Further measurement techniques for ultrashort pulses

We have previously discussed:
Correlation
  Auto
  Cross (briefly)
FROG

Other important techniques:
Spectral Interferometry
  Requires a reference pulse
Unbalanced Correlation (compare the pulse with a modified version of itself)
SPIDER (Spectral Phase Interferometry for Direct Electric-Field Reconstruction)
  Uses “shearing interferometry” to generate replica for reference
  Direct inversion, no iteration required
  More complicated apparatus
Because ultraweak ultrashort pulses are almost always created by much stronger pulses, a stronger reference pulse is usually available.

Use Spectral Interferometry (SI)

\[ S_{Si}(\omega) = S_{ref}(\omega) + S_{unk}(\omega) + 2\sqrt{S_{ref}(\omega)}\sqrt{S_{unk}(\omega)} \cos[\phi_{unk}(\omega) - \phi_{ref}(\omega) + \omega \tau] \]

This involves no nonlinearity! ... and only one delay!

FROG can be used to characterize \( E_{ref} \)

But it is not always necessary...

C. Dorrer, JOSA B 16, 1160 (1999)
SI yields the difference between the two spectral phases.

Subtracting off the spectral phase of the reference pulse yields the unknown-pulse spectral phase.

Sensitivity Comparison

**FROG**

1 microjoule = $10^{-6} \text{ J}$

1 nanojoule = $10^{-9} \text{ J}$

1 picojoule = $10^{-12} \text{ J}$

1 femtojoule = $10^{-15} \text{ J}$

1 attojoule = $10^{-18} \text{ J}$

**Spectral Interferometry**

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1 nanojoule = $10^{-9} \text{ J}$

1 picojoule = $10^{-12} \text{ J}$

1 femtojoule = $10^{-15} \text{ J}$

1 attojoule = $10^{-18} \text{ J}$

1 zeptojoule = $10^{-21} \text{ J}$

Assume multishot measurement of ~800-nm, ~100-fs pulses at a ~100-MHz rep rate.

A pulse train containing only 42 zepto-joules ($42 \times 10^{-21} \text{ J}$) per pulse has been measured (0.5 sec integration). That’s one photon every five pulses! Fittinghoff, et al., Opt. Lett. 21, 884 (1996).
Frequency domain interferometric second-harmonic (FDISH) spectroscopy

The phase of the second harmonic produced on the MOS capacitor is measured relative to the reference second harmonic pulse produced by the SnO$_2$ on glass.

A $\pi$ phase shift is seen at $-4$ V.

Unpolarized light doesn’t exist...

...there is, however, light whose polarization state changes too rapidly to be measured with the available apparatus!

So measure $E(t)$ for both polarizations vs. time using two SI apparatuses (dual channel SI):

Measurement of the variation of the polarization state of the emission from a GaAs-AlGaAs multiple quantum well when heavy-hole and light-hole excitons are excited elucidates the physics of these devices.

Application of Dual channel SI

Excitation-laser spectrum and hh and lh exciton spectra

Evolution of the polarization of the emission:

Spectral interferometry only requires measuring one spectrum. Using the other dimension of the CCD camera for position, we can measure the pulse along one spatial dimension, also.

Fringe spacing is larger due to delay produced by slide (ref pulse was later).
The interferometer must be stable, the beams must be very well aligned, and the beams must be mode-matched.

- The time delay must be stable or the fringes wash out.
- CW background in the laser can add to the signal and mask it.
- Beams must be perfectly collinear or the fringes wash out.
- Mode-matching is important or the fringes wash out.
- Phase stability is crucial or the fringes wash out.
Spectral Interferometry: Pros and Cons

Advantages

It’s simple—requires only a beam-splitter and a spectrometer
Direct inversion – no iteration involved
It’s linear and hence extremely sensitive. Only a few thousand photons are required.
It is sensitive to changes in the overall phase – as long as you have an overall phase stable reference

Disadvantages

It measures only the spectral-phase difference.
A separately characterized reference pulse is required to extract more than a change in phase.
The reference pulse must be the same color as the unknown pulse.
It requires careful alignment and good stability—it’s an interferometer.
Although the inversion is simple, care is required.
Spectrometers work in $\lambda$, algorithm works in $\omega \rightarrow$ resampling can cause problems (work in $1/\lambda$ space, not $t$).
Must know delay independently if delay matters
Need several resolution elements per fringe.
Crossed-Beam Spectral Interferometry

\[
S(\omega, x) = S_{\text{ref}}(\omega) + S_{\text{unk}}(\omega) + 2\sqrt{S_{\text{ref}}(\omega)}\sqrt{S_{\text{unk}}(\omega)} \cos(2kx\sin \theta + \varphi_{\text{unk}}(\omega) - \varphi_{\text{ref}}(\omega))
\]

Crossed-Beam Spectral Interferometry

(a) SEA TADPOLE trace of a Chirped Pulse

(b) Spectrum and Phase of a Chirped Pulse

(a) Spectrum and Phase of a Double Train of Pulses

(b) Temporal Intensity and Phase of a Double Train of Pulses
Unbalanced correlation

What if we compare the pulse not to itself but a modified version of itself?

Perhaps if we know exactly how it was modified, we can learn more...

Use the resulting correlation + spectrum in an inversion algorithm
Unbalanced correlation inversion

Experimental demonstration

Algorithm guesses spectral phase
Describe using polynomial
Calculate pulse from spectrum + assumed spectral phase
Perform multidimensional minimization on difference between calculated and measured correlation
Phase polynomial coefficients treated as variables
Dubbed "Phase and Intensity from Cross-correlation and Spectrum Only (PICASO)"

If we perform spectral interferometry between a pulse and itself, the spectral phase cancels out. (Perfect sinusoidal fringes always occur.)

It is, however, possible to use a modified version of SI to measure a pulse, provided that a nonlinear effect is involved.

The trick is to frequency shift one replica of the pulse compared to the other.

This is done by performing sum-frequency generation between a strongly chirped pulse and a pair of time-separated replicas of the pulse.

SI performed on these two up-shifted pulses yields essentially the derivative of the spectral phase.

This technique is called: Spectral Phase Interferometry for Direct Electric-Field Reconstruction (SPIDER).

How SPIDER works

Chirped pulse

This pulse sums with the blue part of the chirped pulse.

This pulse sums with the green part of the chirped pulse.

Performing SI on these two pulses yields the difference in spectral phase at nearby frequencies (separated by $\delta\omega$). This yields the spectral phase.

SPIDER yields the spectral phase of a pulse, provided that the delay between the pulses is larger than the pulse length and the resulting frequency fringes can be resolved by the spectrometer.
SPIDER: extraction of the spectral phase

Extraction of the spectral phase

Measurement of the interferogram

Extraction of their spectral phase difference using spectral interferometry

Integration of the phase

\[ \phi(\omega + \delta \omega) - \phi(\omega) \]

Experimental measurement:

Advantages and Disadvantages of SPIDER

Advantages

• Pulse retrieval is direct (i.e., non-iterative) and hence fast.
• Minimal data are required: only one spectrum yields the spectral phase.
• It naturally operates single-shot.

Disadvantages

• Its apparatus is complicated – 13 sensitive alignment parameters
  (5 for the Michelson; 2 in pulse stretching; 1 for pulse timing; 2 for spatial overlap in the SHG crystal; and 3 for the spectrometer).
• Like SI, it requires very high mechanical stability, or the fringes wash out.
• Poor beam quality can also wash out the fringes, preventing the measurement.
• It has no independent checks or feedback, and no marginals are available.
• It cannot measure long or complex pulses: TBP < ~3. (Spectral resolution is ~10 times worse than that of the spectrometer due to the need for fringes.)
• It has poor sensitivity due to the need to split and stretch the pulse before the nonlinear medium.
• The pulse delay must be chosen for the particular pulse. And pulse structure can confuse it, yielding ambiguities.