Femtosecond real-time single-shot digitizer

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We demonstrate a single-shot digitizer with a 10 Tsample/s sampling rate. This feat is accomplished with a photonic time stretch preprocessor that slows down the electrical waveform by an unprecedented factor of 250 before it is captured by a commercial electronic digitizer. To achieve such a large stretch factor, distributed Raman optical amplification is realized inside the dispersive element that performs the time stretch. © *2007 American Institute of Physics*.
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Digital signal processing (DSP) has become an indispensable tool in research, communication, and even consumer electronics. Essential for digital signal processing is the analog-to-digital converter (ADC), otherwise known as digitizers, which converts analog signals of the real world into the binary sequences to be processed by DSP. The most difficult signals to digitize are short nonrepetitive transient waveforms, because all the samples required to satisfy the Nyquist criterion must be captured in real time and in a single shot. Examples of applications for such digitizers include characterization of picosecond and subpicosecond electronic devices,[1] characterization of subpicosecond relativistic electron bunches intended for use in advanced accelerators and free-electron lasers,[2–5] and characterization femtosecond electron sources being developed for imaging.[6,7]

Several promising techniques are being developed for digitizing ultrafast waveforms in real time. Electro-optic methods, used for characterizing transient electron bunches, operate by mapping the time domain signal into the spatial-spectral domains.[4] Here, the time resolution depends on the frequency resolution of the spectrometer. Another method achieves high temporal resolution by measuring a nonlinear interaction through optical cross correlation.[5] Both techniques are based on time-wavelength-space transformation and require a parallel array of detector/digitizer channels to capture the signal. It is well known that interchannel mismatch error sets an upper bound on the dynamic range and hence the resolution of parallel arrays.[8,9] Approaches that permit digitization of ultrafast transient using a single channel are of interest because they avoid this limitation.

One such approach operates by stretching of the time scale of an ultrafast transient permitting its capture with a single digitizer channel.[10–12] By slowing down the signal, the sampling rate and input bandwidth of any ADC can be multiplied by orders of magnitude, allowing ultrashort electrical transients to be digitized directly in the time domain using a single digitizer. In addition, the time stretch reduces the impact of the timing jitter of the ADC's sampling clock.[12] This technique has previously achieved real-time digitization at picosecond intervals.[13]

In this letter, we present a time stretch analog to digital system which achieves real-time digitization at 100 fs intervals. The record performance is realized by incorporating distributed Raman amplification within the time-stretch processor. This technique makes it possible to stretch an electrical transient by an extremely large factor of 250, which in turn leads to its digitization at 100 fs intervals. Raman amplification is the key to overcoming the prohibitively large loss that would have otherwise occurred when the signal is stretched by such a large factor.

Figure 1 is a simplified overview of the time stretch system. Before the optical preprocessing, the sampling rate of the electronic ADC is insufficient to capture the high frequency content of the signal; however, after optical preprocessing, the bandwidth is compressed to within the limits of the ADC. The time stretch process may be described in three steps: time-to-wavelength (t-to-λ) transformation, wavelength domain processing, and wavelength-to-time (λ-to-t) transformation.[12] The time-to-wavelength transformation occurs when the electrical signal modulates the intensity of a linearly chirped optical pulse; at the output of the modulator, the temporal profile of the input signal is linearly mapped onto the optical wavelength of the chirped pulse. The second and third steps occur simultaneously in the second dispersive element: as the chirped optical pulse encounters additional

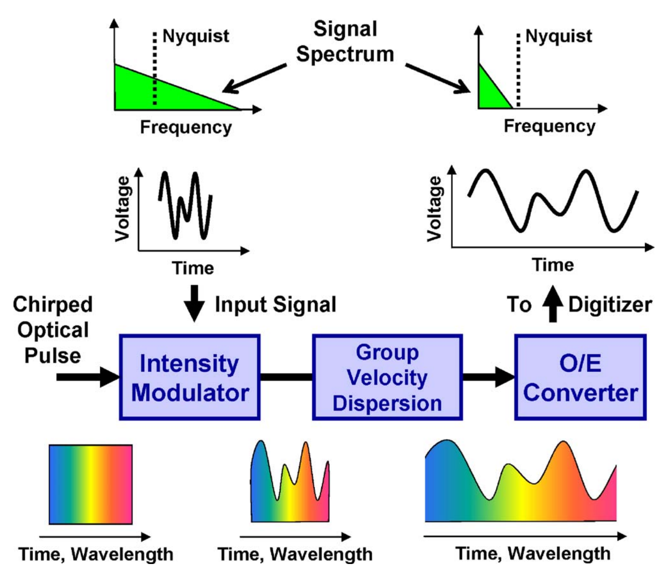

FIG. 1. (Color online) Conceptual diagram of the optical preprocessor. An ultrafast electrical signal is modulated onto the envelope of a chirped optical pulse which is further chirped and photodetected. As a result, the output electrical signal is time stretched, and therefore compressed in bandwidth, to within the Nyquist limit of a real-time oscilloscope.

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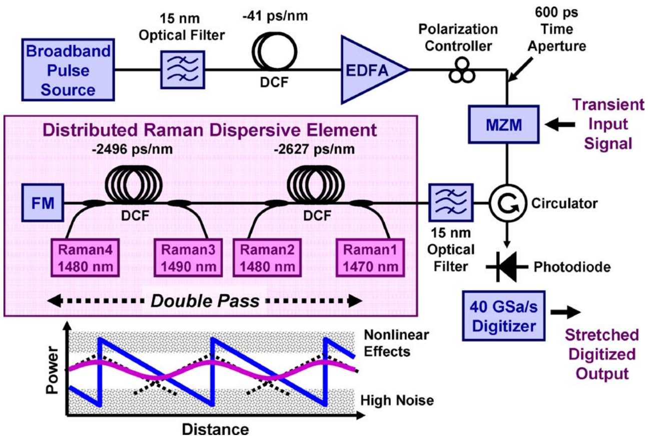

FIG. 2. (Color online) Experimental setup of the optical preprocessor with a 250 times bandwidth compression factor. A distributed Raman amplification scheme is employed to overcome 60 dB of insertion loss in the dispersive element. Below, a conceptual diagram shows the advantage of distributed amplification (sinusoidal curve) over discrete amplification (sawtooth curve), e.g., a chain of EDFAs, in avoiding undesirable regions of high noise and optical nonlinearities. The dashed lines show the propagation of the bidirectional Raman pump lasers. DCF: dispersion compensating fiber; EDFA: erbium-doped fiber amplifier; MZM: Mach-Zehnder modulator; FM: Faraday mirror.

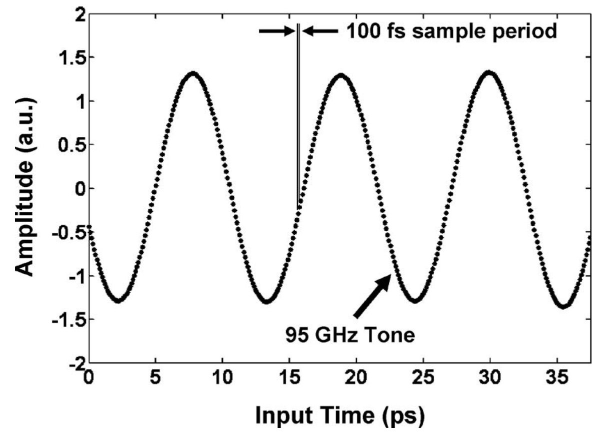

FIG. 3. A 95.3 GHz klystron tone is digitized in real time at 10×10^{12} samples/s.

chromatic dispersion, the modulated envelope undergoes temporal stretching. Serendipitously, higher order dispersion in optical fiber has no impact on time stretch as long as the fibers before and after the modulator have identical dispersion characteristics.[12] Finally, the stretched electrical waveform is extracted by a photodetector.

A central challenge in achieving large stretch factors is the large loss inherent to the dispersive elements. If the standard single mode fiber (SMF-28) is used in the present system (details discussed later), the loss for the second dispersion stage will be an enormous 124 dB. A superior dispersive medium is the commercial "dispersion-compensating fiber" (DCF), which reduces the loss to 62 dB. Although much improved, this is still a very large loss that needs to be compensated by amplification. Previous implementations of the optical preprocessor have utilized a discrete amplification scheme for this purpose.[13] However, this is not ideal. The power versus distance inset in Fig. 2 illustrates the disadvantage of discrete amplification for compensating large loss. A discrete amplifier, such as the erbium-doped fiber amplifier (EDFA), boosts the signal at discrete points in the optical chain. Discrete amplification negatively impacts the system's signal-to-noise ratio (SNR) in two ways: (1) the signal is amplified from its weakest power level, where noise degradation is most significant, and (2) the rapid and large increase in optical power could induce optical nonlinear effects in the fiber. The latter causes distortion of the stretched signal amplitude by an intensity-dependent nonlinear phase shift.[13] However, if the span consists of distributed raman amplification, then gain would exist throughout the entire dispersive medium, alleviating the noise and nonlinear impairments found in discrete amplification.[14,15]

Figure 2 describes the experimental block diagram of the optical preprocessor. A linearly chirped 600 ps optical pulse with a bandwidth of 15 nm is generated by feeding the spectrally filtered output of a broadband optical pulse source into a dispersive DCF fiber with −41 ps/nm dispersion. Next, a time-limited input signal is intensity modulated onto a chirped optical pulse by a single-electrode, dual-output Mach-Zehnder modulator (MZM). An EDFA and a polarization controller are used to compensate for the losses in the MZM and maximize modulation depth, respectively. The modulated chirped optical pulse is then further dispersed using −10 246 ps/nm double-pass DCF span, causing the modulated envelop (i.e., input signal) to be temporally magnified. The stretch factor M is determined by the amount of dispersion used before, $D1$, and after, $D2$, the intensity modulator by the following relationship: $M=(D1+D2)/D1$.[12] For this particular demonstration, the stretch factor is approximately 250.

To create Raman amplification within the dispersive fiber, four high-power optical pumps located at 1470, 1480, 1490, and 1480 nm are coupled at regular length intervals in a counter-propagating configuration. Using this scheme, the net gain of the dispersive stage is set to zero with a spectral profile variation of ±1 dB over the entire signal band of interest. An optical circulator and fiber-coupled Faraday mirror are used to produce a double pass configuration, while an optical bandpass filter is used to eliminate out-of-band amplified spontaneous emission noise. A counterpropagating pumping scheme was chosen to improve the SNR and to reduce the nonlinear distortion penalty. At the output of the optical preprocessor, a fast photodetector demodulates the stretched optical envelop and extracts the analog electrical signal. The output of the photodetector is then digitized by a 40 Gsample/s Agilent (DSO81304B) real-time digitizer. With the 250 stretch factor, the effective sampling rate is 10 Tsample/s.

Figure 3 shows real-time 10 Tsample/s digitization of a 95.3 GHz signal generated by a klystron. An IEEE standard method to characterize the performance of an ADC is the sine curve fit which allows the extraction of the signal to noise ratio, and hence the effective number of bits (ENOB) ($SNR=6.02\times ENOB+1.76$ dB).[16] As expected, the SNR so obtained depends on the bandwidth over which the noise is measured. Over a prestretched bandwidth of 50 GHz, the SNR of the digitized signal is 28.8±1.5 dB, which is equivalent to 4.5±0.2 ENOB. Compared to the 1 Tsample/s time-stretch experiment reported previously,[13] the SNR is higher by 6.05 dB (1 ENOB) over the same poststretch bandwidth. This is remarkable in light of the fact that the five times higher stretch ratio realized here results in an additional 30 dB of loss in the dispersive fiber. This further exemplifies

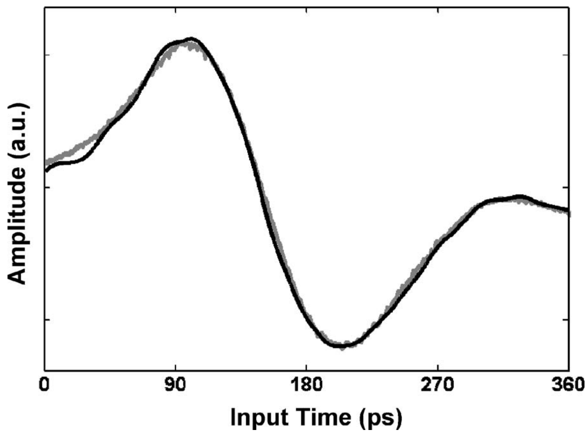

FIG. 4. A single-shot 100 ps electrical impulse digitized at 100 fs sampling intervals. The real-time single-shot waveform (shown in black) is filtered over 50 GHz and compared to a repetitive version recorded by a 50 GHz sampling oscilloscope (shown in gray).

the importance of having distributed Raman amplification within the dispersive medium to create a transparent high-dispersive device.

In the present work, the system input bandwidth is limited by the Mach-Zehnder modulator. Further improvement in modulator technology will allow better utilization of the ultrahigh sampling rates offered by this system. In the absence of such improvements in modulator technology, the extra sampling rate above the Nyquist value can be exploited to improve the digitizer SNR. In a Nyquist type converter, such as the one employed here, every octave of oversampling yields 0.5 effective number of bits improvement in resolution. Ultimately, the maximum input signal frequency is determined by the optical bandwidth of the laser source; distortion will occur when the electrical frequency is not much less than the optical bandwidth.[12] In the current system, a 1.8 THz optical bandwidth corresponds to an allowable signal frequency of several hundred gigahertz. A more practical limit on maximum signal bandwidth is set by a dispersion induced frequency fading effect.[12] Fortunately, this effect can be mitigated using a single-sideband modulation as well as phase diversity by the complementary outputs of the modulator.[12]

To further explore the capabilities of the system, a nonrepetitive 100 ps electrical impulse is slowed down and digitized at 100 fs sampling intervals, as shown in Fig. 4. The impulse is created by a broadband triggerable rf signal generator. The digitized real-time single-shot waveform is filtered over 50 GHz and compared to a waveform recorded by a 50 GHz sampling (non-real-time) oscilloscope. For the latter, the rf signal generator is operated in a repetitive mode. The single-shot real-time waveform exhibits the general characteristics of the averaged reconstruction produced by the sampling oscilloscope. The experiment demonstrates the ability of the time stretch ADC in capturing single-shot wideband electrical waveforms in real time. For applications involving randomly arriving signals, a triggerable continuum pulse source may be used.[17]

In summary, we have demonstrated temporal stretching of an electrical waveform by a record ratio of 250, followed by a real-time digitization at 10 Tsample/s. The key was the use of distributed Raman amplification within the dispersive medium to create a transparent high-dispersive device. The ability to digitize signals with femtosecond sampling periods using conventional digitizers will provide scientists and engineers with a tool to capture and analyze nonrepetitive electronic waveforms.

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