5 Measuring ultrashort laser pulses

The problem: In order to measure an event in time, you need have a shorter one (or: a temporal resolution which is high enough)

The fastest photodetectors have rise times in the low ps range ($\lesssim 100$ GHz) $\rightarrow$ too slow!

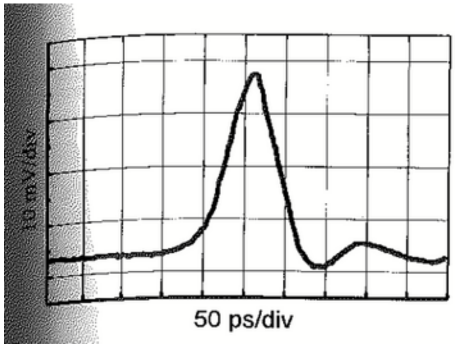
$\Rightarrow$ for fs light pulses: all optical methods needed!

$\rightarrow$ general approach:

1) map space on time ($1\,fs \,\hat{=}\, 0{,}3\,\mu m$)

2) make use of correlation function

Consider two time-dependent functions $F(t)$, $F'(t)$ where $F'(t) < F(t)$, then



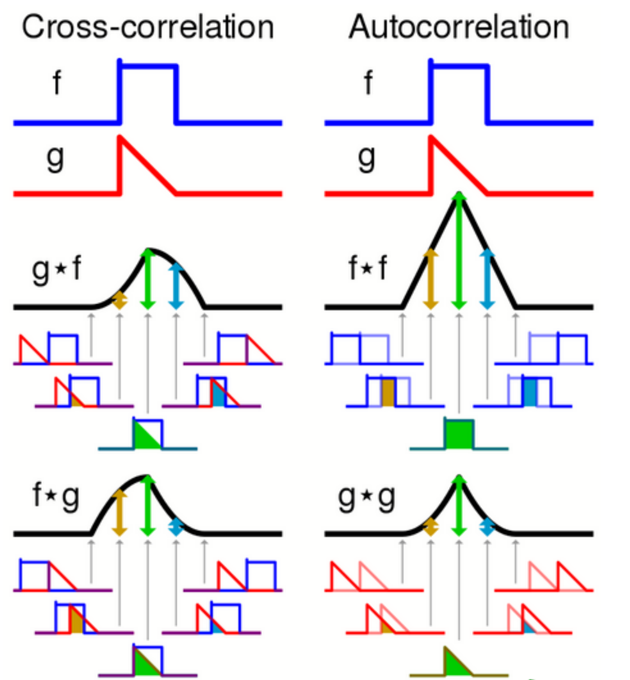
Measurement of a fs light pulse (from Rullière)

(2)

$G(\tau)$ is

$$\boxed{G(\tau) = \int_{-\infty}^{\infty} F'(t)\, F(t-\tau)\, dt}$$

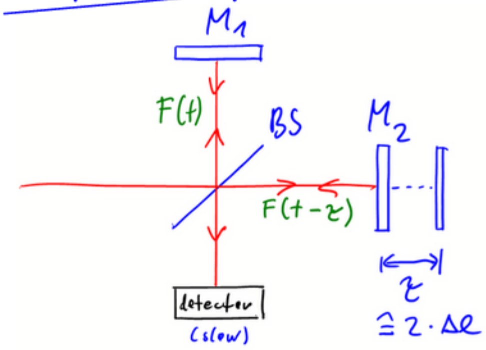
first order correlation function



Cross- and autocorrelation / Wikipedia / cmglee

If we have $F'(t)$ and $G(\tau)$, we also know $F(t-\tau)$. For fs lasers, we generally do not have a shorter test function ⟹ use of „autocorrelation", i.e, we correlate the pulse with itself. For two different pulses, we call this „cross correlation"

Exp. setup: Michelson interferometer



5.1. Optical correlation

$\vec{E}(t) \hat{=} \vec{F}(t)$, however our detector measures $I(t) = \langle \vec{E}(t) \cdot \vec{E}^*(t) \rangle$

$\Rightarrow$ Signal at detector:

$$I_1(\tau) = \int_{-\infty}^{\infty} |\vec{E}(t) + E(t-\tau)|^2 \, dt$$

which, using $G(\tau)$, is $\quad I_1(\tau) \propto 2 \int_{-\infty}^{\infty} \underbrace{I(t)}_{|E(t)|^2} dt + 2\, \underbrace{G(\tau)}_{\int_{-\infty}^{\infty} E(t)\, E(t-\tau)\, dt}$

Does the interference term for 1st order contain the pulse duration? A: NO! → Measures only spectrum of $E(t)$ (Wiener – Khinchin theorem) → No phase information.

Example

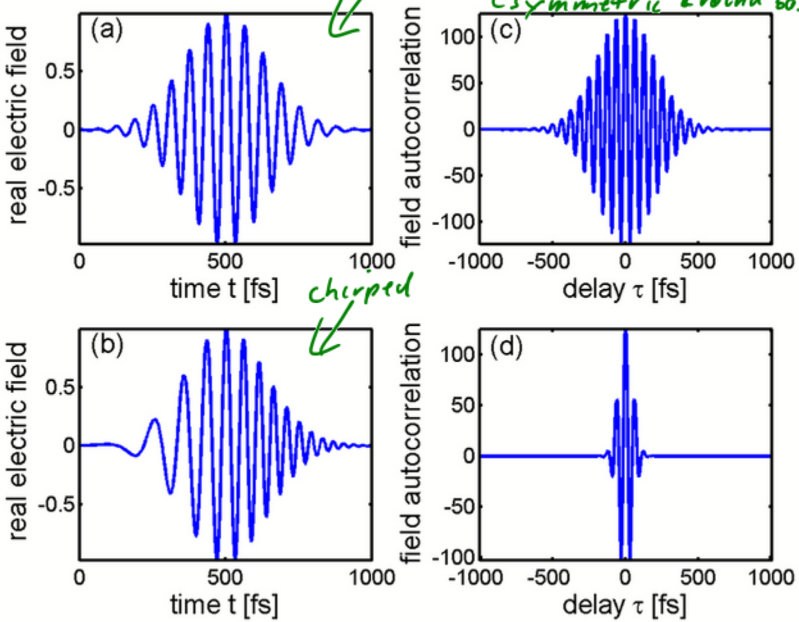
Field $E(t)$ — transform limited

1st order AC (symmetric around baseline)

a)

b)

chirped



Both pulses a) and b) have the same temporal duration, however the 1st order AC differs vastly!

→ pulse b) has higher bandwidth ⟺ shorter coherence length

Source: Wikipedia / Pgabolde

→ Article on optical correlation

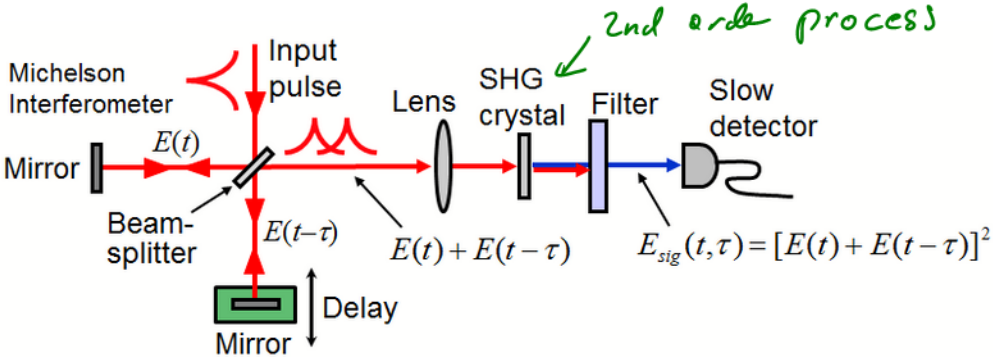
$\Rightarrow$ Need higher order correlation to learn about pulse duration, e.g.:

2nd order: Second harmonic generation, two photon absorption ($h\nu < E_{gap}$)

3rd order: Kerr effect, third harmonic generation

Note: In principle, using only autocorrelation all order $G_n(\tau)$ need to be known to fully retrieve $\vec{E}(t)$, mostly (we hope) 2nd order is enough for realistic approximations.

5.2. 2nd order autocorrelator



Interferometric autocorrelator

Trebino / Ultrafast optics course

2nd order signal

→ Rulliere, Trebino

$$\boxed{\text{Note: } I_{SHG} \propto (I_{Fund})^2 !}$$

$$I_2(\tau) = \int_{-\infty}^{\infty} |[\vec{E}(t) + E(t-\tau)]^2|^2 \, dt = \dots$$

using $\vec{E}(t) = E(t) \cdot e^{i(\omega t + \phi(t))}$

$$= \int_{-\infty}^{\infty} \Big| \underbrace{2E^4}_{\text{constant}} + \underbrace{4E^2(t)E^2(t-\tau)}_{\text{intensity AC}}$$

$$+ \underbrace{4E(t)\,E(t-\tau)\,[E^2(t) + E^2(t-\tau)]\cos(\omega\tau + \phi(t) - \phi(t-\tau)]}_{\text{modified interferogram of } E(t)}$$

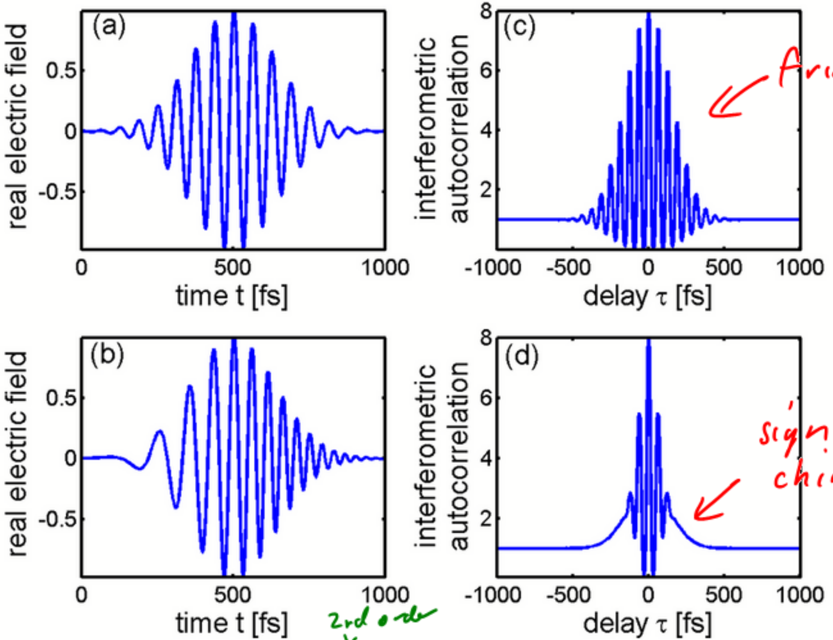
$$+ \underbrace{2E^2(t)\,E^2(t-\tau)\cos[2(\omega\tau + \phi(t) - \phi(t-\tau))]}_{\text{interferogram of SHG}} \Big| \, dt$$

→ (possibly) very complicated signal, however

1) $I_2(\tau=0) = 2^4 \int \vec{E}^4(t)\,dt$ 2) $I_2(\tau=\infty) = 2\int E^4(t)\,dt$

Field $E(t)$

Interferometric 2nd order AC



2nd order Interferometric AC / Wikipedia / Pyasoldp

Well aligned IAC (2nd order)

→ contrast 8 : 1

→ traces have to be symmetric

→ Possibility to learn about presence of chirp

→ Can extract pulse duration

Signal analysis complicated, as chirp changes fringe pattern

Fringes only occur for equal optical frequencies of $E(t)$, $E(t-\tau)$

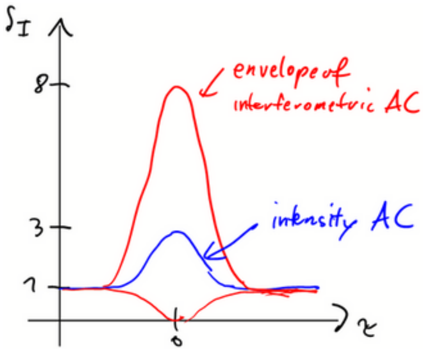
→ chirp makes the pulse look shorter.

⇒ Determination of pulse duration easier using the so-called ..

Intensity autocorrelation

Either numerical filtering or experimentally washing signal out (e.g. sweep fast) yields intensity AC:

$$S_I = 2\int \underbrace{I^2 \, dt}_{\text{background}} + 4 \int \underbrace{I(t)\, I(t-\tau)\, dt}_{\text{2nd order intensity AC (no phase terms)}}$$

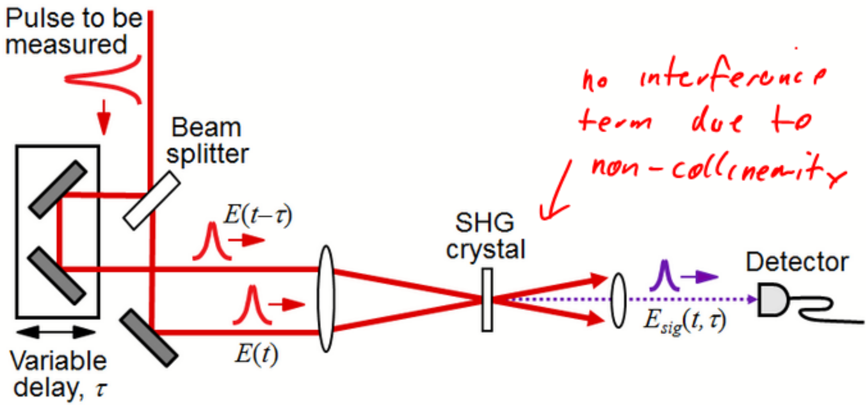


Contrast ratio 3:1, again symmetric in τ

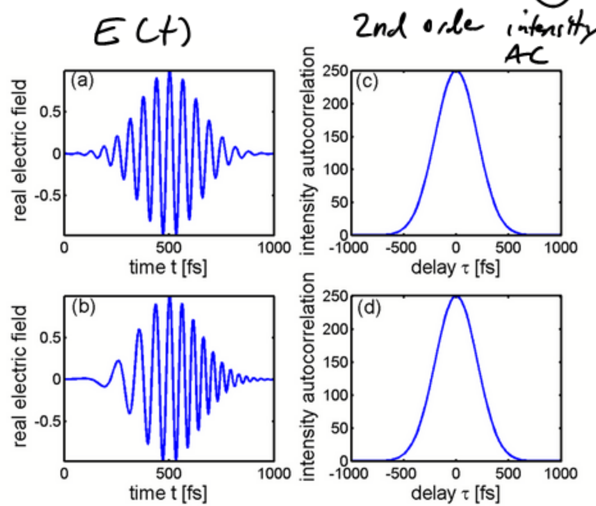
Most common, because easy to use, pulse width given by „Full width at half maximum" (FWHM) and convolving factor.

Alternatively, one may use a non-collinear arrangement, which directly yields the intensity AC without „background".

(drawback: no check for proper alignment)



2nd order intensity AC in non-collinear geometry / Trebino



Background free intensity AC / Wikipedia

Here, we directly see that both pulses have same intensity AC, in order to obtain a pulse duration, we now have to assume a pulse shape!

Signal analysis

If we have a pulse with FWHM Δt, the width of the AC function $\Delta \tau$ is connected to this by a factor depending on the pulse shape. Today, the common choice is gaussian ($\propto e^{-t^2}$) and $\Delta \tau_{Gauss} = \sqrt{2}\,\Delta t$. In earlier literature often a $\text{sech}^2(t)$ pulse is used with $\Delta \tau_{sech^2} = 1.54\,\Delta t$ yielding the shortest pulses.

(end of lecture)
→ FROG slides

Summary: Using 2nd order AC, we can obtain a measure of our pulse duration by guessing a pulse shape.

Conclusions from Summary: 1) However, we do not know the accuracy of that guess
→ it might be terribly bad

2) We also know very little about the pulse phase, no quantitative analysis is possible from AC!

5.3 Frequency-resolved optical gating

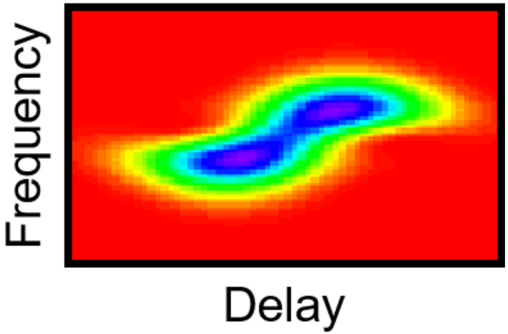
Better ways of characterizing ultrashort pulses measure the AC function spectrally resolved. This is called frequency resolved optical gating or short FROG. Basically, we replace the photodetector with a spectrometer.

For SHG-Frog, e.g., we obtain

$$I_{Frog}(\omega,\tau) = \left| \int_{-\infty}^{\infty} E_{sig}(t,\tau) \exp(i\omega t)\, dt \right|^2$$

where

$$E_{sig}^{SHG}(t,\tau) = E(t)\, E(t-\tau) \qquad (\text{here } E(t-\tau) = G(\tau))$$



FROG trace of pulse with self phase modulation / Trebino

As we can see, the FROG trace is in the (ω, τ)-plane, a projection onto τ yields the intensity AC.

What is the gain?

1) For some FROG geometries, you immediately understand second order chirp (and possibly 3rd order) from traces

2) In contrast to AC you can iteratively retrieve amplitude + phase from FROG traces, i.e., reconstruct $E(t)$ using suitable algorithms for 2D phase retrieval

$\Rightarrow$ See, e.g., frog.gatech.edu $\Rightarrow$ Talks $\Rightarrow$ Ultrafast Optics course
$\Rightarrow$ English lectures $\Rightarrow$ UFO-11-FROG.ppt

$\rightarrow$ Some excerpts follow now

$\rightarrow$ Advertisement: Master lab course FM.ULP $\rightarrow$ Spatiotemporal ...