IMTC 2005 – Instrumentation and Measurement
Technology Conference
Ottawa, Canada, 17 –19 May 2005

One Tera-Sample/sec Real-Time Transient Digitizer

Yan Han and Bahram Jalali
Department of Electrical Engineering, UCLA
Los Angeles, CA 90095, USA
Email: jalali@ucla.edu

Abstract *– We demonstrate a real-time transient digitizer with a record 1 TSa/s (Tera-Sample/sec) sampling rate. This is accomplished by using a photonic time stretch preprocessor which slows down the electrical waveform before it is captured by an electronic digitizer.*

I. INTRODUCTION

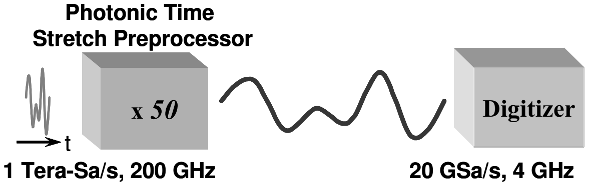

Fig. 1. Concept block diagram of TSa/s Digitizer.

The ability to digitize ultra-wideband waveform is urgently needed in many state-of-the-art instruments and communication systems. One example is the digital oscilloscope that is designed to capture ultrafast transients in real-time. The sampling rate of conventional electronic ADCs (Analog-to-Digital Converter), used in these instruments, is limited by the speed of the electronic circuitry, and in the case where the interleaving architecture is used, by the mismatches in the ADC array [1,2]. While the performance of electronic ADCs continues to improve, the sampling rate of a state-of-the-art system is currently about 20 GSa/s with ~5 ENOB (Effective Number Of Bits). Achieving TSa/s performance is clearly beyond the reach of conventional approaches. One potential solution to overcome the electronic bottleneck is to use photonic pre-processing. In particular, the photonic time stretch approach has proven to be an effective way to extend the sampling rate and bandwidth. Here, the high speed transient waveform is first slowed down and then captured by a conventional electronic digitizer [3,4]. In this paper, we demonstrate such a system that achieves a sampling rate of 1 TSa/s. As shown in Fig. 1, the system consists of a 50x time stretch pre-processor and a 20 GSa/s electronic digitizer. To the best of our knowledge, this is the first time that the real-time digitization at 1 TSa/s has been achieved.

II. TSA/S TRANSIENT DIGITIZER

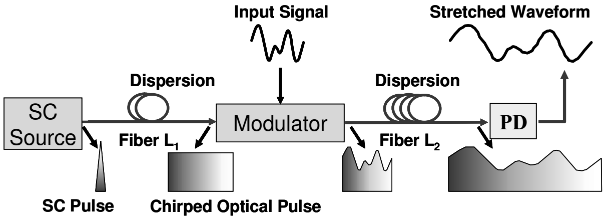

Fig. 2. Block diagram of a photonic time stretch preprocessor. SC: Supercontinuum; PD: photodetector.

The time stretch preprocessing, shown in Fig. 2, consists of three steps: time-to-wavelength transformation, wavelength domain processing, and wavelength-to-time mapping. Time-to-wavelength transformation occurs when the electrical signal modulates the intensity of a linearly-chirped optical pulse. At the output of modulator, the input signal's time scale is linearly mapped onto the optical wavelength. The second and third steps occur simultaneously when the waveform is broadened as it travels through the second dispersive optical medium and is subsequently photodetected.

The major obstacle to achieving a stretch factor of 50x is to overcome the frequency fading that is associated with dispersive propagation. This phenomenon has been described in details elsewhere [4]. Briefly, it occurs due to the dispersion-induced interference between the two modulation-sidebands. We overcome this problem using the recently proposed phase diversity technique, where two stretched waveforms with complementary fading characteristics are realized and combined to eliminate the bandwidth limitation [5]. Another practical concern is the large loss of dispersive fiber required to achieve such a large stretch factor. This problem is mitigated by the judicious use of optical amplification in such a manner as to optimize the overall signal to noise ratio while avoiding degradation from optical nonlinearity.

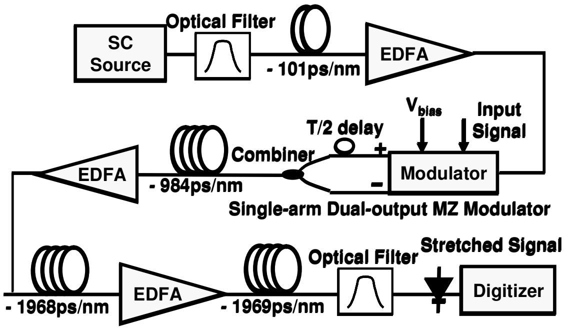

Fig. 3. Experiment setup of TSa/s digitizer with a 50 x photonic time stretch preprocessor. EDFA: Erbium-Doped Fiber Amplifier.

The block diagram of experimental setup for a 50 times photonic time stretch preprocessor is shown in Fig. 3. Ultrashort and broadband optical pulses are produced, with repetition period *T*, through the SuperContinuum (SC) generation process. Around 15 nm of the optical spectrum at (centered at 1590 nm) is sliced using an optical bandpass filter and is used in the experiment. After being linearly chirped by propagation in a spool of dispersive fiber, a given pulse enters the electro-optic modulator where it captures the electrical transient. The chirped optical pulse has finite amplitude variations resulting in distortion of the captured signal. The distortion is removed by using a reference waveform and digital filtering [4]. The modulator has complimentary outputs, and after delaying one by T/2, the outputs are combined and stretched together in the second dispersive fiber. The first fiber has a total dispersion of D_1 = -101 ps/nm, creating a chirped optical pulse with around 1.5 ns duration. The second fiber has a total dispersion of D_2 = -4921 ps/nm. The stretch factor is give by $(D_1+D_2)/D_1$ = 50. To minimize the noise contributed by the optical amplifiers, the waveform is filtered by an optical bandpass filter being photodetection. The detected waveform is subsequently captured by a Tektronix TDS7404 (4GHz analog bandwidth, 20GSa/s) real-time digitizer. The effective sampling rate of this system is 20 GSa/s x 50 = 1 TSa/s and the intrinsic input analog bandwidth is 4 GHz x 50 = 200 GHz. Practically, the input bandwidth is limited by the bandwidth of the electro-optic modulator to approximately 50 GHz.

Figure 5 shows the real-time capture of a 48 GHz tone at 1 TSa/s. The measured voltage Full Width Half Maximum (FWHM) time aperture is 1.1 ns. The measured stretch factor is 50.5. To measure the SNR, similar measurements using 200 optical pulses are obtained. Over a 10 GHz digitally filtered bandwidth, the average SNR (over 200 measurements) within the time aperture is 22.7 ± 1.08 dB corresponding to 3.5 ± 0.2 ENOB. Measurements at other input frequencies resulted in up to 4.2 ENOB.

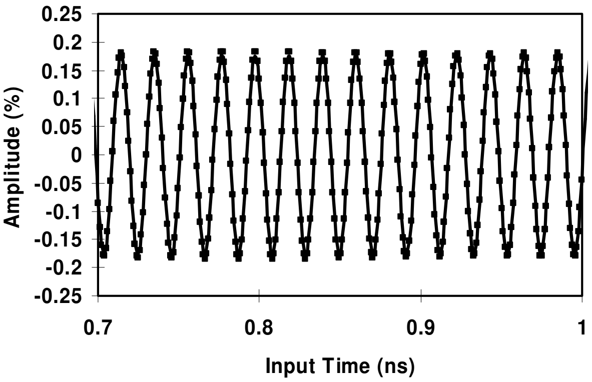

Fig. 4. The measured 48 GHz sinusoid signal after time stretch preprocessing. Lines are obtained using standard sine curve fitting.

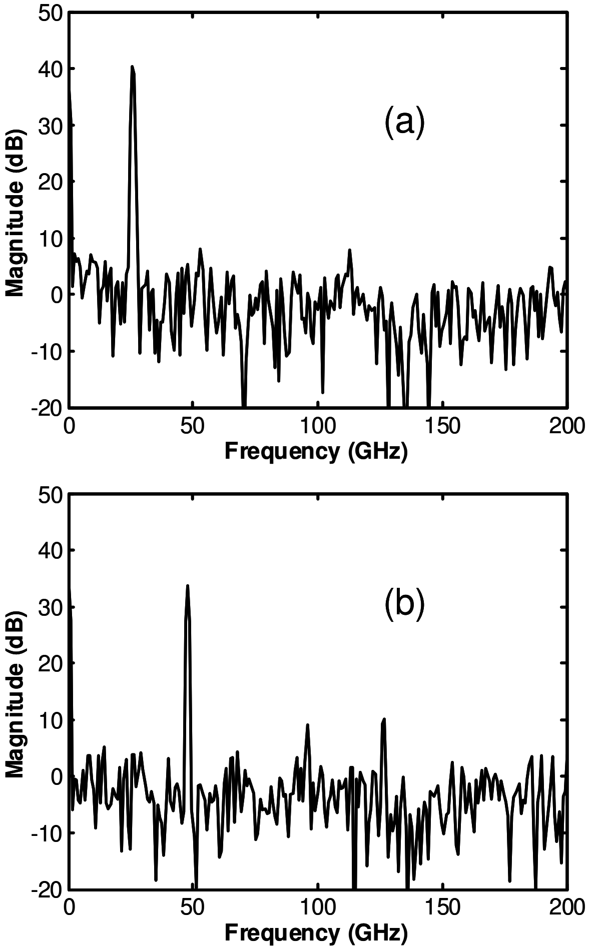

Fig. 5. The digital magnitude spectrum of captured signals at 26GHz and 48 GHz.

The digitizer performance is also measured in the frequency domain. Fig. 5 (a) and (b) show the digital spectrum of a 26 GHz tone and a 48 GHz tone, respectively. The Hanning window was used before discrete Fourier transform [6]. In Fig. 5 (b) the spurious tone at 125 GHz (2.5 GHz after 50x stretch) is due to the electronic digitizer and is not caused by the photonic time stretcher. We note that no digital filter was used to obtain the data in Fig. 5, hence the input analog bandwidth of these spectrums is 0 – 200 GHz. A 2nd harmonic distortion tone is observed in Fig. 5 (b). This arises due to dispersive propagation in the optical fiber and has been previously predicted using theoretical modeling [4]. Post distortion performed in the digital domain can potentially mitigate this type of distortion.

III. CONCLUSION

In summary, the photonic time stretch technique has been used to realize a real-time transient digitizer with 1 TSa/s sampling rate. The system has a FWHM time aperture of 1.1 ns. Measured over a 10 GHz bandwidth, the ENOB of the system ranges from 3.5-4.2 bits depending on the input signal frequency.

ACKNOWLEDGEMENT

The authors would like thank Dr. Ozdal Boyraz for helpful discussions.

REFERENCES

[1] R. H. Walden, “Analog-to-digital converter survey and analysis,” IEEE Journal on Selected Areas in Communications, vol. 17, no. 4, pp. 539-550, Apr 1999.

[2] W. C. Black, and D. A. Hodges, “Time interleaved converter arrays,” IEEE Journal of Solid-State Circuits, vol. SC-15, pp. 1022-1029, Dec. 1980.

[3] F. Coppinger, A.S. Bhushan, and B. Jalali, "Time magnification of electrical signals using chirped optical pulses", Electron. Lett., vol.34, no.4, pp.399-400, Feb. 1998.

[4] Y. Han and B. Jalali, “Photonic Time-Stretched Analog-to-Digital Converter: Fundamental Concepts and Practical Considerations”, IEEE/OSA Journal of Lightwave Technol., vol. 21, no. 12, pp. 3085-3103, 2003.

[5] Y. Han, O. Boyraz and B. Jalali, “Real-time A/D conversion at 480 GSample/s using the phase-diversity photonic time-stretch system,” International Topical Meeting on Microwave Photonics 2004, Oct. 4-6, Ogunquit, Maine, USA.

[6] J. G. Proakis, and D. Manolakis, Digital Signal Processing: Principles, Algorithms and Applications, Prentice Hall; 3rd edition (October 5, 1995).