An Optical Replicator for Single-Shot Measurements at 10 GHz With a Dynamic Range of 1800:1

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Abstract—High-dynamic-range, single-shot pulse shapes were measured by temporally stacking pulses in a passive, fiber-optic network. The 256 replicas were combined to produce optical shapes with a bandwidth of 10 GHz and a dynamic range of 1800:1. The high fidelity of this system enabled the characterization of arbitrary electrical pulses that were used to shape the optical pulse via an electro-optic modulator with a reduced dynamic range of about 60:1.

Index Terms—Electro-optic effects, microwave measurements, optical fiber measurements, signal processing, signal restoration.

I. INTRODUCTION

OPTICALLY assisted measurements of electrical signals have been carried out for more than 30 years [1] to overcome the limitations on speed and dynamic range inherent in oscilloscopes. A number of techniques have been used, including sampling gates based on photoconductive Si switches [2] and the electro-optic Pockels effect [3]. In these methods, the sampling gates are derived from optical pulses that can be as short as 100 fs. Thus, repetitive electrical signals can be characterized on time scales that are much shorter than can be achieved with conventional electronic instruments such as transient digitizers and oscilloscopes. The disadvantages of these techniques are the requirements for a short-pulse laser system and the inability to operate in single-shot mode. The early optically assisted measurements were pump-probe techniques where a single optical pulse sampled a small portion of each of the repetitive train of electrical pulses. Other schemes have used integrated fiber-optic components to create optical replicas that can be sampled at different time delays [4]. The primary aim of these schemes is to increase the number of temporal sampling points beyond that achieved by conventional electronic instruments. Although these techniques can be applied in single-shot mode, the signal-to-noise ratio (SNR) and dynamic range (DR) are severely degraded by the sinusoidal transfer function that relates the electrical input to the output. Furthermore, the

efficacy of these techniques to increase the temporal density of sampling points is mitigated by the steady increase in the sampling rate achieved by conventional electronic instruments. Currently 50 GS/s is available from commercial instruments [5]. As such, single-shot electrical pulse shape measurement requires techniques that do not sacrifice the fidelity of the signal. Recently, an all-fiber-optic network was used to optically replicate pulses, demonstrating a 3-bit enhancement to the DR for optical pulse shape measurements [6]. In this paper, optical pulse replication and electro-optics techniques are combined to achieve high-bandwidth and high-fidelity measurements of electrical pulses. The system is designed to operate in conjunction with conventional electronic analog-to-digital converters while maintaining the highest commercially available temporal bandwidth (BW) and simultaneously increasing the SNR and DR. At 10 GHz, the commercial instruments have a DR of 30 to 60 in single-shot mode. The system described here achieves a DR of approximately 1800:1 for an optical pulse and 60:1 for arbitrary electrical pulses that compare well with the state of the art [1], [7].

The technique presented in this paper utilizes the advantages of the previously cited research to characterize single pulses in a regime that is difficult to achieve with conventional oscilloscopes. This regime is comprised of pulses with durations of 0.1 to 10 ns, temporal features with bandwidths up to 12 GHz, and signal levels spanning three orders of magnitude. To produce signals with these characteristics, a shaped electrical pulse drives an electro-optic modulator (EOM) that produces a shaped optical pulse. A train of replicated optical pulses is generated and measured with a photodiode (Discovery Semiconductor DSC30S) and a digital sampling oscilloscope (Tektronix TDS6154c). The optical replicas are temporally aligned and averaged (or summed) to produce signals with a dynamic range of 1800:1. An inverse transfer function is applied to the optical pulse to infer the input electrical pulse. This system enables single-shot acquisition of electrical transients with enhanced SNR. It also provides electrical isolation between the detector and the electronic recording device via the optical system. This isolation feature makes such a system particularly useful for measuring electrical signals in an environment with high levels of electromagnetic interference (EMI) and ionizing radiation, as can be found in large, low-repetition-rate laser systems such as OMEGA EP [8] at the University of Rochester.

II. EXPERIMENTS

Fig. 1 shows a diagram of the experimental setup. A fiber laser, operating at a 1053-nm wavelength, produces continuous-wave (cw) laser radiation. This light passes through a

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Fig. 1. A cw fiber-optic laser is shaped by an EOM. The modulated pulse is then amplified before being replicated and detected by a photodiode and digital oscilloscope.

Mach-Zehnder integrated electro-optic modulator fabricated on LiNbO_3 . This is a two-stage modulator. A square electrical gate pulse is applied to the first modulator to eliminate any light outside of the temporal duration of the electrical pulse. This step is necessary because the optical replicator will support only a fixed, 12.5-ns acquisition window. Extraneous light outside this temporal window will cause interference among replicas. The electrical pulse to be measured is fed into the second stage of the modulator. The power transmitted through the second modulator, $P(t)$, is given by

$$P(t) = P_0 \times \sin^2 \left[\frac{V(t) \times \pi}{2 \times V_\pi} + \phi \right] \quad (1)$$

where P_0 is the optical power entering the modulator, $V(t)$ is the applied voltage, and V_π is the half-wave voltage of the modulator. The phase term ϕ has two components: The first component arises from the intrinsic optical-path difference between the two arms of the interferometer; the second component is induced by an applied dc voltage. In these experiments the applied dc voltage was actively controlled (± 10 mV) to maintain zero total phase ($\phi = 0$). V_π is approximately 5 V and a 50-mV change causes a noticeable distortion in the pulse shape. With this arrangement, well-characterized electrical pulses are used to produce stable optical pulses.

The optical pulse is amplified to ensure that each of the replicas has enough photons to overcome shot noise in the detector. A fiber amplifier [9] and a regenerative amplifier [10] are used to amplify the signal, providing 1 mJ of optical energy at $\lambda = 1.053$ nm for seeding the OMEGA Laser System [10], [11] and ~ 1 μJ for our measurement. A stand-alone measuring system would use a much simpler, cheaper, and less-energetic fiber amplifier in place of the regenerative amplifier. Alternatively, the amplifier could be placed in front of the EOM or incorporated as part of the input laser to eliminate the possibility of amplification-induced optical pulse shape distortion. The distortion induced by the regenerative amplifier can be characterized by a single parameter, the square-pulse distortion (SPD). A square pulse entering the regenerative amplifier will, in the general case, emerge as a pulse with an exponentially

decaying profile. However, the regenerative amplifier is operated as described in [10], where the effective time constant of the decay is much greater than the pulse length resulting in a linearly decaying ramp. The ramp has a normalized value of 1 at the beginning of the optical pulse and $(1.0-S)$ at the end of the pulse, where the parameter S is the SPD and is constrained to be between 0 and 1. For all waveforms shown in this paper $S = 0.15$. To determine the optical pulse shape that entered the regenerative amplifier, for any arbitrary pulse shape of duration τ , it is necessary to multiply the output waveform by the function

$$1 + S \times t/\tau \quad (2)$$

where t is the time measured from the beginning of the pulse. The point-to-point rms fluctuations of the pulse shape from the regenerative amplifier are less than 1% [10].

After amplification, the optical pulse is replicated by dividing its energy among 256 copies using fiber-optic splitters as shown in Fig. 2. A series of nine 2×2 fused-fiber splitters are spliced with $2^{m-1} \times 12.5$ - ns (where m ranges from 1 to 9) differential delay fibers between each stage. Each stage produces two pulse sets $2^{m-1} \times 12.5$ ns apart as input to the next stage. Since successive combinations use splits from previous combinations, the only place light is forfeited is in the last split. Ideally, all of the replicas should have the same amplitude, but variations in the 2×2 splitters result in a characteristic distribution of replicated amplitudes. The input optical pulse must have sufficient energy to allow all of the replicated pulses to be well above the noise in the detection system. It was necessary to keep the length of optical fiber preceding the replicator less than 30 m to keep the stimulated Raman scattering (SRS) threshold less than $37\text{-MW}/\text{cm}^2$ in the input fiber. For nanosecond-duration pulses, this permitted operation at approximately 70% of the photodiode saturation limit without SRS (sidebands < 40 dB). Once the pulse enters the replicator, the intensity immediately decreases by a factor of 2 and SRS is no longer a problem. The pulses are nominally spaced at 12.5 ns, although precise spacing is not critical since the computer software that recombines the pulses can be configured for any set of pulse separations. The

Fig. 2. The optical replicator consists of nine 2×2 fiber-optic splitters. At the m th stage, the first output is directly connected to the input of the following stage. The second output is connected to the second input of the following stage with an optical fiber that has a propagation delay of approximately $2(m - 1)$ times the interpulse spacing.

Fig. 3. The entire train of 256 pulses (a) produced by the optical replicator illustrates the characteristic distribution of pulse amplitudes caused by deviation in the splitter ratio from the idea 50/50. (b) Two pulses from the train.

256-pulse waveform is acquired from the digitizing oscilloscope with 25 ps resolution. Fig. 3 shows the raw data acquired from the oscilloscope.

The individual pulses from the pulse train are separated in post-processing by temporal binning. The fine temporal alignment between two pulses in the train is measured once, with subpixel resolution, by determining the peak of the cross-correlation with a parabolic fit. The fixed offsets are stored and used to reduce all subsequent data acquisitions. Once the alignment has been determined, the individual replicas can be combined to produce a single low-noise composite pulse shape. Normalizing the energy (area) of each of the replicas, the standard deviation of the pulse optical power at each power level is used to determine the SNR. $N_i(t_j)$ is the normalized waveform of the i th replica at sampling time, t_j . The SNR is determined by taking several identical measurements, $N_i(t_j)$, where $i = 1$ to 256 (identical being defined as occurring at the same time within

Fig. 4. Based on the SNR, the optical pulse emerging from the $256 \times$ optical replicator has a DR of approximately 1800:1. The vertical lines indicate the SNR for signal levels that are listed as a percentage of the peak amplitude.

the pulse), and averaging them to get the signal, $N_{\text{avg}}(t_j)$. The noise is the standard deviation of those points about the mean divided by the square root of the number of points. The SNR is the ratio of those two quantities [12]. This formalism was chosen because the users of this data must specify the error bars on the optical amplitude at each point in time. As shown in Fig. 4, the SNR's dependence on the signal level is dominated by the noise characteristics of the oscilloscope's input amplifier. At signal levels below 20% of the peak, the SNR depends linearly on the signal level. The point where the SNR equals 1 (as determined from this linear fit) represents the minimum credible signal that can be measured. The DR (defined as the ratio of the peak to the signal level where the SNR equals 1) is 1769 for the recombined optical pulse out of the replicator. The effective number of bits at a time resolution of 25 ps (ENOB) of this measurement is 10.8, where

$$2^{\text{ENOB}} = \text{DR}. \quad (3)$$

The Tektronix 6154 C oscilloscope used for these measurements has a true analog of 12 GHz and an ENOB between 4 and 5.5 [13], [14]. Thus, the $256 \times$ replicator makes it possible to almost double the ENOB of this particular oscilloscope.

In addition to increasing the SNR of the signal, the optical replicator enhances the high-frequency response of the detected optical pulse beyond that of a single measurement. The oscilloscope has an analogue BW of 12 GHz, and the photodiode has a flat response out to 18 GHz and a 3-dB cutoff frequency

Fig. 5. The (red) x's represent the FFT of a single optical pulse. The (black) squares represent the FFT of the combined output of the optical replicator. The horizontal lines represent the average of the FFT in the frequency range of 15 GHz to 20 GHz—a region where the system has no sensitivity and represents the white-noise limit in the single-pulse case.

of 22 GHz [15]. Therefore, the measurement system should support frequencies as high as 12 GHz. The temporal data can be converted to a frequency response by using fast Fourier transforms (FFT's). Fig. 5 shows the magnitude of the FFT of a single optical pulse emerging from the replicator (red x's) and the combined, averaged output (black squares). With a sampling window of 25 ps, the FFT algorithm generates a frequency spectrum out to 20 GHz. Beyond the cutoff frequency of 12 GHz, this measured spectrum should contain only white noise. The average of the spectrum over the 15-GHz to 20-GHz BW represents the noise floor limits for each curve, displayed as horizontal lines. The single trace falls below the noise floor at about 8 to 10 GHz, while the averaged trace does not cross the noise floor until the 12- to 15-GHz range. Ideally the noise floors should differ by a factor of 16, but the 256 replicas had amplitudes that varied by a factor of 3, therefore reducing the difference in the noise floors. The particular single optical trace was chosen at the mode of the amplitude distribution shown in Fig. 3. In this case the ratio of the noise floors was 11.7. The frequency-dependent signal-to-noise-and-distortion-ratio [16] (SINAD) can be estimated by dividing the replicated and averaged FFT of the signal [black squares (Fig. 5)] by the high-frequency white-noise limit given by the solid black line. Therefore, at approximately 13 GHz, the SINAD would be 1, at 10 GHz it would be 3.55, and at DC it would be about 4000. This is an approximate measurement because a perfect δ function was not used as the input. Had a temporally narrower pulse been used as the input to the replicator, the frequency content in the 8 to 12-GHz range would be enhanced and these numbers would improve slightly.

While this replicator was shown to enhance the SNR of optical pulses, it can also be used to characterize any electrical signal from an arbitrary detector. The signal must be input into the radio frequency port of the EOM. Ideally, the amplitude of the electrical signal should be slightly less than V_π of the EOM. (For this paper, $V_{\max} < 0.75 \times V_\pi$.) The formula in (2) can be used to remove the effect of the amplifier saturation from the replicator-enhanced signal to determine the output of the mod-

ulator. To remove the distortions caused by the EOM and amplifier and obtain the voltage signal, the inverse of (1) must be used:

$$V(t) = \pm \frac{2 \times V_\pi}{\pi} \arcsin \left[\sqrt{\frac{P(t)}{P_0}} - \phi \right]. \quad (4)$$

Fig. 6 shows the input voltage obtained by applying (4) to a single-shot optical waveform at the output of the modulator. Because of the sinusoidal nature of the modulator response there is an ambiguity in the sign of the inferred signal. This can be removed by setting ϕ to $\pi/2$ at the expense of losing a factor of 2 in the dynamic range or 1 ENOB. Also plotted in Fig. 6 is an input voltage waveform measured with a conventional oscilloscope. This electrical signal was stable and repetitive, so the average of 256 different traces reproduces the input signal with a low level of noise. The agreement between these two curves is excellent. At voltage levels above 10% of the peak, the average of the absolute difference between the two curves is 2.5%. There are small discrepancies that can be highlighted by considering the SNR of the two cases. For the input voltage, the SNR was calculated by using the standard deviation, at each point, of the acquired waveforms. The data are plotted by (dark blue) triangles in Fig. 7 along with a dotted line fit of the form, e^{mV+b} . This curve represents the single-shot performance of the oscilloscope alone. For this comparison the samples were not averaged, and, correspondingly, the standard deviation was not reduced by the factor $N^{1/2}$, where N is the number of samples. The direct measurement is compared with the single-shot measurement from the output of the $256 \times$ replicator. For the voltage inferred from the optical signal, $V_{\text{opt}}(t)$, the SNR was deduced by using (4) with $P^\pm(t) = P(t) \pm \Delta P(t)$, where $\Delta P(t)$ is the rms (root-mean-square) variation in the average of the $P(t)$ from the replicator output. The variation or noise in $V_{\text{opt}}(t)$, where $\Delta V_{\text{opt}}(t) = V_{\text{opt}}^+(t) - V_{\text{opt}}^-(t)$ and $V_{\text{opt}}^\pm(t)$ are the voltages deduced from $P^\pm(t)$. The SNR of this data, $V_{\text{opt}}(t)/\Delta V_{\text{opt}}(t)$, is plotted in Fig. 7 as (black) x's. The SNR of the voltage derived from the non-averaged optical data is always lower than the SNR of the conventionally measured voltage data. The dashed (green) horizontal line indicates an SNR of 1. The DR can be determined for each curve by taking the ratio of the peak voltage to the voltage where the curve crosses the green line. The DR also drops from 81 for the single-shot direct-voltage measurement to 14 for the single-shot non-averaged optical measurement. However, when the replicated data are averaged, the SNR increases by a factor of 16, yielding the curve marked with (red) squares. Over most of the DR of 56.2, the SNR of the averaged optical signal, which exceeds 800 at the peak, is higher than that which can be achieved with a conventional oscilloscope.

The reason that the voltage derived from the non-averaged optical signal performs poorly and the SNR of the voltage derived from the averaged optical signal degrades from the optical-pulse measurement can be traced to (4). Taking the derivative of (4) with respect to the optical power $P(t)$ and multiplying by ΔP yields

$$\Delta V = \frac{dV}{dP} \times \Delta P = \frac{V_\pi \times \Delta P}{\pi \times P_0 \times \sqrt{\frac{P}{P_0} - \frac{P^2}{P_0^2}}}. \quad (5)$$

Fig. 6. The measured input voltage (black) dashed line is nearly identical to the input voltage derived from the optical pulse (blue) solid line. The red dotted curve is the difference between the measured and derived curves multiplied by ten.

Fig. 7. The measured SNR of the single-shot input voltage, inferred from the averaged optical output (red squares) is greater than that of the directly measured input voltage (blue triangles). The form of the SNR curve is governed by the ideal response of the EOM (solid red line). Without averaging the SNR of the EOM output (light blue x's) is always less than the directly measured voltage input. The green horizontal line represents an SNR of 1.

This equation relates the variation in the inferred voltage signal to the measured in the optical signal. Using the fitted relationship of the purely optical SNR to give ΔP , ΔV can be determined and used to generate the solid black curve in Fig. 7. This curve closely matches both the form and amplitude of the SNR of the voltage inferred from the optical measurement [red squares]. Therefore, the degradation in the SNR can be traced to the mapping function given by (4).

III. CONCLUSION

Manufacturers of conventional electronic oscilloscopes have steadily increased the bandwidth of their machines. However, the analog-to-digital converters have remained fixed at 8 bits, giving a maximum possible dynamic range (DR) of 256:1 for single-shot events. In practice, the noise floor limits the DR to about 32:1 or five ENOB's. Multi-shot averaging increases the ENOB, but that option is not available for single-shot events.

In this work, an optical replicator has been constructed that acquires single-shot pulses with a dynamic range of 1800:1, extending the capabilities of conventional oscilloscopes. The device can be used to measure optical pulses that have been shaped by an electric pulse in an EOM. The optical signal can be used to infer the shape of the electrical pulse. The high DR and SNR of optical pulse ensures that the inferred electrical pulse shape has a higher SNR than an electrical pulse directly measured with a conventional electronic oscilloscope. The optical replicator preserves the high bandwidth of the system.

To move from a demonstration system to a working device, it will be necessary to move to the telecommunication bands at either 1.3 μm or 1.55 μm . These wavelength ranges have a wide range of affordable, off-the-shelf components for the EOM, splitters, and amplified laser. In addition, the availability of wavelength-division-multiplexing components means the system can be operated at multiple wavelengths simultaneously, thus further increasing the number of replicas that are averaged.

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