly chirped optical carrier obtained by dispersing a femtosecond pulse from a mode-locked laser (MLL). Propagation through dispersive fiber stretches the pulse in time. The photodetector converts this optical signal back to electrical domain and the resultant rf signal is a stretched replica of the original signal with much reduced analog bandwidth. TS or bandwidth compression factors of up to 250 have been achieved, and electrical signals up to 95 GHz have been digitized in real time at 100 fs intervals using the TS-ADC.[7] As in a conventional sampling scope, time-stretching also distorts the signal, but these distortions can be removed digitally.[5,8–11] Thanks to digital postprocessing algorithms, the bandwidth of the TiSER at present is limited only by the bandwidth of the electro-optic modulator, which can be well over 100 GHz.[12]

In TiSER, each segment of the input waveform is captured by a chirped optical pulse. For nth laser pulse, the signal recorded at absolute time instant t (by a real-time digitizer) is displayed on time axis of the scope window at the time point,

$$t_{\mathrm{out}} = \left(nT_{\mathrm{laser}} + \frac{t - nT_{\mathrm{laser}}}{M} \right) \text{ modulo } T_{\mathrm{trigger}}. \tag{1}$$

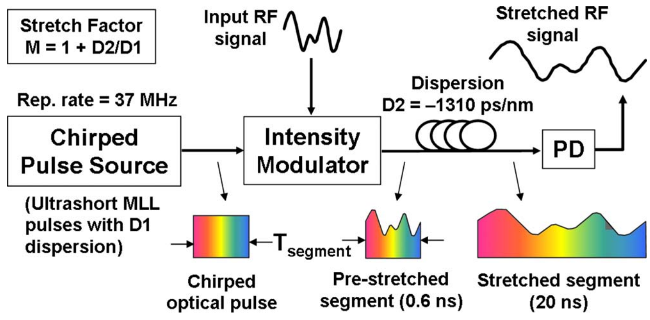

FIG. 3. (Color online) Schematic of the photonic TS preprocessor. The rf signal is modulated over a linearly chirped optical pulse. Signal obtained at the photodetector output is a TS replica of the original rf signal.

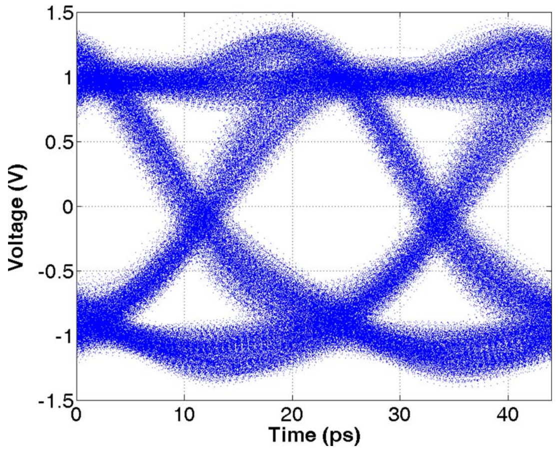

FIG. 4. (Color online) Eye diagram of 45 Gbit/s PRBS data captured in 10 μm using TiSER scope with a stretch factor of 34. The experiment used a 50 GS/s commercial real-time digitizer with 16 GHz analog bandwidth. However, a 1.5 GHz low pass filter was applied in software to emulate it as a monolithic commercial off-the-shelf ADC.

Here, T_{laser} is the pulse repetition period of the laser, T_{trigger} is the period of the trigger signal (eye diagram time window) that is synchronous with the signal to be captured, and M is the stretch factor. The expression in the braces converts the time scale of the captured (stretched) signal segments to original signal time scale (division by M is for unstretching the segments). The *modulo* operation generates the eye diagram by chopping and overlaying these time segments. The trigger and laser periods can be obtained separately in software or by using digital phase locking.

Using the TiSER scope, the eye diagram of a 45 Gbit/s pseudorandom bit sequence (PRBS), generated by Anritsu pattern generator MU181020A, has been obtained (as shown in Fig. 4). The system consisted of a TS preprocessor with a stretch ratio of 34 and a backend electronic digitizer with 1.5 GHz analog bandwidth (i.e., 3-GS/s Nyquist sampling rate). Therefore, time stretching increased the effective analog bandwidth to 50 GHz and Nyquist sampling rate to 100 GS/s, respectively. The segment length, given by the length of the chirped optical pulse that captures the analog signal was 0.6 ns (Fig. 3). As a result, every captured segment consisted of 60 independent samples, which repeated every 37 MHz (pulse repetition period of the laser). Hence the system had a sample collection rate of 60×37 MHz $= 2.2$ GHz. The highest sampling frequency in a sampling scope available today is only 10 MS/s. Therefore, in our experiments, the TiSER achieved equivalent time sampling at approximately 220 times faster speeds than the fastest sampling scope available.

Eye diagrams give vital information about signal integrity in a serial data communication link. Jitter, measured by variations in zero-crossing transitions in the eye diagram, indicates channel response and phase noise characteristics of the transmitter. Measurement of jitter for long pseudorandom data patterns is required for ensuring better than 10^{-12} BERs (bit error rates), which takes a very long time. Eye diagram measurements done using BER tester scopes can take from a few hours to more than a day to scan the data eye completely.[13] For faster results, jitter is analyzed statistically by obtaining eye diagrams from a sampling scope. However, only a very small fraction of samples recorded by the sampling scope lie close to the zero crossings and can be reliably

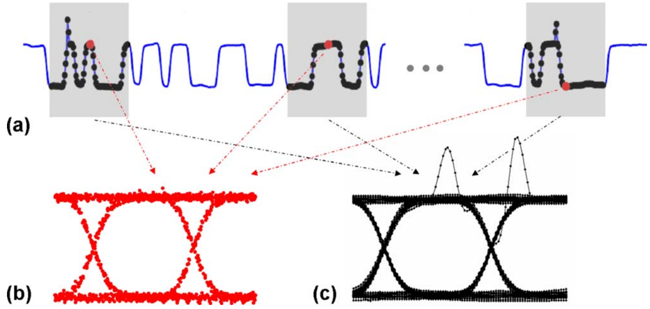

FIG. 5. (Color online) Comparison between different digitizing mechanisms. (a) Serial digital data waveform (in blue) can be captured by real-time digitizers only if data rates are low. (b) Data eye captured by a sampling oscilloscope. (c) Data eye captured by TiSER scope, which can potentially capture the rare spikes as well.

included in the jitter histogram, making this process also very slow. On the other hand, each segment from the TiSER has a continuous capture of samples. Since the samples are connected, signal amplitudes within sample-to-sample time intervals can be obtained by interpolation. As a result, time points for all zero crossings occurring within one segment can be obtained, improving jitter histogram acquisition times by three to four orders of magnitude when compared to today's fastest sampling scopes. This improvement is even higher than improvement in sample acquisition rate. Additionally, fluctuations that occur over very short time intervals, such as short time jitters, can be analyzed by measuring the data periods. For diagnostics, frequencies of the captured signals can also be equalized for the signal within a segment.

The TiSER scope can also be useful in capture of rare events and their dynamics in high data rate communications. For example, Fig. 5 shows a hypothetical data stream with rare spikes. Because the data is captured in real time within a segment by TiSER, there is a substantial probability of capturing such rare events, which is not possible with sampling scopes because of their limited sample rates.

TiSER scope can achieve very high sensitivity in case of purely repetitive waveforms by averaging. For example, in automatic test equipment employing TDR, waveform averaging over multiple scans can improve sensitivity enormously, or effectively reduce the test time significantly for a given sensitivity value. When the required sensitivity is not high and reflected pulses have short time apertures, even single shot TDR measurements can be performed (with proper synchronization), making these measurements extremely fast. From the device reliability perspective, high voltage spikes can damage the front-end of sampling oscilloscopes. On the other hand, since the front end is a $LiNbO_3$ modulator in TiSER, much higher voltages can be tolerated without damaging the system. Interestingly, the high voltage tolerance of electro-optic modulation has been exploited in creating rf front ends that are survivable in electromagnetically hostile environments.[14]

In conventional digitizers, jitter in the sampling clock[15] can become the dominant source of noise or the measured jitter. The noise added due to sampling jitter increases with signal frequency as it is proportional to the square of the signal frequency and the clock jitter. By virtue of time stretching, the effective signal frequency is reduced, which decreases the effect of electronic clock jitter by the stretch factor. It must be noted, however, that the laser jitter in the TS system has the same effect as the clock jitter in conventional digitizers.[16] Fortuitously, MLLs can have much lower jitter than electronic clocks. For example, fiber laser with only 18 fs timing jitter has recently been reported.[17] On the other hand, the best clock jitters achieved by electronic sampling clocks are of the order of 180 fs.[18] Therefore, from jitter and SNR perspective as well, the TiSER can prove to be very beneficial. In fact, advantages of time stretching made it possible to achieve a 10 GHz bandwidth ADC with a *world record* of 7.2 effective-bits of resolution.[8]

In conclusion, in this letter we introduced an oscilloscope that combines advantages of both real-time digitizers and sampling oscilloscopes. It offers the large equivalent time bandwidth of sampling scopes with much larger sample acquisition rates (220× demonstrated) and can capture short time transients that are missed by a sampling scope. It therefore compliments the two established technologies and fills an important performance gap between them. For proof of principle, the capture of a 45 Gbit/s pseudorandom data sequence eye diagram is demonstrated.

This work was supported by the DARPA PHOBIAC program (Grant No. N66001-07-1-2007). The authors thank Mr. Pat Murray from Anritsu for loaning their high-speed data pattern generator and the reviewer for very useful comments.

[1] M. Abrams, IEEE Spectrum **40**, 24 (2003).
[2] I. Wilke, A. M. MacLeod, W. A. Gillespie, G. Berden, G. M. H. Knippels, and A. F. G. van der Meer, Phys. Rev. Lett. **88**, 124801 (2002).
[3] S. Corey and A. Yang, IEEE Trans. Microwave Theory Tech. **43**, 2151 (1995).
[4] A. S. Bhushan, F. Coppinger, and B. Jalali, Electron. Lett. **34**, 839 (1998).
[5] Y. Han and B. Jalali, J. Lightwave Technol. **21**, 3085 (2003).
[6] B. Jalali and F. Coppinger, U.S. Patent No. 6,288,659 (September 11, 2001).
[7] J. Chou, O. Boyraz, D. Solli, and B. Jalali, Appl. Phys. Lett. **91**, 161105 (2007).
[8] S. Gupta and B. Jalali, Opt. Lett. **33**, 2674 (2008).
[9] S. Gupta, B. Jalali, J. Stigwall, and S. Galt, 2007 IEEE International Topical Meeting on Microwave Photonics, 2007 (unpublished), pp. 141–144.
[10] S. Gupta, G. C. Valley, and B. Jalali, J. Lightwave Technol. **25**, 3716 (2007).
[11] Y. Han, O. Boyraz, and B. Jalali, IEEE Trans. Microwave Theory Tech. **53**, 1404 (2005).
[12] D. Chen, H. R. Fetterman, A. Chen, W. H. Steier, L. R. Dalton, W. Wang, and Y. Shi, Appl. Phys. Lett. **70**, 3335 (1997).
[13] J. Patrin and M. Li, DesignCon, Proceedings of the High Performance System Design Conference, 2002 (unpublished).
[14] R. C. J. Hsu, A. Ayazi, B. Houshmand, and B. Jalali, Nat. Photonics **1**, 535 (2007).
[15] R. H. Walden, IEEE J. Sel. Areas Commun. **17**, 539 (1999).
[16] S. Gupta, G. C. Valley, R. H. Walden, and B. Jalali, arXiv:0901.2767v1.
[17] J. Chen, J. Sickler, E. Ippen, and F. Kärtner, Opt. Lett. **32**, 1566 (2007).
[18] A. Zanchi and F. Tsay, IEEE J. Solid-State Circuits **40**, 1225 (2005).