Attosecond Optics

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Why attosecond pulses?

Zeptosecond $(10^{-21} \text{s})$
Attosecond $(10^{-18} \text{s})$
Femtosecond $(10^{-15} \text{s})$
Picosecond $(10^{-12} \text{s})$

- Nuclear dynamics
- Electron motion
- Vibration
- Rotation
1 atomic u. of time is 24 as.

24 as corresponds to 73 eV.

As light is XUV/soft x-ray.

\[ \tau_{\text{XUV}}(\text{fs}) \approx \frac{1.825}{\Delta hv(\text{eV})} \]

\[ \Delta hv = 73 \text{eV} \]
Attosecond revolution: 2001

Outline

- Generation of attosecond pulses
- Characterization
- Applications
Ti:Sapphire CPA
25 fs, 800 nm
2.5 mJ, 2kHz
X-ray generation in one laser cycle

Proposed by Corkum & Kulander, 1993

1. Electron emission (tunneling ionization)
2. Acceleration (in E field of laser)
3. X-ray emission (recombination)
Multi-cycle lasers generate as pulse trains

Laser \((h\nu=1.5 \text{ eV})\)

Ar gas

XUV \((h\nu\sim73 \text{ eV})\)

20 fs driving laser

Gas

as pulse train

Half cycle: 1.3 fs

Paul et al, Science 292, 1689 (2001)
Isolated attosecond pulses

- Pump-probe experiments.
- Well-defined start and stop time.
Isolated as pulses with few-cycle lasers

Hentschel et al, Nature 414, 509 (2001)

Main difficulties:

- 4 fs white-light laser pulse is hard to produce.
- Carrier-envelope phase stabilization.

Other issues:

- Low photon flux (1 nJ).
Carrier envelope phase

\[ \phi_{CE} \]

Envelope

Electric Field
Our solution: Double Optical Gating

Objectives:

- Isolated as pulse generation with 25 fs lasers.
- No CE phase stabilization.

DOG = Two color gating + polarization gating.

Chang, PRA 76, 051403(R) (2007).
Mashiko et al., PRL 100, 103906 (2008).
Feng et al., PRL 103, 183901 (2009).
Two-color gating

Laser: $\omega$

Gas

as pulse train

Half cycle=1.3 fs

Laser: $\omega + 2\omega$

as pulse train

Full cycle=2.6 fs
Double Optical Gating

Two-color gating

Gas

Full cycle

as pulse train

Polarization gating

Gas

Full cycle

Single pulse
Laser field for polarization gating

Requires two-cycle pulses (<7 fs).

References:
- P. B. Corkum et al., OL 19, 1870 (1994)
- V. T. Platonenko et al., JOSA B 16, 435 (1999)
- Z. Chang, PRA 70, 043802 (2004)
Optics for DOG

Feng et al., PRL 103, 183901 (2009)

Double Optical Gating setup

- 1st quartz plate
- 2nd quartz plate
- Neon gas
- Transmission grating
- 50μm pinhole
- Spherical mirror
- BBO
- Focusing mirror

- Pulse duration: 800 μJ
- Input energy: 8 fs
- Gate width: 2.5 fs
- Peak intensity: $1.4 \times 10^{16}$ W/cm$^2$

Mashiko et al., Optics Letters 34, 3337 (2009).
XUV pulses extending to the “water window”

Full cycle gating

Two-color gating

Polarization gating

Gas

as pulse train

Single pulse

Full cycle
Full cycle gating

Two-color gating

Gas

as pulse train

Full cycle

Polarization gating

Gas

Single pulse

Full cycle
Few-cycle CE phase locked laser

- Prism-based CPA.
- One feedback loop for both oscillator and amplifier.

![Diagram of laser system with phases and components labeled.]
CE phase locking of grating-based CPA

- Two feedback loops: long locking time.
- Grating based CPA: high pulse energy.
Our CE phase stabilization

- **Our discovery**
  - CE phase susceptible to gating spacing.

- **Our scheme**
  - Using grating spacing to stabilize CE phase.
  - Independent loop for amplifier.

- **Advantage**
  - High energy lasers.
  - Long locking time.

Moon *et al.* LPR 4, 160 (2010)
4.5 hours of CE phase locking


f-to-2f fringe
Sweeping stabilized CE phase
Effect of carrier envelope phase on “water window” x-ray

- CE phase effect covers both the cutoff and plateau orders.
- Proof of gating method effectiveness for very broad spectra.
Soft x-ray supercontinuum from DOG

- Generation of the **shortest** soft x-ray pulse?

Single isolated 107 as pulse

Mashiko et al., Optics Letters 34, 3337 (2009).
Outline

- Generation of attosecond pulses
- Characterization
- Applications
Attosecond streaking

Attosecond streak camera for DOG

8-28 fs, 1-2 mJ laser
Attosecond streak camera

Photonics spectra, April, 14 (2010)
FROG measurement of 25 fs laser
Isolated 148 as pulse from 28 fs lasers

Feng et al., PRL 103, 183901 (2009).
Gilbertson et al., PRA 81, 043810 (2010).
DOG makes attosecond easy

Attoseconds for all


Feng et. al., PRL 103, 183901 (2009).
Outline

- Generation of attosecond pulses
- Characterization
- Applications
Solution look for problems

Short time scale
- Freezing electron motion.
- Direct mapping out visible field.

Broad bandwidth
- X-ray spectroscopy.
- Nanoscale OCT.

Short wavelength
- X-ray microscopy.
- Free space communication.
Summary

**Double Optical Gating**
- Driving laser: up to 28 fs.
- Arbitrary CE phase.
- Pulse energy: scalable.
- Pulse duration: <25 as?

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Reaching the ultimate time-limit…