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Swamp Optics Tutorial

The Coherent Artifact in Modern Pulse Measurements

Unless you're using a GRENOUILLE, your pulse measurements are probably wrong. Sorry to be the bearer of this bad news.

Nearly all lasers have fluctuations. In particular, their pulse shape (the intensity and phase) varies from pulse to pulse. Unfortunately, when a measurement averages over many different events, it faces an impossible task: providing one result when no single result can be correct. In ultrafast optics, this issue has been particularly problematic when using the traditional method for measuring laser pulses, called intensity autocorrelation and introduced in the 1960s. When autocorrelation was used to measure trains of different, complex pulses, the resulting measured autocorrelation trace vs. delay (see the figure below) consisted of a narrow spike atop a broad structureless background. Although early researchers often mistook the spike, or "coherent artifact," for the measure of their pulse length, its width actually only yields the much shorter, nonrandom ("coherent") component of the pulse. The correct pulse length is actually almost always much longer and is instead indicated by the temporally much broader background, which also takes into account the much longer, random ("incoherent") pulse component.

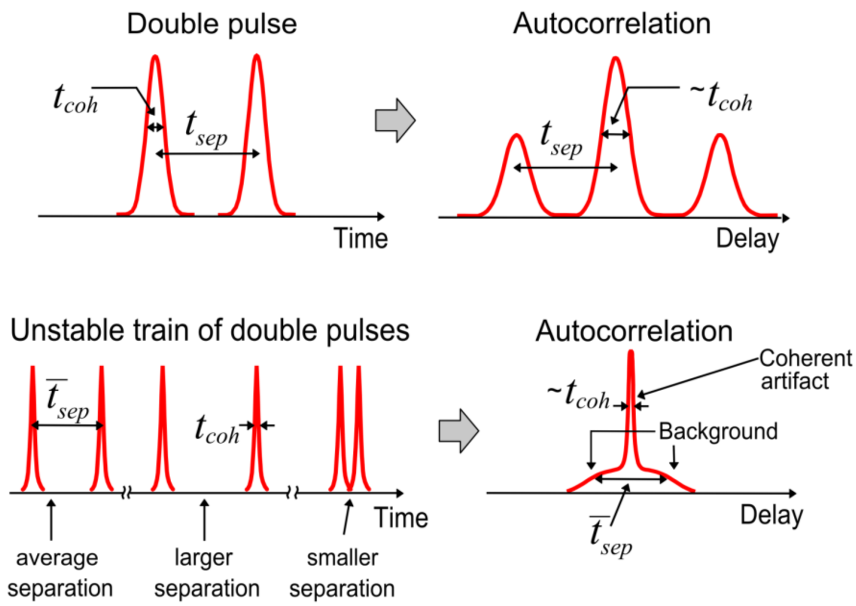

Fig. 1. The coherent artifact in autocorrelation. Top: Double pulse and its autocorrelation. Bottom: A train of variably spaced double pulses and their multi-shot autocorrelation (averaged over many pulses in the train). The coherent artifact results from the short nonrandom coherent component of the double pulses (specifically, a single pulse), while the broader background results from the overall average pulse length (the combination of both pulses). This trace is typical of autocorrelations of nearly all trains of unstable complex pulses.

Given that the task is inherently impossible, it's worth asking what we should expect. The answer is that the technique should yield a pulse with some characteristics of the typical pulse in the train (e.g., its duration), but, more importantly, give an indication of the stability, or randomness, of the pulses in the train.

Although autocorrelation actually does yield some of this information, it yields neither the pulse intensity nor its phase for the simpler case of a stable train of identical pulses and so is now generally considered obsolete.

The Coherent Artifact in Modern Pulse-Measurement Techniques

The next question—one whose answer is long overdue—is how more modern pulse-measurement techniques, which do yield the pulse intensity and phase for a stable train of identical pulses, react to an unstable train of random pulses. This question was recently considered for the two most popular techniques in use today: frequency-resolved optical gating (FROG) and spectral-phase interferometry for direct electric-field reconstruction (SPIDER). To answer this question, a simple analytical calculation for

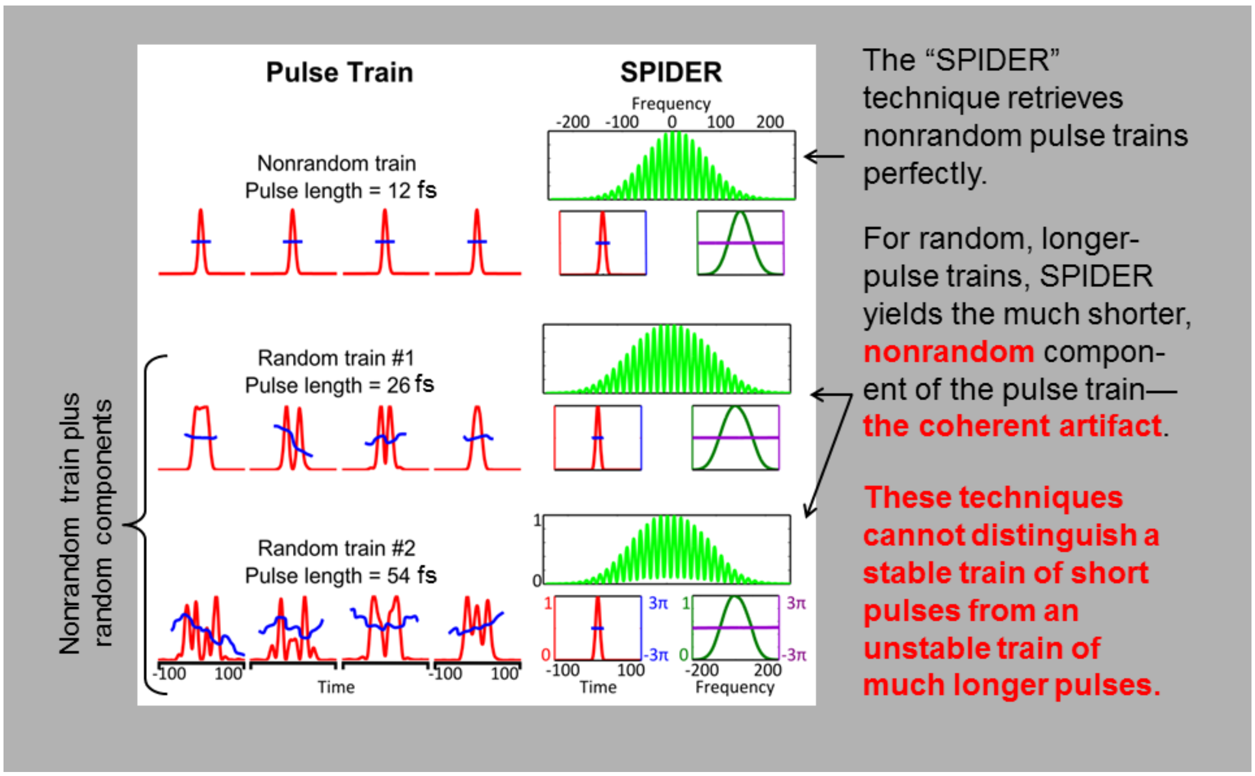

Fig. 2. Nonrandom- and random-pulse trains of varying complexity, and simulated multi-shot SPIDER measurements of them. Top row: nonrandom train of identical Gaussian flat-phase pulses. Middle and bottom rows: random-pulse trains of different average complexity and duration. Red curves indicate intensity, blue phase, green spectrum, and purple spectral phase. The black dotted SPIDER traces are fits assuming flat-phase Gaussian pulses and slight misalignment of the SPIDER device (unequal intensities of the two pulses in it), confirming that a stable train of short pulses and an unstable train of longer pulses cannot be distinguished by SPIDER. For all three pulse trains, SPIDER retrieves only the nonrandom pulse component and exhibits decreasing fringe visibility (100%, 98%, and 90%, respectively). In short, SPIDER only measures the coherent artifact. As a result, it cannot be used to measure pulse lengths with confidence.

SPIDER shows that it actually only measures the coherent artifact! Simple simulations confirmed this result. *As a result, SPIDER cannot distinguish a stable train of short pulses from an unstable train of much longer ones.* Many previous SPIDER measurements will now need to be re-evaluated. And SPIDER should not be used for pulse measurement because there simply is no way to guarantee that a given pulse train out of a laser is stable—it is the task of the measurement technique to determine this and SPIDER cannot do so. Indeed, by tuning their laser for the minimum SPIDER-measured pulse length, SPIDER users often inadvertently *maximize their pulse length and instability*! Thus SPIDER measurements are, at worst, wrong, and, at best, unconvincing.

What about other recently developed pulse-measurement techniques? Alas, they also measure only the coherent artifact! Other versions of SPIDER, 2DSI, MIIPS, D-Scan, and several other methods also measure only the coherent artifact! In a couple of cases, there is an indication of instability, but these techniques ignore this hint that the measurement may be wrong!

On the other hand, the simulations also show that SHG FROG (and hence GRENOUILLE, which is a type of SHG FROG) measurements are more reliable, yielding the correct pulse length. Indeed, FROG measurements actually can also reveal whether the pulse train is stable or not. FROG also does not see the pulse structure, but it does yield the correct durations. More importantly, in FROG, the measured and retrieved FROG traces disagree for the random trains, and their rms differences are large. This is the key: such disagreement is the indication that instability is present.

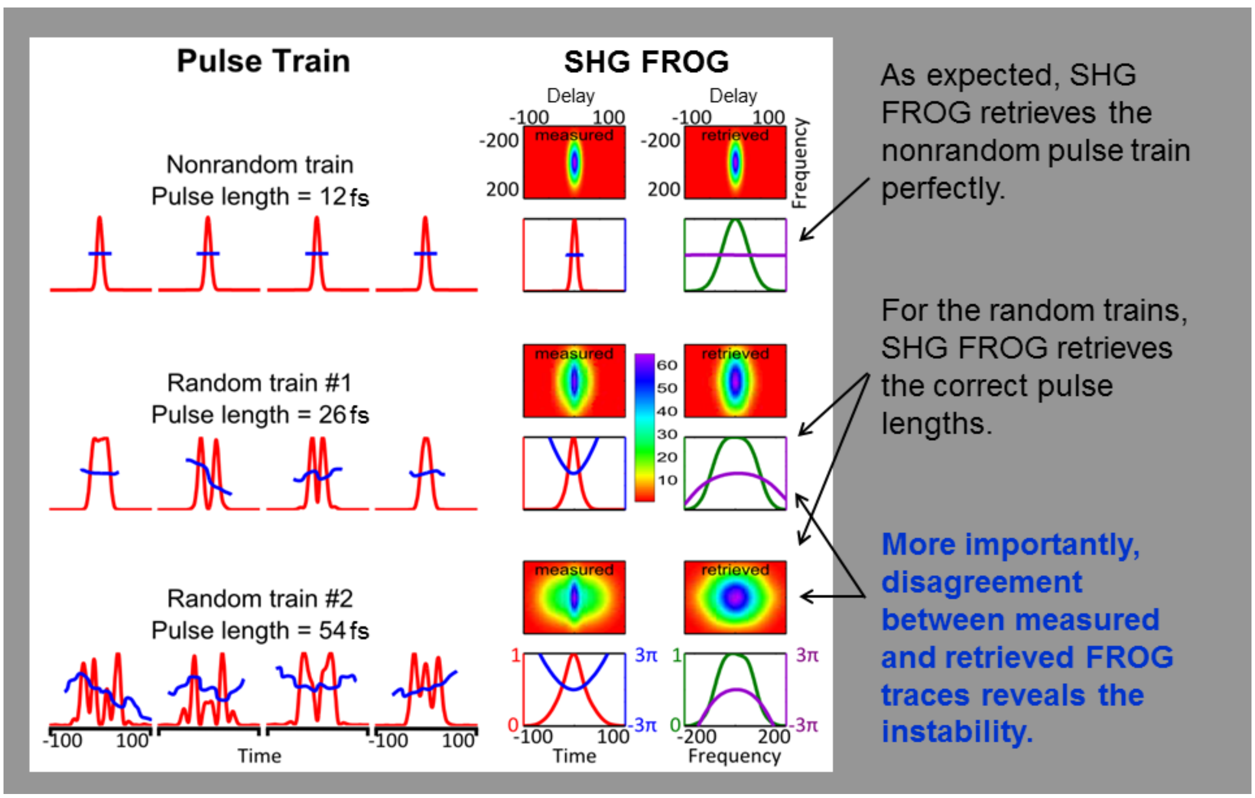

Fig. 3. Nonrandom- and random-pulse trains of varying complexity, and simulated multi-shot SHG FROG (GRENOUILLE) measurements of them. Top row: nonrandom train of identical Gaussian flat-phase pulses. Middle and bottom rows: random-pulse trains of different average complexity and duration. Red curves indicate intensity, blue phase, green spectrum, and purple spectral phase. Note that, while SHG FROG misses the structure, it still yields the correct pulse length, and it also reveals the instability by the discrepancies between the measured and retrieved traces.

To summarize, we find that SPIDER retrieves an excellent estimate of the nonrandom component of the pulse train. But it does not see any randomly varying component of the pulse. In short, for an unstable pulse train, SPIDER measures only the coherent artifact.

This should not be surprising: it's been known for over 200 years that interferometric methods (of which SPIDER is one), in general, are not sensitive to random phase variations, responding only with reduced fringe visibility and increased background. The same holds for other interferometric methods.

Alas, we are unaware of any SPIDER measurements with fringe visibilities greater than 90%, a value that, in our simulations, corresponds to a measured pulse length too short by more than a factor of 4.5. Indeed, in supercontinuum measurements, much smaller values—as low as 10%—have been reported. Without deeper insight into the underlying physics or additional independent measurements (only a FROG measurement has been shown so far to yield this information!), it appears impossible to determine whether an imperfect SPIDER fringe visibility is due to benign misalignment effects (and so corresponds to a stable train of short pulses) or instability (and so corresponds to an unstable train of potentially much longer ones). Thus, unless the pulse-to-pulse stability of the temporal intensity can otherwise be ensured (which does not appear to be possible unless a FROG measurement is made), it appears that pulse-length claims from measurements with imperfect SPIDER fringe visibility require re-evaluation.

So how did some of the brightest scientists in the world make the same mistake twice? Perhaps it was wishful thinking: every ultrafast scientist likes to be able to brag about having extremely short pulses, and SPIDER routinely gives shorter pulses than other methods do, as these results have shown.

Actually, some FROG measurements will also require re-evaluation. While SHG FROG yields the correct pulse lengths in our simulations, it, like SPIDER, misses the pulse structure and so could also yield misleading results in the presence of instability. However, SHG FROG provides a strong indicator of instability: disagreement between the measured and retrieved SHG FROG traces.

Unfortunately, some authors have attributed such disagreement to possible non-convergence of the FROG algorithm. In view of these results and the FROG algorithm's demonstrated robustness for all but extremely complex pulses, such discrepancies appear much more likely to be due to instability. Fortunately, instability is, in fact, more often considered as the cause, having previously been encountered experimentally in FROG measurements of supercontinuum pulse trains. In that case, FROG retrieved a pulse with the extreme complexity of a typical pulse in the train, and it was the disagreement between the measured and retrieved traces that indicated a problem and inspired single-shot spectral measurements and extensive theoretical investigations, confirming the highly unstable nature of the continuum.

In any case, pulse trains should be considered guilty of instability until proven innocent. Also, in FROG measurements, retrieved traces should always be reported. Only good agreement between measured and retrieved FROG traces can confirm good pulse-train stability.

The good news is that, if one requires a good indication of the pulse structure in an unstable train, other versions of FROG can do this. The figure below shows the same simulations, but for the polarization-gating version of FROG and the cross-correlation version of FROG. These devices are available on a custom basis from Swamp Optics.

Finally, the Trebino group has been testing other new methods for measuring pulses, and essentially every one of them (2DSI, SRSI, MIIPS, etc.) yields only the coherent artifact! So buyer beware!

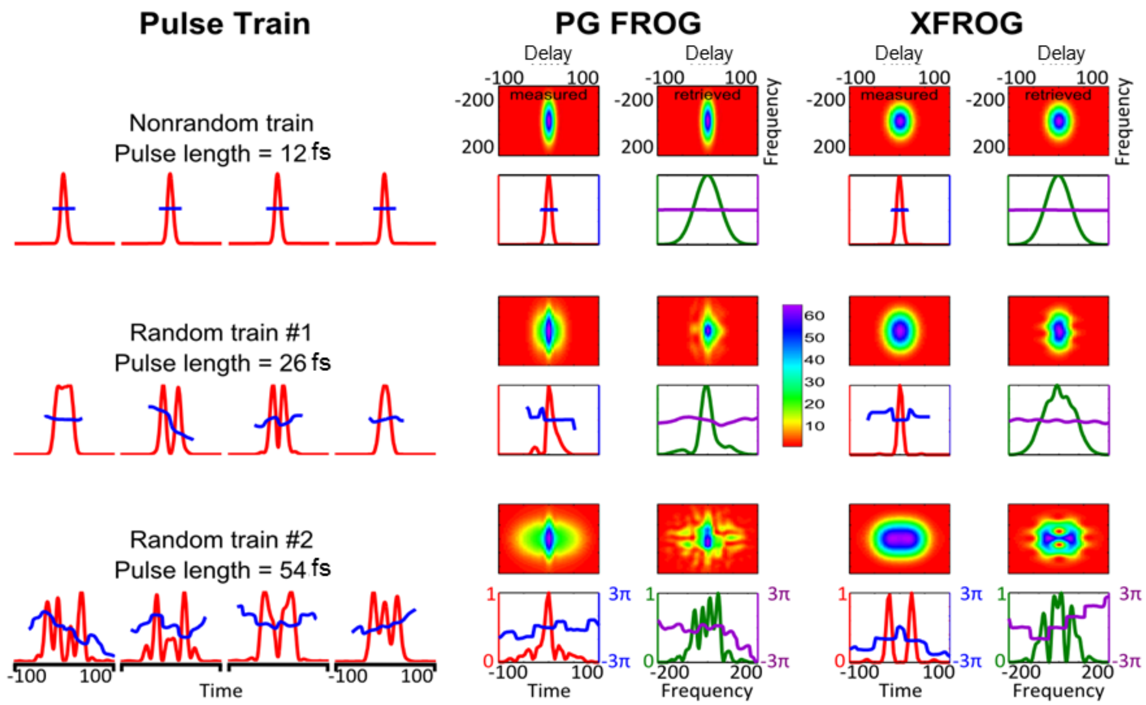

Fig. 4. Other versions of FROG reveal instability and a reasonable typical pulse in the train.

About Swamp Optics

Founded in 2001, Swamp Optics, LLC offers cost-effective quality devices to measure ultrashort laser pulses. It specializes in frequency-resolved optical gating (FROG) and GRENOUILLE (an experimentally simple version of FROG), the gold standards for measuring the time-dependent (or, equivalently, frequency-dependent) intensity and phase of an ultrashort pulse.

Swamp Optics also sells an innovative pulse compressor.

For more information, visit us on the Web at www.swampoptics.com.