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Ultrashort Optical Pulse Measurements

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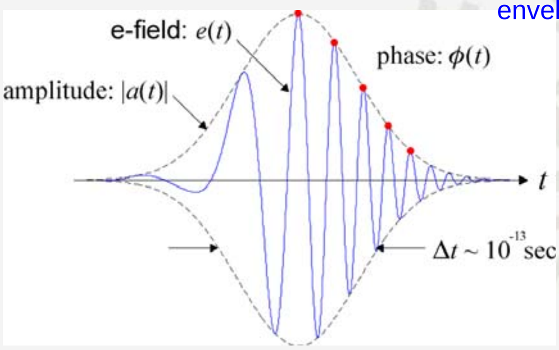
What's ultrashort pulse?

Restrict to scalar plane waves:

$$e(t) = |a(t)|\cos[2\pi f_0 t + \phi(t)] = \mathrm{Re}\left\{ \underbrace{|a(t)|e^{j\phi(t)}}_{\text{temporal envelope}} \cdot \underbrace{e^{j2\pi f_0 t}}_{\text{carrier}} \right\}$$

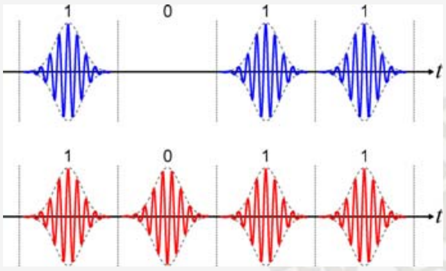


Application (1)

Digital telecommunications

Amplitude modulation

Phase modulation



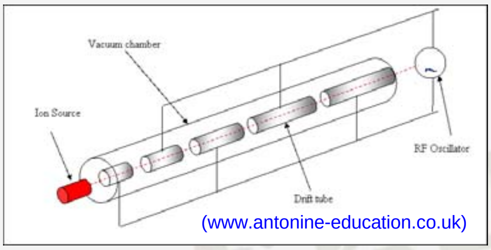
5.1×10^{12} bit/sec on a single wavelength channel using 410 fs pulses has been demonstrated

(H. C. Hansen Mulvad, et. al. LEOS post deadline, 2009)

Application (2)

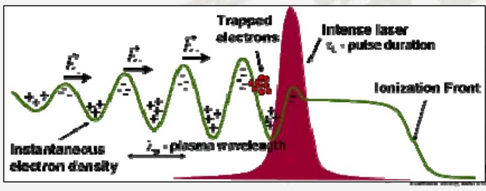
Wakefield electron acceleration

Conventional linear RF accelerator: < 10's MeV/m



(www.antonine-education.co.uk)

Plasma Wakefield accelerator: 10's GeV/m



(www.engin.umich.edu)

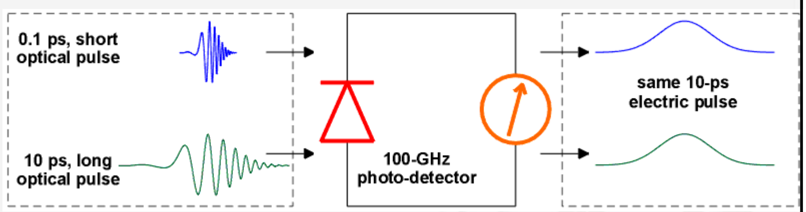
How to measure it? (1)

- Goal: get complex envelope in time or frequency domain
$$\begin{cases} a(t) = |a(t)| e^{j\phi(t)} \\ A(\omega) = |A(\omega)| e^{j\psi(\omega)} \end{cases}$$
- Strategy: use an even faster shutter(gate)

(graphics.stanford.edu/~levoy/research.html)

How to measure it? (2)

- OE conversion? Too slow…



- Optical approaches: correlation, time-frequency, spectral shearing, …

Outline

- Review of ultrashort pulse measurement techniques
- Modified interferometric field autocorrelation (MIFA)
- Experimental results
- Summary & perspective

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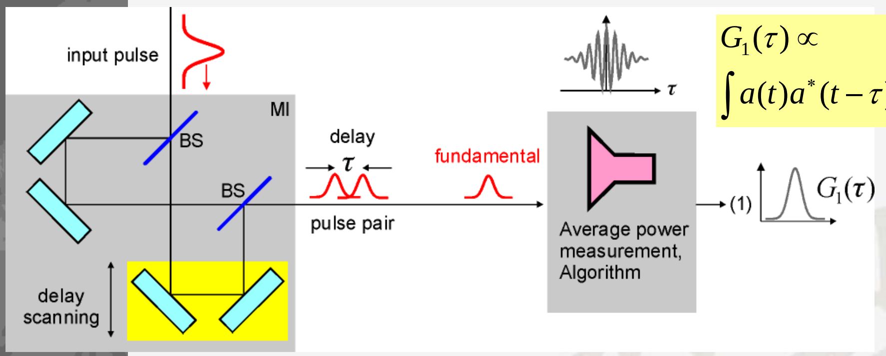
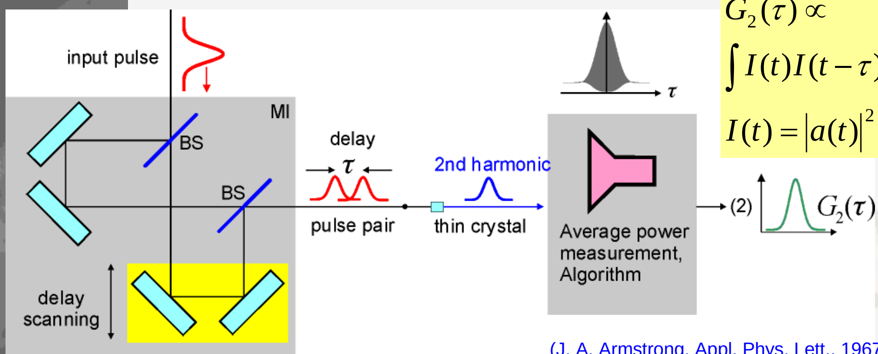
1. Linear self-gating



$G_1(\tau) \propto \int a(t) a^*(t-\tau) dt$

- Got field autocorrelation function: $G_1(\tau)$
- Equivalent to power spectrum: $F\{G_1(\tau)\} \propto |A(\omega)|^2$

2. Self-gating by SHG



$G_2(\tau) \propto \int I(t) I(t-\tau) dt,$

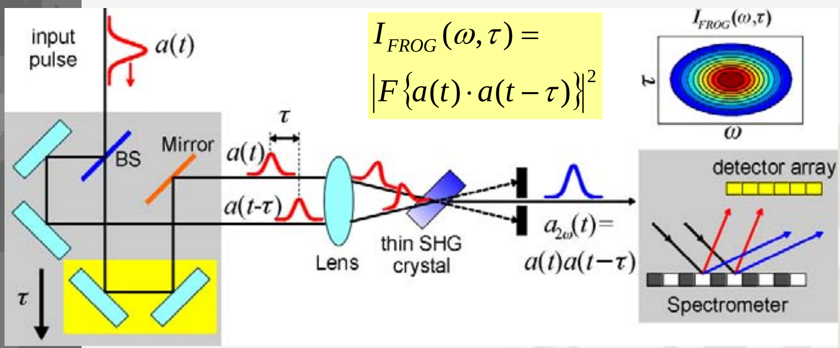
$I(t) = |a(t)|^2$

(J. A. Armstrong, Appl. Phys. Lett., 1967)

- Got intensity autocorrelation function: $G_2(\tau)$
- $F\{G_2(\tau)\} \propto |F\{I(t)\}|^2$

3. FROG (frequency-resolved optical gating)

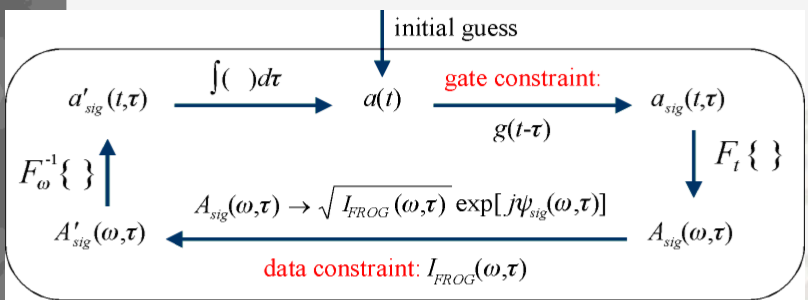
Step 1. Spectrogram measurement



(D. J. Kane, JQE, 1993)

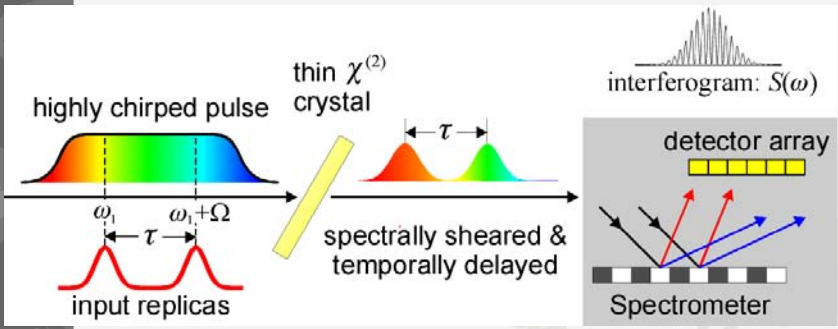
3. FROG (frequency-resolved optical gating)

Step 2. Iteration to get the complex envelope (2D phase retrieval problem)



- Need spectrometer & detector array (costly) and iteration (slow)

4. SPIDER (spec phase interferometry for direct e-field reconstruction)



(C. Iaconis, Opt. Lett., 1998)

- Obtain spectral phase: $\psi(\omega)$
- Need high-resolution spectrometer & detector array (costly)

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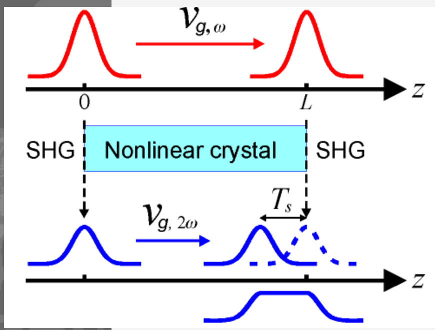
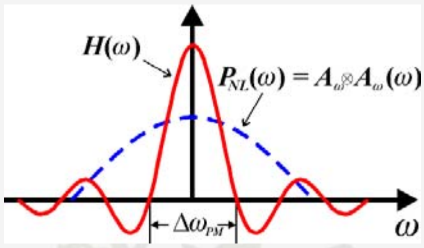
SHG of short pulses



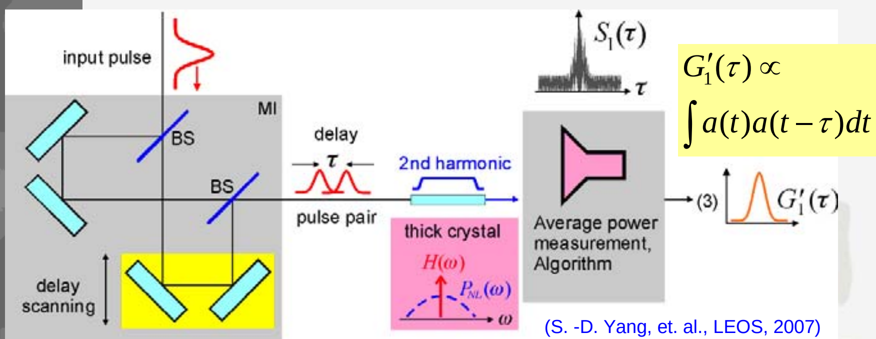
$A_{2\omega}(\omega) \propto P_{NL}(\omega) \cdot H(\omega)$



- GVM walk-off: $T_s \propto \Delta(v_g^{-1}) \cdot L$
- Thick crystal → stretched, square SH pulses

- PM BW: $\Delta\omega_{PM} \propto 1/T_s$
- Narrow $H(\omega)$ "filters" $P_{NL}(\omega)$, not $A(\omega)$ itself.

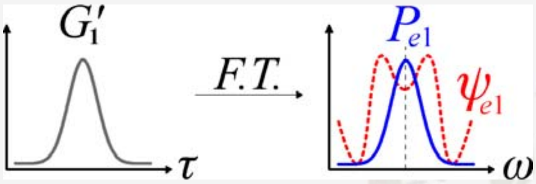
Self-gating by narrowband SHG (1)



- $S_1(\tau)=1+2|G'_1(\tau)|^2+4\text{Re}[G'_1(\tau)]\cos(\omega_0\tau)+\cos(2\omega_0\tau)$
- $G'_1(\tau) \propto \langle a(t)\cdot a(t-\tau)\rangle$ (v.s. $G_1(\tau) \propto \langle a(t)\cdot a^*(t-\tau)\rangle$)

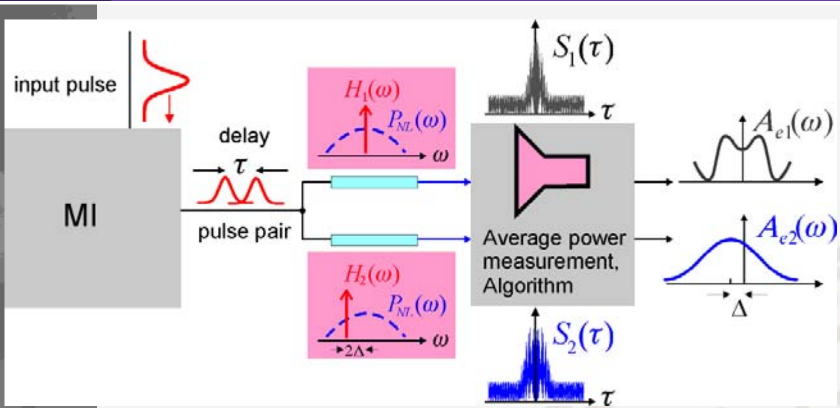
Self-gating by narrowband SHG (2)

Information contained in modified field autocorrelation function $G_1'(\tau)$



- $F\{G'_1(\tau)\} \propto A(◆)\cdot A(-◆) = P_{e1}(◆)\cdot\exp[j2□_{e1}(◆)]$
- $□_{e1}(◆)$ = [□(◆)+□(−◆)]/2…(even phase)
- $P_{e1}(◆)$ = |A(◆)·A(−◆)|…(even intensity)

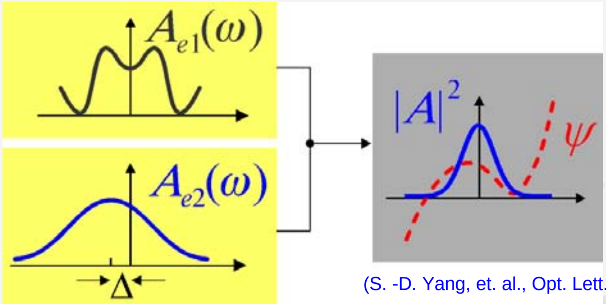
Double traces scheme (1)



- $A_{e2}(◆)=P_{e2}(◆)\cdot\exp[j2□_{e1}(◆)]$,

  $P_{e2}(◆)=|A(◆)\cdot A(-◆-2☟)|$ and $□_{e2}(◆)=[□(◆)+□(-◆-2☟)]/2$

Double traces scheme (2)



(S. -D. Yang, et. al., Opt. Lett., 2009)

- Recursive relations:

⍓(◆-2☟)−⍓(◆) =2[⍓$_{e2}$(◆-2☟)−⍓$_{e1}$(◆)]

|A(◆-2☟)/ A(◆)|^2 = [♋P$_{e2}$(◆-2☟)/ P$_{e1}$(◆)]^2

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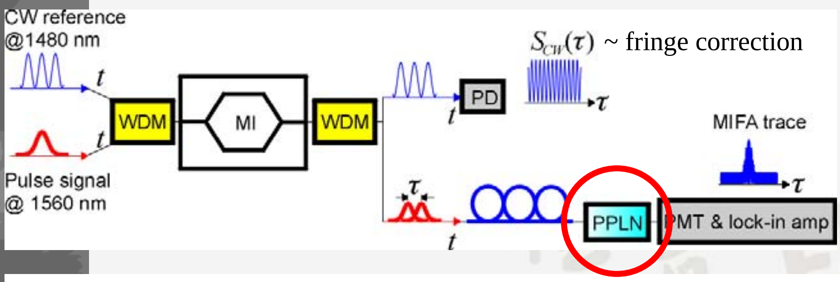
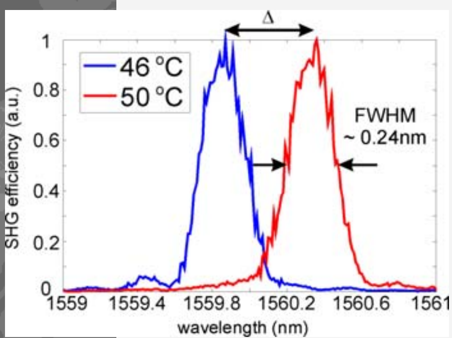
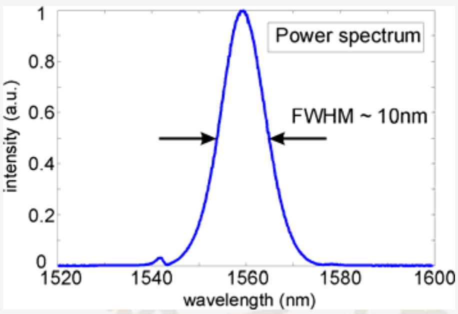
Experimental setup



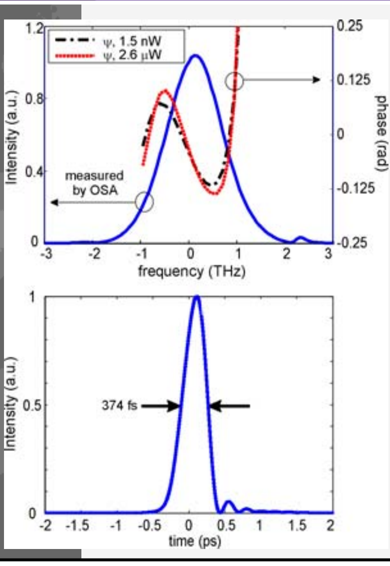
- Lock-in time constant = 640 ❍s
- Delay resolution = 0.64 fs < $1/4f_0$ = 1.3 fs
- It takes 10 sec to acquire one trace with a 10-ps delay window

Phase-matching bandwidth of 5-cm PPLN waveguide





Record high sensitivity



$\psi(f) = c_2 f^2 + c_3 f^3$

- At low power (1.5 nW):
  c_2 = **0.065ps²**, c_3 = **0.29ps³**;
- At high power (2.6 ❍W):
  c_2 = **0.061ps²**, c_3 = **0.36ps³**.
- 1.5 nW average power = 75 ❍W peak power **= 28 aJ** per pulse
- Sensitivity = 1.1×10^{-7} mW², 20 times better than the previous record.

(S. Yang, et. al., Opt. Lett., 2009)

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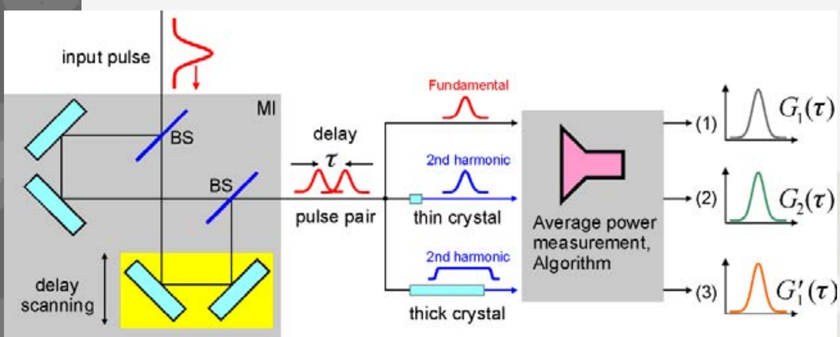
Summary

- We have proposed and demonstrated MIFA method that can retrieve complex envelope of ultrashort pulses
- By using 5-cm PPLN waveguide, we achieve a measurement sensitivity of 1.1×10^{-7} mW^2, ~20 times better than the previous record

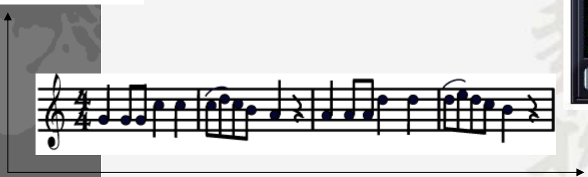
Comparison of correlation techniques



Perspective

- Ultrafast temporal phase detection by narrowband SHG
- Apply pulse shaper-based autocorrelator for MIFA to improve the sensitivity
- From femtosecond to attosecond regime?

Appendix: Spectrogram?

frequency

time