Introduction to Ultrafast Laser

Lecture 1: Basic Facts & Outline

Wenjie Chen

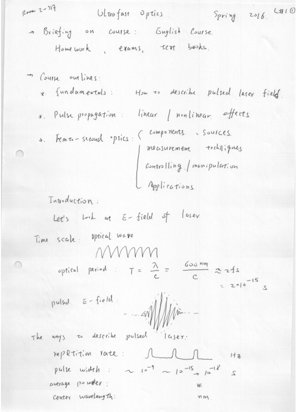
Peking University
International Center for Quantum Materials
Prof. Dr. Yuan Li

wenjiechen@pku.edu.cn

April 30, 2019

Before we start ...

- References;
- All lecture slides are **available online**;
- You are encouraged to stop me and ask any questions related to the lecture.


Room 2-317 Ultrafast Optics Spring 2016. L#1 ①

→ Briefing on course: English Course.
Homework, exams, text books.

→ Course outlines:
*. fundamentals: How to describe pulsed laser field.
*. Pulse propagation: linear / nonlinear effects
*. Femto-second optics: components, sources.
measurement techniques
controlling / manipulation
Applications.

Introduction:
Let's look at E-field of laser

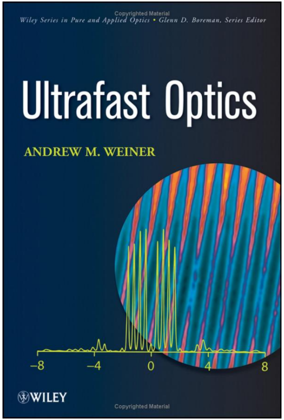
Time scale: optical wave

optical period: $T = \frac{\lambda}{c} = \frac{600\,nm}{c} \approx 2fs$
$= 2 \times 10^{-15}\,s$

pulsed E-field:

The ways to describe pulsed laser:
repetition rate: Hz
pulse width: $\sim 10^{-9} \sim 10^{-15} \to 10^{-18}$ s
average power: W.
center wavelength: nm

Prof. Kebin Shi, Spring 2019



by Andrew M. Weiner

Overview

1. Basic Facts about Ultrafast Laser
   - Time Scale
   - Shape
   - Important Parameters
   - Remark
2. Outline for Following Lectures

Time Scale

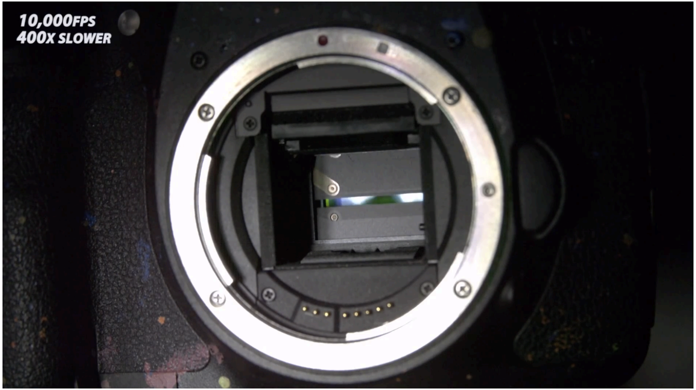
How fast is ultrafast?

second (1 s): Light travels 299,792,458 m ($\approx 3/4$ moon-earth distance) in vacuum.

Time Scale

How fast is ultrafast?

millisecond (1 ms $= 10^{-3}$ s): The fastest standard shutter speed for a normal camera.



Time Scale

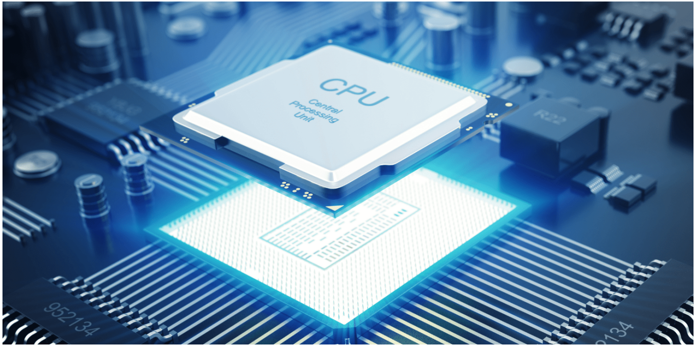
How fast is ultrafast?

microsecond (1 μs $= 10^{-6}$ s): Time duration for a high speed camera flash (to freeze the motion). J-20 can only travel about 1 mm at its maximum speed (2.8 Mach).

Time Scale

How fast is ultrafast?

nanosecond (1 ns $= 10^{-9}$ s): Modern CPUs' common clock rate (GHz).



Time Scale

How fast is ultrafast?

picosecond (1 ps = 10^{-12} s): Light travels about 0.3 mm in vacuum. Typical time scale for many dynamical processes (e.g. chemical reactions, molecular rotation).

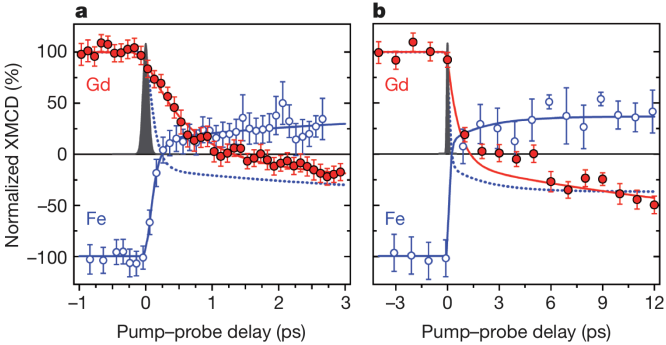


Figure: Spin reversal in ferrimagnetic alloy GdFeCo. I. Radu *et al.*, *Nature* **472**, 205–208 (2011).

Time Scale

How fast is ultrafast?

femtosecond (1 fs $= 10^{-15}$ s): The time period of light with $\lambda = 632.8$ nm is about 2 fs. Typical time scale for ultrafast laser pulses.

The Nobel Prize in Chemistry 1999 was awarded to Ahmed H. Zewail "*for his studies of the transition states of chemical reactions using femtosecond spectroscopy.*"

Figure: Ahmed H. Zewail

Time Scale

How fast is ultrafast?

attosecond (1 as $= 10^{-18}$ s): Typical time scale for dynamical processes inside atoms (e.g. tunneling in ionization).

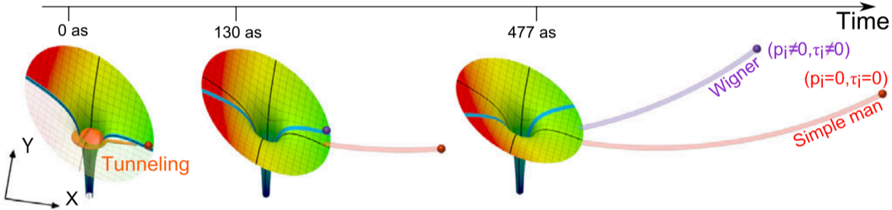
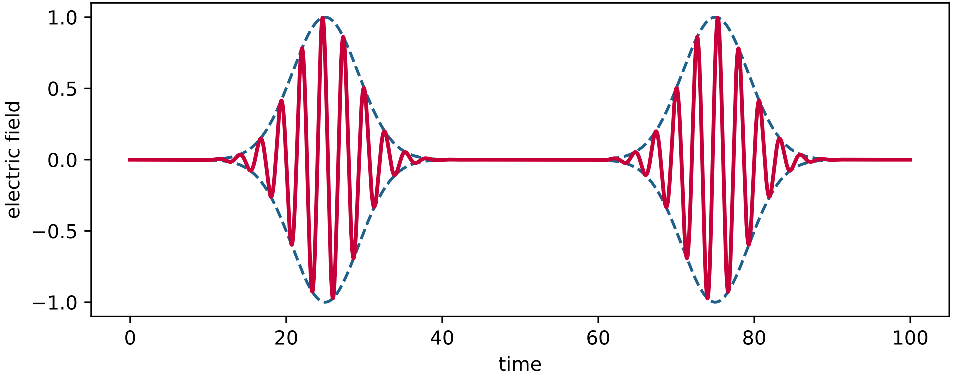


Figure: Ionization process in atoms. Nicolas Camus *et al.*, *Phys. Rev. Lett.* **119**, 023201 (2017).

Overview

Shape of the Ultrafast Laser Pulses

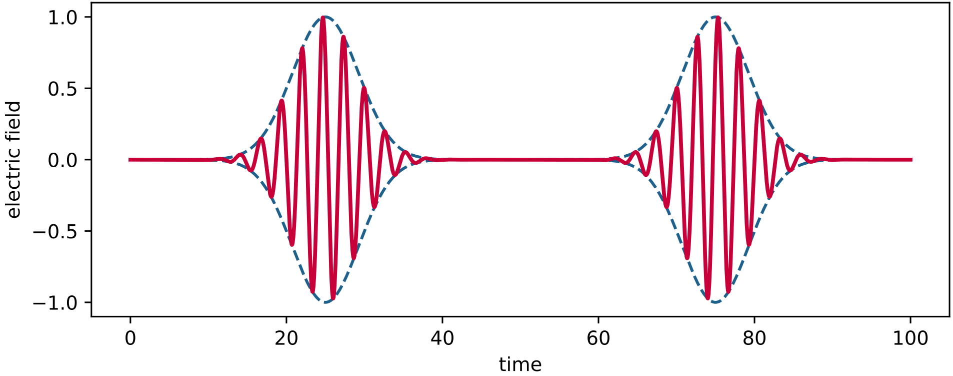
Envelope and carrier.



Totally wrong in quantity!

Shape of the Ultrafast Laser Pulses

Envelope and carrier.



Totally wrong in quantity!

Overview

1. Basic Facts about Ultrafast Laser
   - Time Scale
   - Shape
   - Important Parameters
   - Remark
2. Outline for Following Lectures

Important Parameters

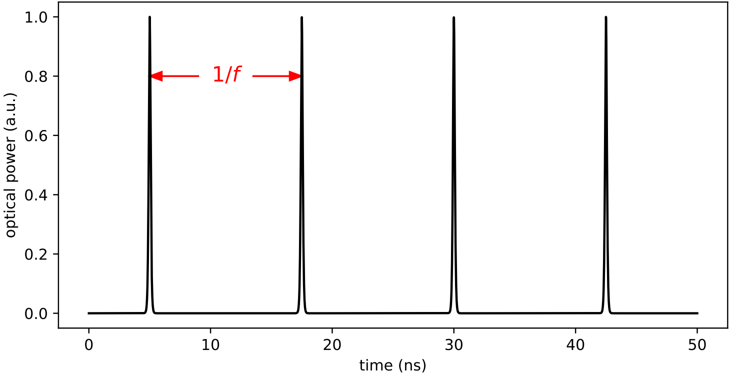
How to describe pulsed laser?

- **repetition rate**
- **pulse width**
- **average power**
- **center wavelength**

Important Parameters

Repetition rate: the number of pulses in one second. [kHz to MHz]

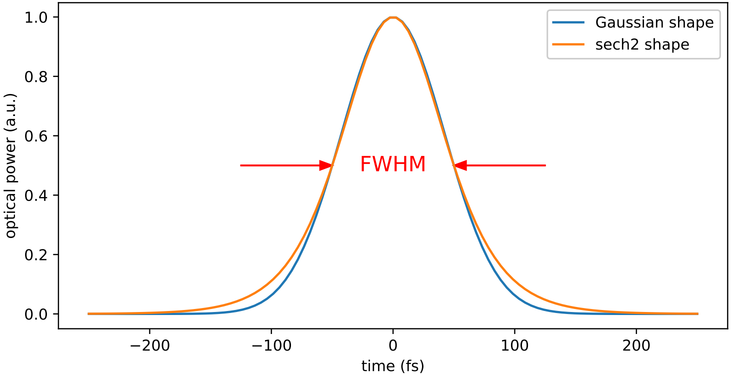
- Mai Tai ® Ultrafast Ti:Sapphire laser: 80 MHz $\pm$ 1 MHz.
- Period time: 12.5 ns.



Important Parameters

Pulse width (a.k.a pulse duration or pulse length): FWHM (*usually*). [fs]

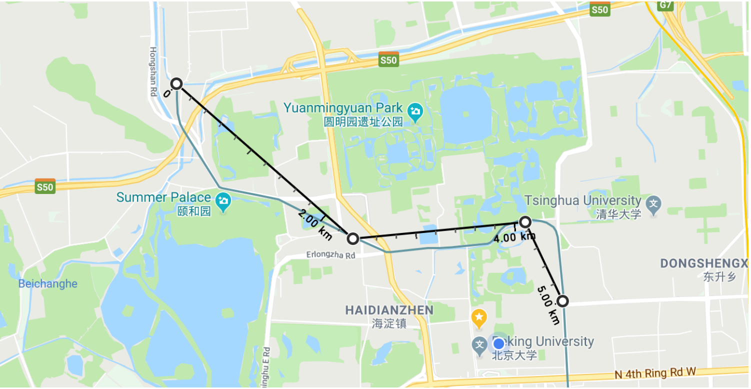
- Mai Tai ® Ultrafast Ti:Sapphire laser HP: < 100 fs.
- **Gaussian**: $I(t) = I_0 \exp[-4\ln(2)t^2/\tau^2]$. **sech2**: $I(t) = I_0\ \mathrm{sech}^2(-t/\tau)\ \{1.665\ \tau\}$.



Important Parameters

Pulse width (a.k.a pulse duration or pulse length): FWHM (*usually*). [fs]

- duty cycle = pulse width$/T = 8 \times 10^{-6}$.
- 4 minutes in 1 year, ping pong ball in 5 km!



Important Parameters

Average power. [W]

- Mai Tai HP at 800 nm: > 2.5 W.
- Pulse energy:

$$E_p = 2.5\ \text{W}/80\ \text{MHz} = 0.3125\ \mu\text{J}$$

- Peak power (Gaussian):

$$P_p = 0.94 \times E_p/100\ \text{fs} = 2.94 \times 10^6\ \text{W}$$

- Peak intensity (focus on a 10 μm diameter spot)

$$I = P_p/A = 3.74 \times 10^{12}\ \text{W/cm}^2$$

Important Parameters

Average power. [W]

- Mai Tai HP at 800 nm: > 2.5 W.
- Pulse energy:

$$E_p = 2.5 \text{ W}/80 \text{ MHz} = 0.3125 \text{ µJ}$$

- Peak power (Gaussian):

$$P_p = 0.94 \times E_p/100 \text{ fs} = 2.94 \times 10^6 \text{ W}$$

- Peak intensity (focus on a 10 µm diameter spot)

$$I = P_p/A = 3.74 \times 10^{12} \text{ W/cm}^2$$

Important Parameters

Average power. [W]

- Mai Tai HP at 800 nm: > 2.5 W.
- Pulse energy:

$$E_p = 2.5 \text{ W}/80 \text{ MHz} = 0.3125 \text{ µJ}$$

- Peak power (Gaussian):

$$P_p = 0.94 \times E_p/100 \text{ fs} = 2.94 \times 10^6 \text{ W}$$

- Peak intensity (focus on a 10 µm diameter spot)

$$I = P_p/A = 3.74 \times 10^{12} \text{ W/cm}^2$$

Important Parameters

Average power. [W]

- Mai Tai HP at 800 nm: > 2.5 W.
- Pulse energy:

$$E_p = 2.5 \text{ W}/80 \text{ MHz} = 0.3125 \text{ µJ}$$

- Peak power (Gaussian):

$$P_p = 0.94 \times E_p/100 \text{ fs} = 2.94 \times 10^6 \text{ W}$$

- Peak intensity (focus on a 10 µm diameter spot)

$$I = P_p/A = 3.74 \times 10^{12} \text{ W/cm}^2$$

Important Parameters

Average power. [W]

- Electric field:

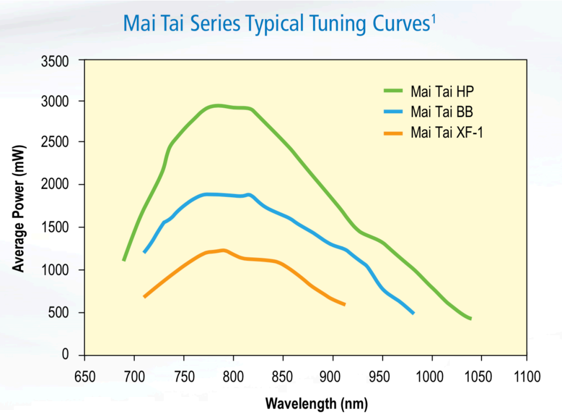
$$I = \frac{1}{2} c\epsilon_0 E^2 \Rightarrow E = 5.3 \times 10^9 \text{ V/m}$$

- An extremely intense field, about 5.2 Å away from an electron (recall: $a_0 = 0.53$ Å)!

Important Parameters

Center wavelength. [nm]

- Mai Tai HP: tunable from 690 nm to 1040 nm.



Important Parameters

How to describe pulsed laser?

Mai Tai ® Ultrafast Ti:Sapphire laser HP

- **repetition rate**: 80 MHz (maybe too large).
- **pulse width**: 100 fs (two shapes).
- **average power**: 2.5 W (peak power $\sim 3 \times 10^6$ W).
- **center wavelength**: tunable from 690 nm to 1040 nm.

Overview

1. Basic Facts about Ultrafast Laser
   - Time Scale
   - Shape
   - Important Parameters
   - Remark

2. Outline for Following Lectures

Remark

Frequency spectrum.

- Continuous Wave (CW) laser: infinity long laser $\rightarrow$ narrow bandwidth
- Ultrafast laser: short laser pulses $\rightarrow$ wide bandwidth with "teeth" (frequency comb).

Remark

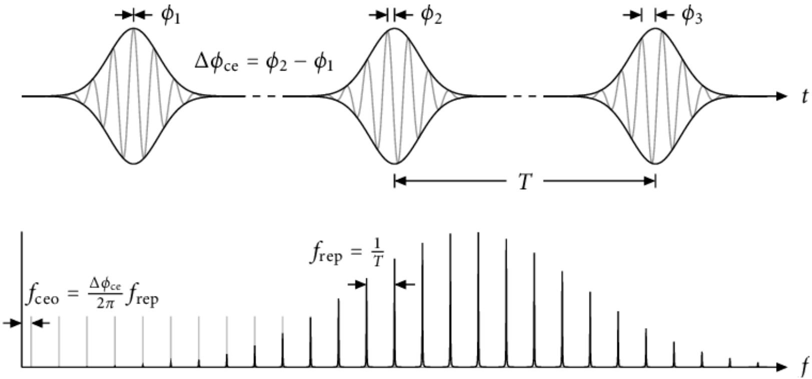
Frequency spectrum.

- Continuous Wave (CW) laser: infinity long laser $\rightarrow$ narrow bandwidth
- Ultrafast laser: short laser pulses $\rightarrow$ wide bandwidth with "teeth" (frequency comb).

Remark

Frequency spectrum.

- Continuous Wave (CW) laser: infinity long laser $\rightarrow$ narrow bandwidth
- Ultrafast laser: short laser pulses $\rightarrow$ wide bandwidth with "teeth" (frequency comb).



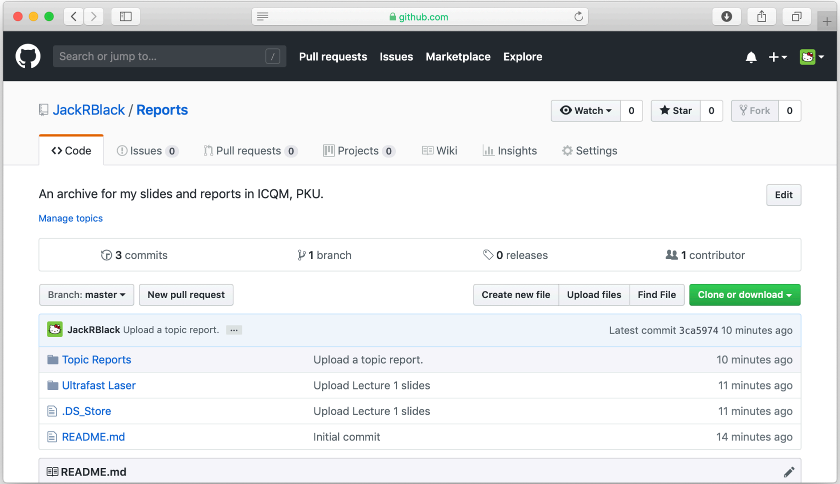
Overview

Outline for Following Lectures

Topic	# of lectures
mathematical description	1-2
propagating and dispersion	1-2
nonlinear and chirping effect	2
optical components	2
methods to generate ultrafast laser	?
paper reading	?
...	...

How to Download Lecture Slides

Go to [https://github.com/JackRBlack/Reports].



The End