Enhanced-Dynamic-Range, Single-Shot Measurement of Nanosecond Pulses via Optical Replication

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Summary

A 3-bit enhancement in dynamic range has been achieved for single-shot pulse-shape measurements.

- Oscilloscopes are the limiting factor in accurately measuring single-shot, high-contrast pulse shapes.
- Optical-pulse replication allows averaging of a single pulse, thereby reducing noise in the detection system.
- Optical-pulse replication is accomplished using a low-loss, passive, all-fiber network.
- Single-shot dynamic-range enhancements are equivalent to those achieved with conventional multi-shot averaging.
- A 3-bit \((8\times)\) enhancement of dynamic range is measured.
- Up to 7 bits of dynamic-range improvement \((128\times)\) is achievable.
Accurate measurement of single-shot laser pulse shapes can be critical in specific applications

- Single-shot capture is important when a single laser pulse can be correlated to a physical effect
  - internal confinement fusion, where the pulse shape determines the performance of the compressed target
  - one-on-one damage testing, where a single laser pulse can be associated with one damage spot on a surface
  - laser-induced electron-emission characteristics
  - noise-initiated processes, such as nonlinear pulse generation via stimulated Brillouin scattering, stimulated Raman scattering, or sonoluminescence
  - anywhere else multi-shot averaging is used!
High-contrast, single-shot, pulse-shape measurements are required for laser-fusion experiments

- Laser systems used for inertial confinement fusion (ICF) are required to produce stable, high-contrast pulse shapes in order to achieve the highest possible compression of the target.
Nanosecond-length pulses are difficult to measure with high bandwidth and high contrast

- Streak cameras have high bandwidth and high dynamic range but a slow update rate (0.1 Hz).
- Nanosecond pulse lengths prohibit nonlinear measurement methods normally used for ultrafast pulses.
- Photodiodes can measure long pulses with over 40-GHz bandwidth at very high contrast.
  - they meet the requirements but require oscilloscopes for readout
- Oscilloscopes can not meet all of the requirements
  - they have sufficiently high bandwidth (12-GHz analog)
  - the 8-bit dynamic-range resolution is limited by noise and digitization to an ~5.5 effective number of bits (ENOB)

A 45:1 dynamic range is insufficient for an accurate measurement of 100:1 contrast optical pulses.
Averaging replicated pulses can produce the benefits of averaging while retaining single-shot events

- It is well known that averaging $N$ repetitive events can yield a signal-to-noise (SNR) improvement of $\sqrt{N}$.

- If a single pulse could be optically replicated, it could be averaged with its replicas in order to yield the $\sqrt{N}$ improvement for a single-shot measurement.

- Previous work* used a fiber amplifier loop to produce a series of pulse replicas
  - pulse amplitudes had an exponential decay
    - only low pulse-repetition rates can be utilized
  - each pass added ASE to the signal
    - optical noise is different on each replicated pulse in the series

  A method is required for passive pulse replication that produces a finite pulse train.

A passive all-fiber pulse stacker produces a finite pulse train of optically identical pulses

- Low-loss pulse stacking is achieved with a serial application of 50/50 fused fiber splitters.
- Passive fiber enables delays between pulse replicas

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Delay (ns)</th>
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<tbody>
<tr>
<td>2.5</td>
<td>12.5</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
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<td>20</td>
<td>100</td>
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<td>40</td>
<td>200</td>
</tr>
<tr>
<td>80</td>
<td>400</td>
</tr>
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</table>

- The unit is low loss, low cost, and compact
- No power is required

A finite number of pulses are generated with the same optical noise on each pulse
Individual pulses are selected, temporally aligned via cross correlation, and averaged

- The train of replicated pulses is acquired from the scope.

- Temporal alignment is achieved by maximizing the cross correlation between pulses.

\[
X_{1j}(t) = F^{-1}\left\{F[P_1(t)] \times F^*[P_j(t)]\right\}.
\]
Single-shot averaging shows nearly identical performance to conventional multi-shot averaging.

![Graph showing normalized intensity vs. time (ns) with traces labeled as Single shot, Single-shot averaged, Multi-shot averaged, and notes that traces are offset for clarity.](image-url)
We demonstrate a dynamic-range enhancement of 3 bits by averaging optically replicated pulses.

- The multi-shot data averages each pulse with its twin in each of 64 consecutive traces.

- A variation in multi-shot data occurs due to uneven pulse amplitudes in the replicated pulses.

- Single-shot data behaves according to the average of the pulse amplitudes.

\[ \sqrt{N} \] SNR improvement is achieved.
Passive pulse replication can be extended to yield an increase of up to 7 bits of additional dynamic range.

- The upper range on fiber-launched power is limited to a few microjoules
  - stimulated Brillouin scattering (SBS)
  - optical damage (~5 J/cm²)
- The upper range for undistorted OE conversion (Discovery DSC-30 photodiode) was measured at 10 pJ.
- After the Nth split stage, the energy per pulse follows
  \[ E_N = E_0 \left( \frac{\eta}{2} \right)^N, \]
  where \( \eta \) is the transmission of each stage.
- Assuming conservative fused fiber splitter and splice losses (0.6 dB), 14 stages can be utilized.

A 7-bit (128×) enhancement in dynamic range can be achieved, yielding a net dynamic range of 12.5 bits (5800:1) on conventional oscilloscopes.
Summary/Conclusions

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