
Averaging of Replicated Pulses for Enhanced-Dynamic-Range, Single-Shot Measurement of Nanosecond Optical Pulses

Introduction

Nanosecond-length laser pulses are commonly used in applications such as light detection and ranging (LIDAR) and remote sensing. Accurate measurement of the pulse shape can be critical for specific applications. In particular, laser systems used for inertial confinement fusion (ICF) are required to produce stable, high-contrast pulse shapes to achieve the highest-possible compression of the target.^{1,2} While non-linear techniques can measure pulse shapes with a contrast of the order of 10^7 (Refs. 3 and 4), reliable measurement of nanosecond-length pulses can only be achieved with either streak cameras or photodiodes in conjunction with oscilloscopes. Streak cameras offer high-dynamic-range (700:1), multichannel (>8) measurements with 30-ps temporal resolution.⁵ However, the relatively slow update rate of single-shot, high-dynamic-range streak cameras (0.1 Hz) precludes their use in applications that require real-time monitoring. Such applications include real-time pulse-shape adjustment or the diagnosis of intermittent problems.

Although oscilloscope sampling rates are continually increasing, the vertical resolution has remained stagnant at 8 bits. Additionally, the effective number of bits (ENOB) is limited to 5 or 6 due to inherent noise floor and digitization effects. Therefore, when using photodiodes with oscilloscopes to measure an optical pulse shape, the oscilloscope becomes the limiting factor of measuring contrast, reducing the measurable dynamic range ($DR = 2^{ENOB}$) to ~ 45 . Such a contrast is insufficient for the accurate measurement of high-contrast ICF pulse shapes that require measurement of pulses with up to 100:1 shape contrast at a reasonable level of accuracy.

The conventional method for reducing noise on periodic signals is to average temporally sequential events, which has the benefit of reducing the signal-to-noise ratio (SNR) by a factor of \sqrt{N} , where N is the number of traces. However, non-repetitive, single-shot events get washed out in the averaging process; this is particularly important when trying to diagnose intermittent failures. Furthermore, the acquisition speed in sequential averaging is reduced by a factor of N .

To capture single-shot events, the pulse can be replicated and averaged with itself to reap the benefits of averaging. In previous work, the pulse of interest was sent through an active fiber loop to produce a replicated pulse train.⁶ With gain in the loop, the signal was kept near maximum throughout the pulse train at the expense of amplifier noise added to the signal at every pass. Additionally, the amplitudes of the resultant pulse train followed an exponential decay curve, making it difficult to operate at high repetition rates. In this work, a passive pulse-replication structure is implemented to achieve the series of pulses. The signal is power divided, then recombined with a fixed time delay. Multiple split/recombine stages with digitally increasing delay can yield an arbitrary number of pulses, provided there is sufficient energy in the initial pulse. The replicated pulses are read from a single oscilloscope trace and subsequently averaged in order to achieve increased dynamic range. Similar pulse replication schemes have previously been implemented for increased temporal resolution in measuring picosecond pulses.^{7,8}

Experimental Configuration and Measurements

The configuration for passive pulse replication is shown schematically in Fig. 109.64. A series of 2×2 fused-fiber splitters are spliced with $m \times 12.5$ -ns-delay fibers between the individual stages. Since successive combinations use splits from previous combinations, the last split is the only place where light is forfeited. It should also be mentioned that since the first splitter has two input ports, two separate pulses can be run simultaneously through this architecture, provided their timing is such that the resultant pulse trains do not overlap in time.

Figure 109.65 shows the resultant 64 pulses from the raw photodiode output as measured on a Tektronix TDS 6154C digital storage oscilloscope, which has a 12-GHz analog bandwidth. The pulses are nominally spaced at 12.5 ns, although precise spacing is not critical to the method.

The trace is acquired from the scope at 25-ps resolution, and the individual pulses are separated by temporal binning. The fine temporal alignment between two pulses $P_i(t)$ and $P_j(t)$

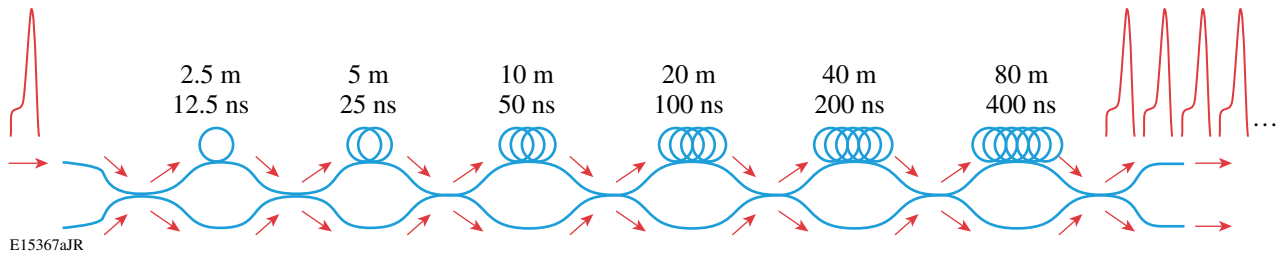


Figure 109.64
Schematic of 64-pulse passive pulse-stacking architecture.

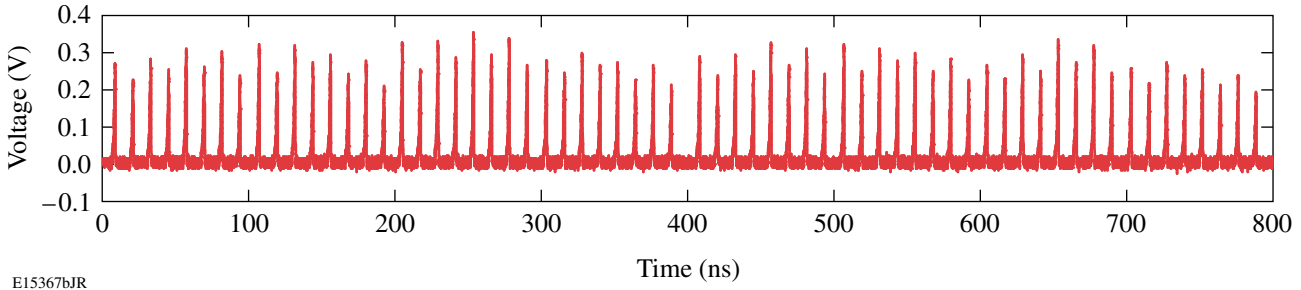


Figure 109.65
Oscilloscope trace showing 64 pulse replicas.

in the pulse train is measured once with a cross-correlation method using the formula

$$X_{ij}(t) = F^{-1} \left\{ F[P_i(t)] \times F^*[P_j(t)] \right\}, \quad (1)$$

where F and F^{-1} denote the discrete fast Fourier transform and its inverse and the asterisk denotes the complex conjugate. The temporal offset t_{ij} is the value of t that maximizes the function $X_{ij}(t)$. $P_j(t)$ is offset by this amount before averaging with the other pulses from the pulse train.

Figure 109.66 shows the single-shot, self-averaged pulse together with a multi-shot-averaged pulse (64 averages) and a single pulse (no averaging) for comparison. Similar to the multi-shot average, the single-shot average shows clear performance enhancement compared to the single-shot case. Additionally, due to the jitter inherent in temporal acquisitions, the multi-shot-averaged case has a reduced effective bandwidth compared to the single-shot-averaged trace, as can be seen in the relative sharpness of the leading edges of the corresponding pulses in Fig. 109.66.

The dynamic range of the measurement is defined as the ratio of the peak of the signal to the signal level where the SNR is equal to unity. Figure 109.67 shows the calculated dynamic

range for the single-shot and multi-shot averages as a function of the peak signal on the photodiode. In the multi-trace averages, there are 64 temporally displaced copies at different signal amplitudes (as can be seen in Fig. 109.65), each of which is plotted independently. Given that the noise level is identical

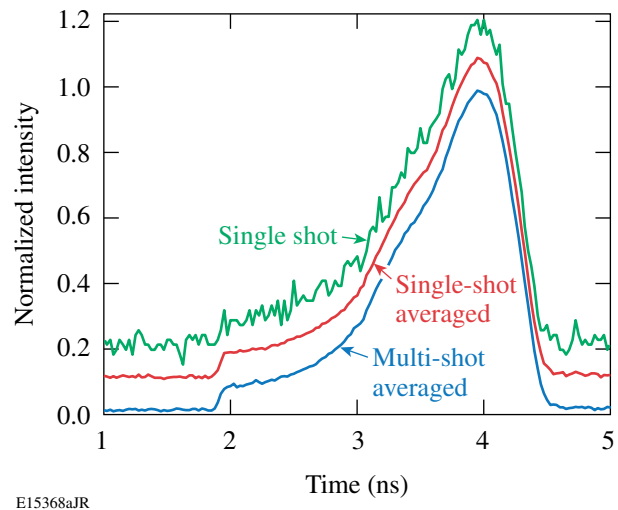


Figure 109.66
Single-shot, single-shot-averaged, and multi-shot-averaged pulse shapes. Arbitrary offsets have been added for clarity.

for all cases, increased signal amplitude corresponds directly to increased dynamic range. For the single-shot-averaging case, the data point is plotted versus the average amplitude of all of the peaks in the 64-pulse train. This plot clearly demonstrates that single-shot averaging works just as well as multi-shot averaging without the disadvantages of reduced acquisition time and the loss of single-shot events. For further comparison, the manufacturer’s specifications rate the oscilloscope at 5.5 ENOB, corresponding to a maximum dynamic range of 45. The single-shot-averaging technique demonstrates a dynamic range of 312, or an ENOB of 8.3, an improvement of nearly 3 bits over the nominal performance of the oscilloscope. This level of improvement is expected from the averaging function; since the SNR is reduced by \sqrt{N} and the maximum signal remains nearly the same, the dynamic range is improved by the same factor, for which $\sqrt{64} = 2^3$.

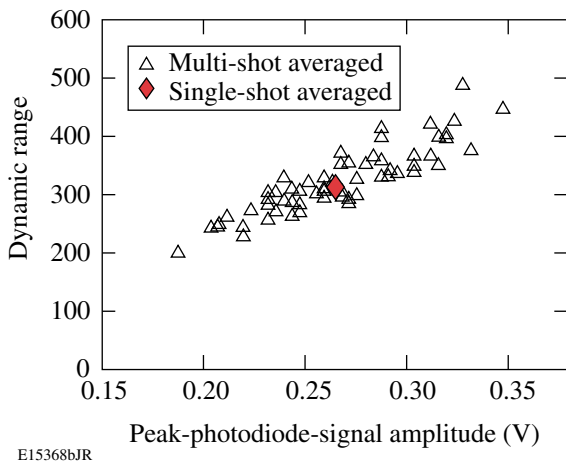


Figure 109.67
Dynamic range of single-shot-averaged and multi-shot-averaged pulses

Discussion and Conclusions

In principle, this method can be extended to a larger number of pulses in the pulse stacker, thereby achieving even better dynamic range and SNR. The ultimate limitation is peak-detected signal power, which is reduced by a factor of 2 every time the number of pulses is doubled. Provided the laser system has sufficient energy to spare for the measurement, the upper limitation on power launched is driven by damage and nonlinear effects in the fiber.

For spectrally narrowband pulses, stimulated Brillouin scattering (SBS) becomes the limiting factor in power launched into the fiber. The conventional threshold equation for the SBS threshold is $g_B P_0 L_{eff} / A_{eff} = 21$, where g_B is the Brillouin gain,

P_0 is the threshold peak power, L_{eff} is the effective interaction length, and A_{eff} is the effective mode area.⁹ Since the light scattered by SBS is in the reverse propagation direction, the effective length of the interaction is determined by the time of flight of the pulse in the fiber. Using typical numbers for 1053 nm, the SBS energy threshold for a 1-ns pulse is of the order of several microjoules.

Conventional damage thresholds for fibers are near 5 J/cm² for a 1-ns pulse, although higher values have been reported.¹⁰ Using the more-conservative value leads to an upper energy limit of the order of a few microjoules for a single-mode fiber at 1053 nm (~6-μm core). Together, damage and SBS considerations limit the maximum launched power to a few microjoules.

The receiver of the system also has its limitations. Generally, detection of low light levels may lead to signal-to-noise issues; therefore, higher light levels are desired. However, the photodiode itself has an upper limit of peak signal power before the pulse becomes distorted by space-charge effects that arise when the extracted charge exceeds more than a few percent of the charge stored in the photodiode. For the Discovery DSC-30 photodiodes that were used, the power was limited to approximately 10 pJ per pulse in the pulse train; reasonably beyond that value, pulse-shape distortion became noticeable.

Together, the fiber launch energy and the photodiode linearity determine the maximum dynamic range of the detected signals. The single-pulse energy after passing through the system is given by $(\eta/2)^N$, where η is the transmission of the coupler and N is the number of stages. Using the energy limitations described above with a conservative 0.6-dB insertion loss for the couplers, a total of 14 stages can be utilized. Thus, this technique can be extended to achieve an increase of 7 bits over the nominal oscilloscope performance.

In conclusion, measuring pulse shapes beyond the dynamic range of oscilloscopes is achieved by passive temporal-pulse stacking. Pulses are averaged with their time-delayed replicas without introducing additional noise or jitter, allowing for high-contrast pulse-shape measurements of single-shot events. A dynamic-range enhancement of 3 bits is demonstrated experimentally, and the technique can be extended to yield an increase of up to 7 bits of additional dynamic range over nominal oscilloscope performance. Moreover, single-shot averaging does not suffer from temporal jitter; therefore it can produce higher bandwidth measurements than conventional multi-shot averaging.

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