Ultrashort Pulse Characterization

Presented by:

OSA Nonlinear Optics Technical Group
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ULTRASHORT PULSE CHARACTERIZATION

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Nonlinear Optics Technical Group
Technical Group at a glance

• Focus
  – “Physics of nonlinear optical materials, processes, devices, & applications”
  – **3800** members (**largest** in OIS, 3**rd** largest in OSA)

• Mission
  – To benefit **YOU**
  – webinars, e-Presence, publications, technical events, business events, outreach
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Today’s webinar

Ultrashort Pulse Characterization

Speaker’s short Bio:
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Ultrashort pulse characterization

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Why short pulses?

When detectors are too slow...

... you need a light pulse which is faster than the process to be recorded

- Fastest incoherent light pulse: $100\cdot10^{-9}$ s
- **Lasers pulses**: duration down to $10\cdot10^{-18}$ s
- They are the **shortest artificial events** ever generated
- They are the **ruler** to measure ultrafast events in nature

Photograph taken by Harold Edgerton, MIT, 1964
A travel in time and space

Electron motion: $10^{-18}$ s

Molecular motion: $10^{-12} - 10^{-15}$ s

Macromolecules dynamics: $10^{-9}$ s

Heart beat: 1 s

Average life of man: $10^9$ s

Age of universe: $4.3 \times 10^{17}$ s

Laser

Incoherent light
Properties of a light pulse

**Pulse** $E(t)$:
Product between *envelope* and *carrier*

**Slow response:**
Measures the time integral of the pulse intensity from $-\infty$ to $+\infty$:

$$V_{\text{detector}} = \int_{-\infty}^{\infty} |E(t)|^2 \, dt$$

Pulse energy

Increasing Optical Cycle (seconds)

- $33 \cdot 10^{-18}$
- $10^{-15}$
- $5 \cdot 10^{-15}$
- $100 \cdot 10^{-15}$
- $3 \cdot 10^{-12}$
Representation of optical pulses

\[ E(t) \]

\[ \varphi(\omega) \]

\[ \tilde{E}(\omega) \]

**Chronocyclic Wigner function**

Examples of chronocyclic functions

Ludwig van Beethoven

Symphony No. 5
C minor op. 67
Allegro con brio

ff

The musical score lives in the **time-frequency** domain

https://www.gw-openscience.org/GWTC-1/
Examples of pulses

Transform-limited

Group-delay dispersion (GDD)

Third-order dispersion (GDD)

Two identical pulses

\[ \omega(t) = \omega_0 - \frac{d\phi}{dt} \]

Phase: determines the pulse’s frequency (i.e., color) vs. time.

doi: 10.1088/0953-4075/43/10/103001
Direct measurement techniques

Example 1

- **Range**: MIR, optical cycle >100 fs
- **Process**: Electro optic effect

Example 2

- **Range**: IR, visible, optical cycle <3 fs
- **Process**: electron acceleration

Scan the electric field of the pulse with a time-gate

*Gate*: shorter than optical cycle

DOI: 10.1126/science.aac9788
Representation of optical pulses

Role of spectral phase

**MILAN**

Fourier Transform → Amplitude Phase → Fourier Transform\(^{-1}\)

**ROME**

Fourier Transform → Amplitude Phase → Fourier Transform\(^{-1}\)
Linear autocorrelation: Fourier Transform spectroscopy

- Michelson Interferometer
- Linear interferometry

2 field replicas

Wiener-Khinchin-Einstein theorem
- Wiener (1930): deterministic function
- Khinchin (1934): stationary stochastic processes
- Einstein (1914): the idea in a two-page memo

The FT of the interferogram only provides the spectrum - and vice versa -
Intensity autocorrelation

$I_{AC}(\tau) \propto \int_{-\infty}^{\infty} |E(t) E(t-\tau)|^2 dt \propto \int_{-\infty}^{\infty} I(t)I(t - \tau) dt$.

Second-order process (second harmonic generation): product between intensities

Intensity autocorrelation

- Symmetric (even with non symmetric pulses)
- An autocorrelation typically corresponds to more than one intensity: an initial shape must be inferred (Gaussian, $\sec^2$, ...)
- The spectral phase cannot be determined
- Bandwidth of SHG: broad enough to double all band

Prof. Rick Trebino, www.frog.gatech.edu
Fringe-resolved Autocorrelation (FRAC)

\[ I_{LAC}(\tau) \propto \int_{-\infty}^{\infty} \left| [E(t) + E(t - \tau)]^2 \right|^2 dt. \equiv \int_{-\infty}^{\infty} \left| E^2(t) + E^2(t - \tau) + 2E(t)E(t - \tau) \right|^2 dt \]

New terms, due to collinear interaction

Old terms
Fringe-resolved Autocorrelation (FRAC)

\[
= \int_{-\infty}^{\infty} I^2(t) + I^2(t-\tau) \, dt
\]

Constant (uninteresting)

\[+ 4\int_{-\infty}^{\infty} I(t)I(t-\tau) \, dt\]

Intensity autocorrelation

\[+ 2\int_{-\infty}^{\infty} [I(t) + I(t-\tau)]E(t)E^*(t-\tau) \, dt + c.c\]

Sum-of-intensities-weighted interferogram of \(E(t)\)

(osillates at \(\omega\) in delay)

\[+ \int_{-\infty}^{\infty} E^2(t)E^{*2}(t-\tau) \, dt + c.c\]

Interferogram of the second harmonic;

equivalent to the spectrum of the SH

(osillates at \(2\omega\) in delay)

Combines several measures of the pulse.
They occur with different oscillation frequencies: 0, \(\omega\) (fundamental), and \(2\omega\) (second harmonic).
Examples of FRAC traces

- Symmetric (even with non-symmetric pulses)
- Sensitive to the temporal phase of the pulse
- Requires reconstruction methods to infer spectral phase
Advanced Pulse characterization

**Spectrographic techniques**
- FROG (Trebino, 1993)
- D-scan (Miranda, 2012)
- MIIPS (Lozovoy, 2004)
- ...

**Interferometric techniques**
- SPIDER (Iaconis, 1999)
- SEA-SPIDER (Kosik, 2005)
- CAR-SPIDER (Gorza, 2007)
- ZAP-SPIDER (Baum, 2004)
- 2DSI (Birge, 2006)
- SPIRIT (Messager, 2003)
- ...
Chronocyclic measurements

Measurement of the time-frequency information of the pulse: **spectrogram**

### Sonography

**Sonography** measures the time dependence of adjacent spectral slices

- Spectral filtering ($\Omega$)
- Temporal intensity analyzer ($\tau$)

### Spectrography

**Spectrography** measures the spectrum of sequential time slices

- Temporal gating ($\tau$)
- Optical spectrum analyzer ($\Omega$)

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General form of a spectrogram

$E(t)$: the waveform of interest:

$g(t-\tau)$: a variable-delay gate function, delayed by $\tau$

$$S(\omega, \tau) = \left| \int_{-\infty}^{\infty} E(t) g(t-\tau) \exp(-i\omega t) dt \right|^2$$

The product is guaranteed by the **nonlinear process**

Without $g(t-\tau)$, $S(\omega, \tau)$ would simply be the spectrum.

**Frequency Resolved Optical Gating (FROG)**
FROG measurements

\[ S(\omega, \tau) = \left| \int_{-\infty}^{\infty} E(t)g(t - \tau) \exp(-i\omega t)\,dt \right|^2 \]

Various **nonlinear processes** can be employed:

- **Second-harmonic generation**: by adding a spectrometer to the Intensity autocorrelator, we can easily measure a Spectrogram, where:

  \[ g(t - \tau) = E(t - \tau) \]

  \[ \text{SH-FROG} \]

- **Polarization gate**: By a third-order process (Kerr effect), the polarization of the probe is rotated by the gate:

  \[ g(t - \tau) = |E(t - \tau)|^2 \]

  \[ \text{PG-FROG} \]
Examples of FROG traces

- SH-FROG
- PG-FROG

- SH more sensitive than PG by 1 order of magnitude
- PG does not depend on phase-matching
- PG is sensitive to the sign of chirp
- Phase is retrieved by an iterative algorithm
Phase-scanning techniques

- New paradigm in pulse measurement: pulse is modified before measurement
- Advantage: simultaneous characterization and compression of the pulse

**Multiphoton intrapulse interference phase scan (MIIPS)**

**Dispersion scan (d-scan)**

Multiphoton Intrapulse Interference Phase Scan (MIIPS)

- $\phi(\omega)$
- $\varphi(\omega) = \phi(\omega) + f(\omega)$

Shaper $f(\omega)$

Spectrometer

SHG process: maximized at $\omega$ where $\varphi''(\omega) = 0$

- a shaper adds various known phase profiles to the test pulse.
- the spectrum of the frequency-doubled pulses is recorded as a function of the added phase.
- Phase retrieval: iterative algorithm

Dispersion scan (d-scan)

- Variable quadratic phase imposed by moving one of the wedges.
- The spectrum of the frequency-doubled pulses is recorded as a function of the added phase.
- Phase retrieval: iterative algorithm.

Representation of optical pulses

\[ E(t) \]

Phase \[ \varphi(\omega) \]

Amplitude \[ \tilde{E}(\omega) \]

Fourier Transform

Chronocyclic Wigner function

Spectral Interferometry (SI)

Measure the spectrum of the sum of:

- A reference field with known spectral phase $\phi_{\text{ref}}(\omega)$
- The unknown field with spectral phase $\phi_0(\omega)$

\[
\Delta \phi(\omega) = \phi_0(\omega) - \phi_{\text{ref}}(\omega)
\]

\[
S(\omega) = S_0(\omega) + S_{\text{ref}}(\omega) + \sqrt{S_0(\omega)S_{\text{ref}}(\omega)} \cos[\omega T + \Delta \phi(\omega)]
\]

THE RESULTING SPECTRUM IS MODULATED
Signal / reference Power Spectrum

\[ S(\omega) = S_0(\omega) + S_{\text{ref}}(\omega) + \sqrt{S_0(\omega)S_{\text{ref}}(\omega)} \cos[\omega T + \Delta\phi(\omega)] \]

The density of the interference pattern is the inverse of:

- Replicas delay \( T \)
- First derivative of \( \Delta \phi(\omega) \): \( d\Delta \phi(\omega)/d\omega \)

**INTERFERENCE PATTERN**

**DENSE FRINGES:** require high spectral resolution

**SPARSE FRINGES:** low-accuracy spectral phase retrieval
Spectral interferometry

\[ S(\omega) = S_0(\omega) + S_{\text{ref}}(\omega) + \sqrt{S_0(\omega) S_{\text{ref}}(\omega)} \cos[\omega T + \Delta \phi(\omega)] \]

2D (= Time vs frequency) ACQUISITION METHOD:
- It uses the full available spectral resolution
- Possibility of single-shot approaches: SEA-TADPOLE
- This involves no nonlinearity
- It requires a reference/known field

What if a reference beam is not available?

Doi: 10.1364/OE.14.011892
Spectral shearing interferometry

- The pulse interferes with a frequency-shifted replica of itself
- Up/down-conversion with two ancillary fields $\omega_1$ and $\omega_2$

$$S(\omega) = S_0(\omega) + S_{\text{ref}}(\omega) + \sqrt{S_0(\omega) S_{\text{ref}}(\omega)} \cos[\omega \tau + \Delta \varphi(\omega)]$$

Spectral shear: $\Omega = \omega_1 - \omega_2$

Interference: $\omega \tau + \varphi(\omega) - \varphi(\omega - \Omega)$
Spectral phase interferometry for direct electric-field reconstruction (SPIDER)

- Calibration of $\tau$: zero-delay shearing interferometry

- Calibration of $\Omega$

Interference term:
$$\frac{\omega \tau + \varphi(\omega) - \varphi(\omega-\Omega)}{\Omega} \approx \frac{\tau}{\Omega} \omega + \frac{\partial \varphi}{\partial \omega}$$

Variants of SPIDER


Spatially encoded arrangement (SEA) SPIDER


Zero-added-phase (ZAP) SPIDER

Two-dimensional spectral shearing interferometry (2DSI)

Perform a measurement at delays around $\tau_{cw} = 0$

Ancillae generation

Test pulse

Ancillary fields

Pulse under test

Auxiliary pulse

Dispersive material

SFG/DFG + Spectrometer

Ancillae generation

10.1364/JOSAB.32.001851
Sub-10 fs pulses characterization

- Direct measurement of Group Delay
- Calculation of spectral phase
- Reconstructed pulse

Transform Limited duration: 3.6 fs
Reconstructed pulse duration: 3.8 fs

Pulse characterization by 2DSI

Conclusions

Many descriptions of optical pulses:

- Time: the ruler is the *optical cycle*
- Frequency: most information in the *spectral phase*

Autocorrelation techniques:

- Simple, 1D measurement (time)
- Symmetric traces, temporal profile is inferred, indirect information on spectral phase

Chronocyclic techniques:

- Frequency-resolved optical gating, d-scan, MIIPS
- 2D measurements (frequency-time, frequency-chirp,...)
- Retrieval of spectral phase

Interferometric techniques:

- Linear interferometry
- SPIDER, ZAP-SPIDER, SEA-SPIDER, 2DSI
- 2D measurements (frequency-time, frequency-chirp,...)