원자분자겨울학교
대전, 카이스트, 2022. 2. 9 - 11

# 원자분자 겨울학교

## 극초단 레이저 원자 물리 I


**김경택**

**부교수, 물리광과학과, 광주과학기술원**
**부연구단장, 초강력레이저과학 연구단, 기초과학연구원**

# Contents

- Laser
  - Laser history
  - Principle of laser
  - Laser oscillator / mode-locking
  - Chirped pulse amplification
  - Amplifier
  - Chirped pulse amplification
  - Ultrashort pulse generation
  - Dispersion control
  - CEP measurement
  - Pulse measurement
  - Field measurement
- Strong field physics
  - Above threshold ionization
  - High harmonic generation
  - Frustrated tunneling ionization

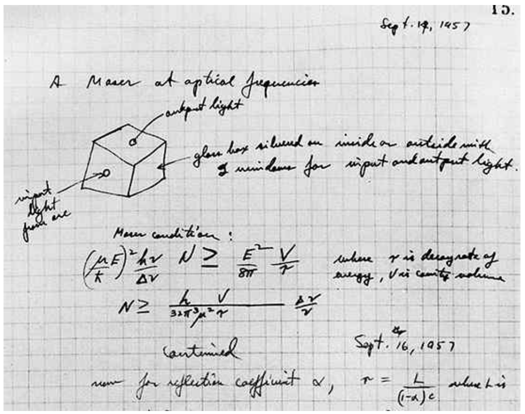
# Laser history

**Charles Hard Townes (1915~2015)**

1964 in Physics
Creation of MASER
Prof. at Columbia Univ.

- 1951, MASER (similar to LASER, but works in a microwave range
- 1954, First demonstration of MASER
- 1957, Suggest optical MASER in a visible wavelength range

1957. 9. 14

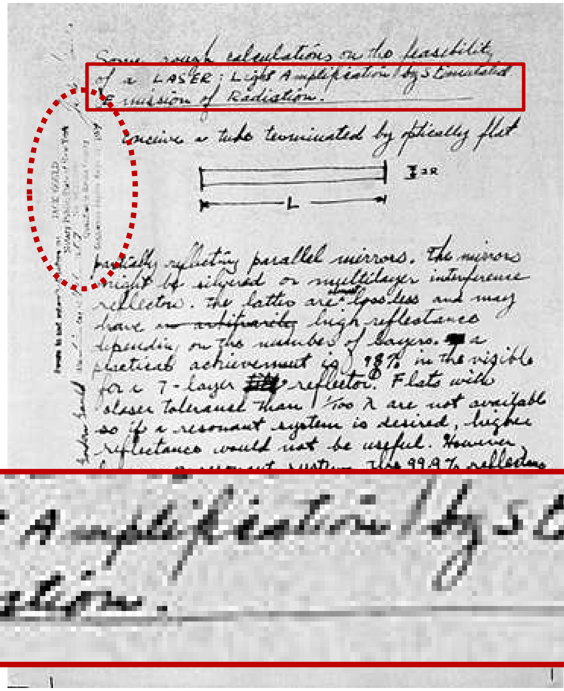


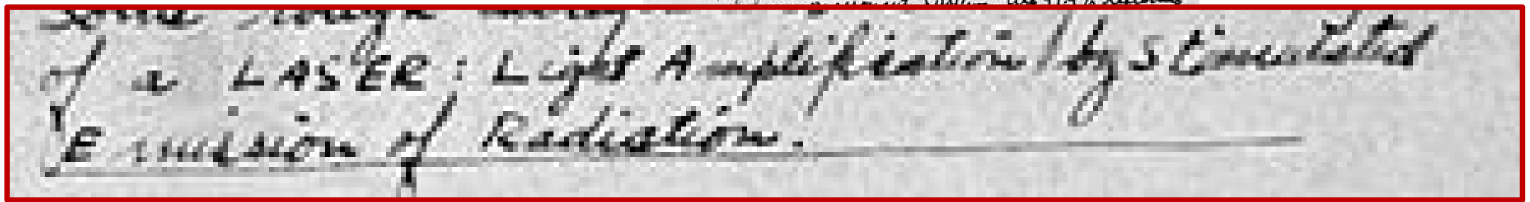
# Laser history

**Gordon Gould (1920~2005)**

Graduate student (1957) at Columbia Univ.

- Optical pumping reseach
- 1957, design “LASER”



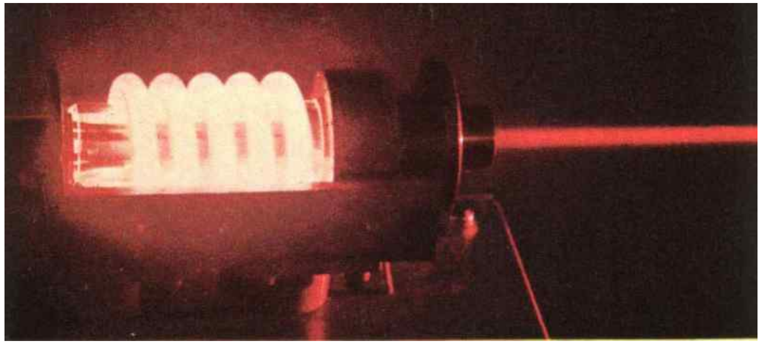

이후 Townes와 30년간 특허 분쟁을 함 (결국 승소)
1958, Townes and Schawlow published a paper on "optical masers"

# Laser history

**Theodore H. Maiman**
**(1927~2007)**

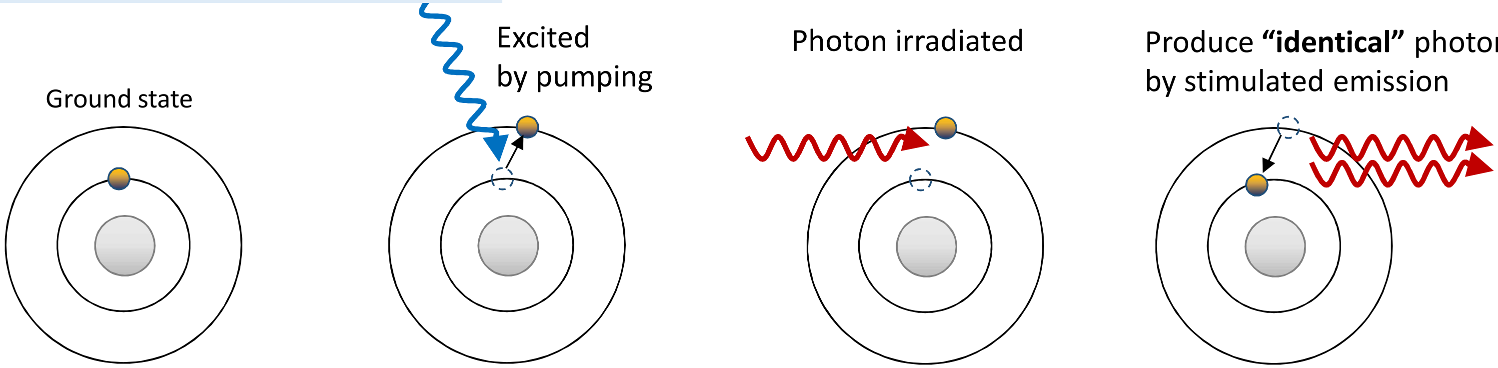
Researcher at
Hughes Research Laboratories

1960, first demonstration of a laser using a ruby crystal and a flash lamp.

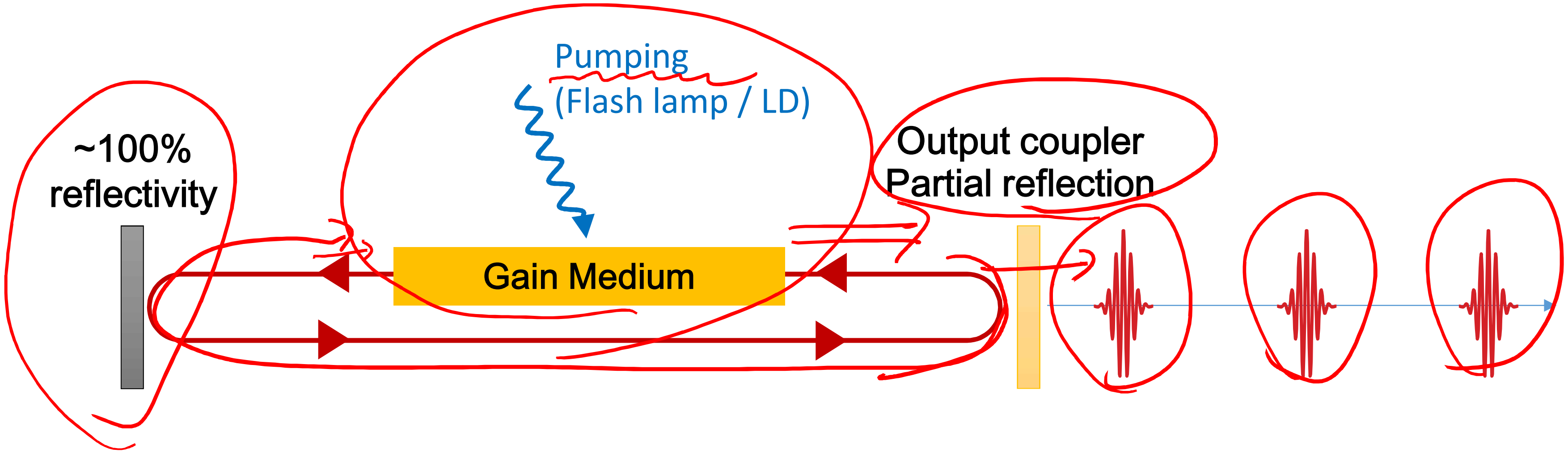


# Principle of Laser

## Optical pumping and stimulated emission



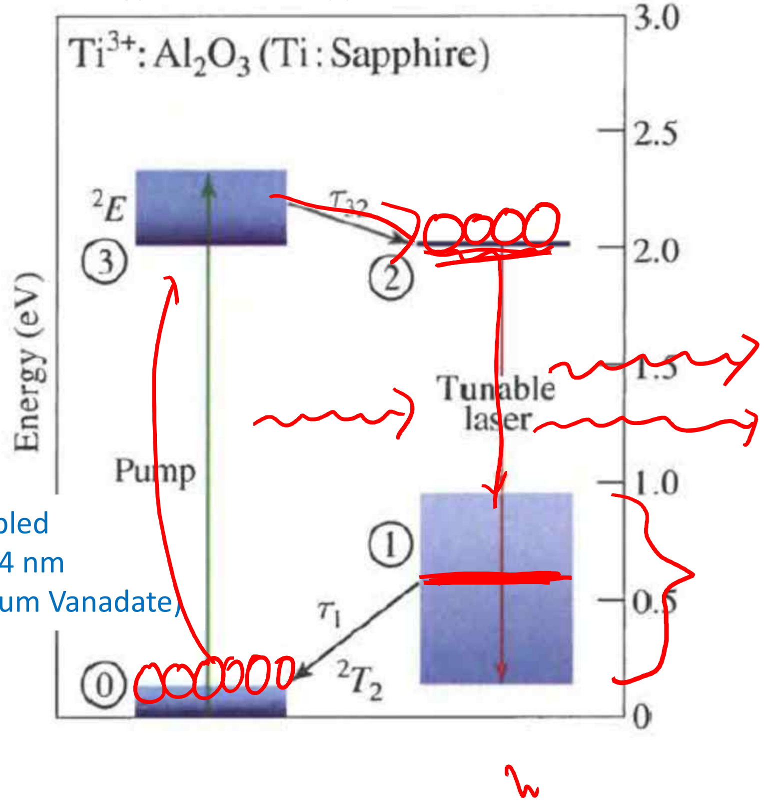

## Laser cavity




$$R = \frac{c}{2L}$$

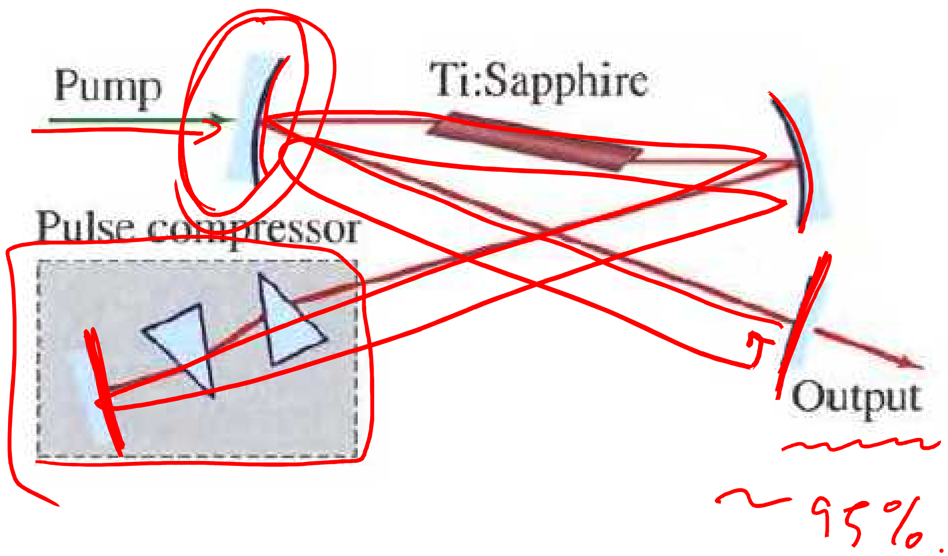
# Laser oscillator (Ti:sapphire laser)

Energy band of Ti:sapphire laser



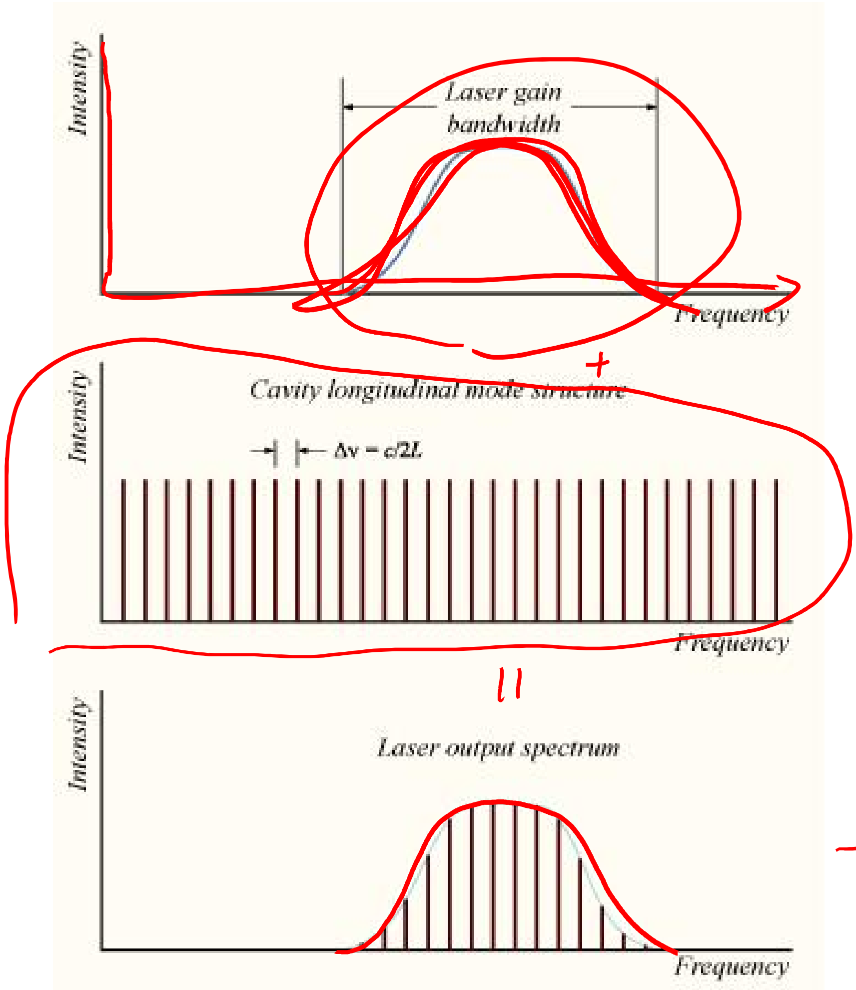

Frequency doubled
**$Nd^{3+}$:$YVO_4$**, 1064 nm
(Nd doped Yttrium Vanadate)

Ti:sapphire laser
- Kerr lens mode-locked laser




Fundamental of photonics, 2nd Ed,
B.E.A Saleh and M.C. Teich

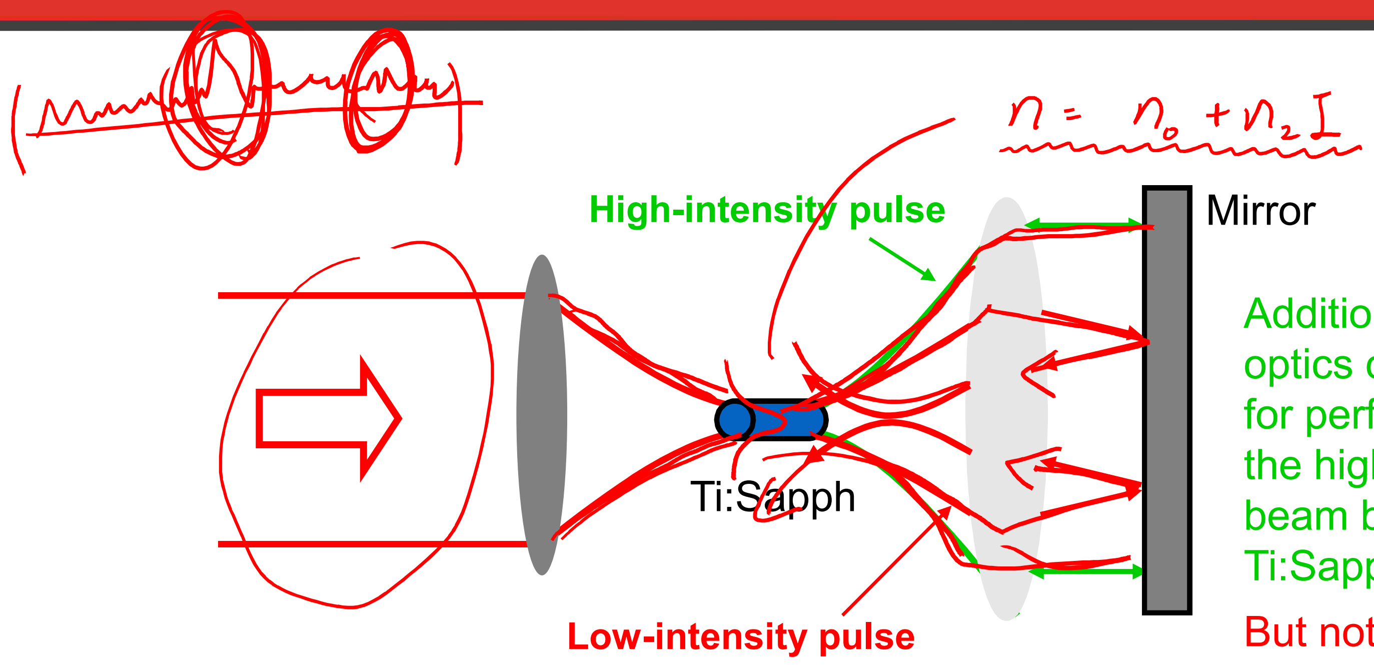
# Spectrum of a broad-band laser




**For Ti:sapphire laser**

- Gain bandwidth = 300nm
- If the cavity length L = 2m
- $\Delta\nu$ (C / 2L) = 75MHz
- $10^6$ longitudinal modes

# Cavity design for Kerr-lens mode-locking




Additional focusing optics can arrange for perfect overlap of the high-intensity beam back in the Ti:Sapphire crystal.

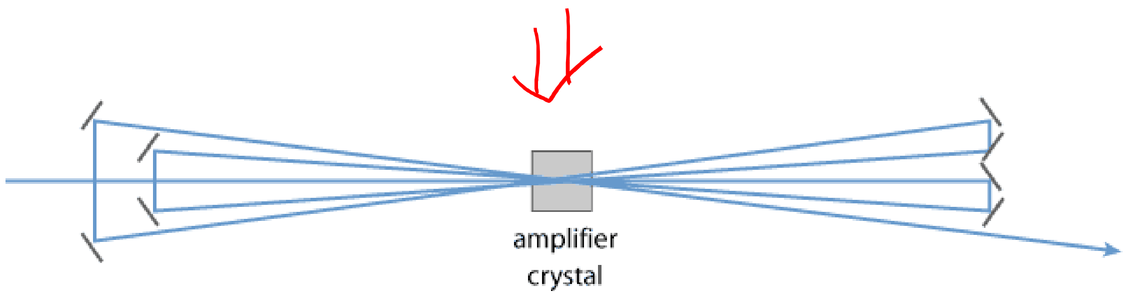
But not the low-intensity beam!

Therefore, the weak pulses will be suppressed like a saturable absorber.

# Regen amplifier vs multi pass amplifier

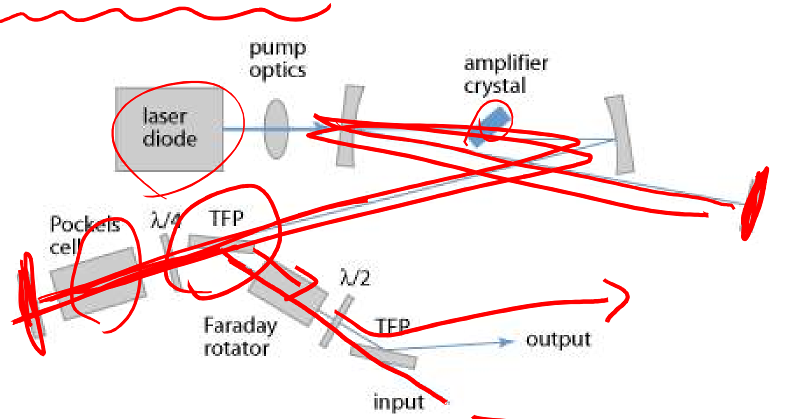
- The output energy of an oscillator is very low. Need to amplify.

Multi pass amplifier



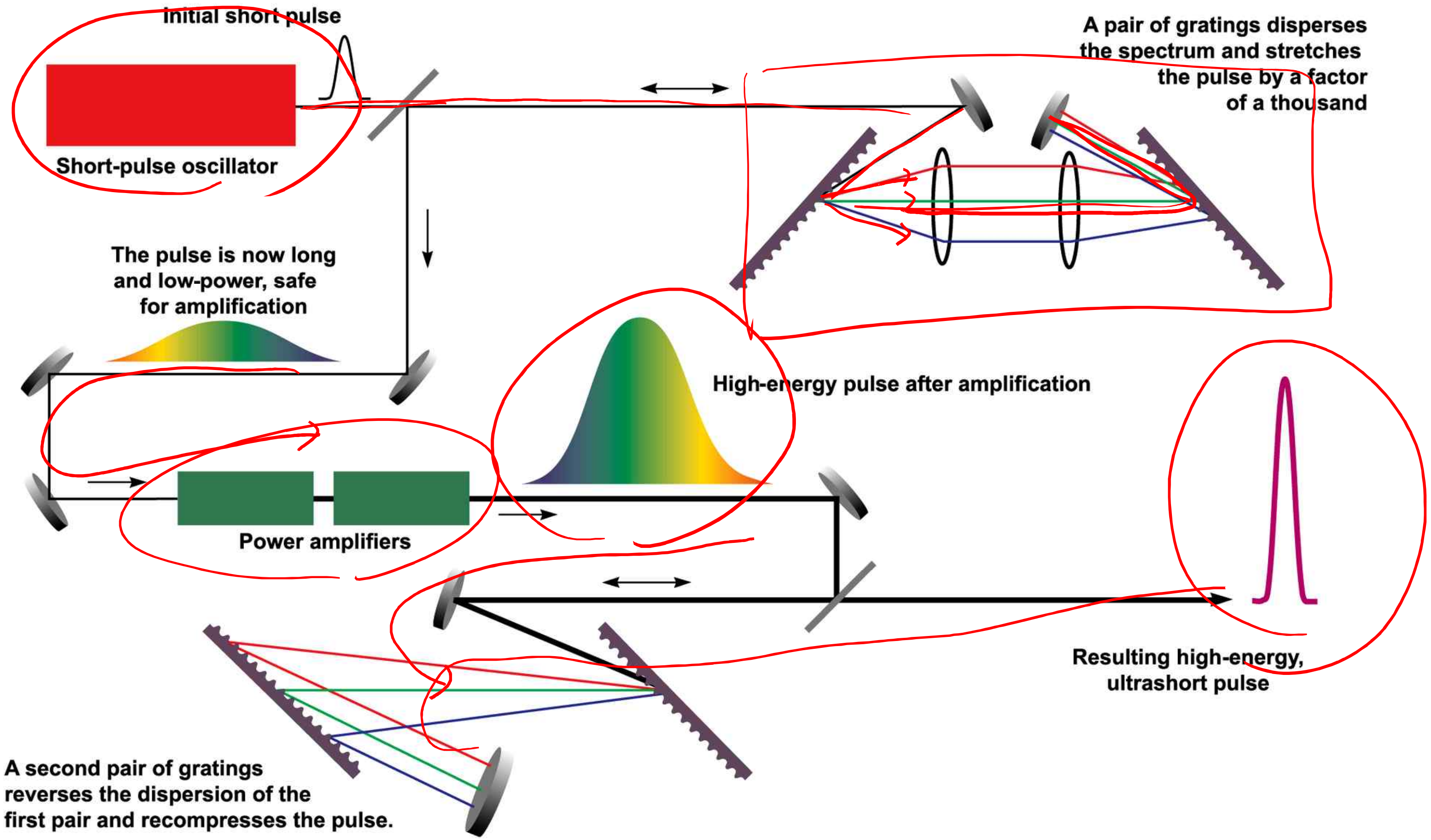

Simple

Regen amplifier

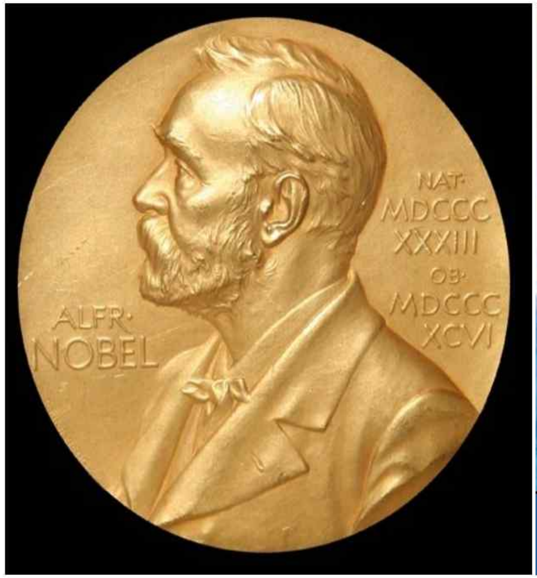



More efficient
Complicated
Pre pulse issue
Duration limit

# Chirped Pulse Amplification



## "for their method of generating high-intensity, ultra-short optical pulses"





The Nobel Prize in Physics 2018 was awarded "for groundbreaking inventions in the field of laser physics" with one half to Arthur Ashkin "for the optical tweezers and their application to biological systems", the other half jointly to Gérard Mourou and Donna Strickland "for their method of generating high-intensity, ultra-short optical pulses."

# 2018 Nobel prize in Physics: Highpower ultrashort laser generation technology

Volume 56, number 3 OPTICS COMMUNICATIONS 1 December 1985

## COMPRESSION OF AMPLIFIED CHIRPED OPTICAL PULSES ☆

Donna STRICKLAND and Gerard MOUROU

*Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, NY 14623-1299, USA*

Received 5 July 1985

We have demonstrated the amplification and subsequent recompression of optical chirped pulses. A system which produces 1.06 μm laser pulses with pulse widths of 2 ps and energies at the millijoule level is presented.

The onset of self-focusing of intense light pulses limits the amplification of ultra-short laser pulses. A similar problem arises in radar because of the need for short, yet energetic pulses, without having circuits capable of handling the required peak powers. The so- pulse would be free from gain saturation effects, because the frequency varies along the pulsewidth and each frequency component sees gain independently.

A schematic diagram of the amplifier and compression system is shown in fig. 1. A CW mode-locked,

# First CPA experiment (D. Strickland and G. Mourou)



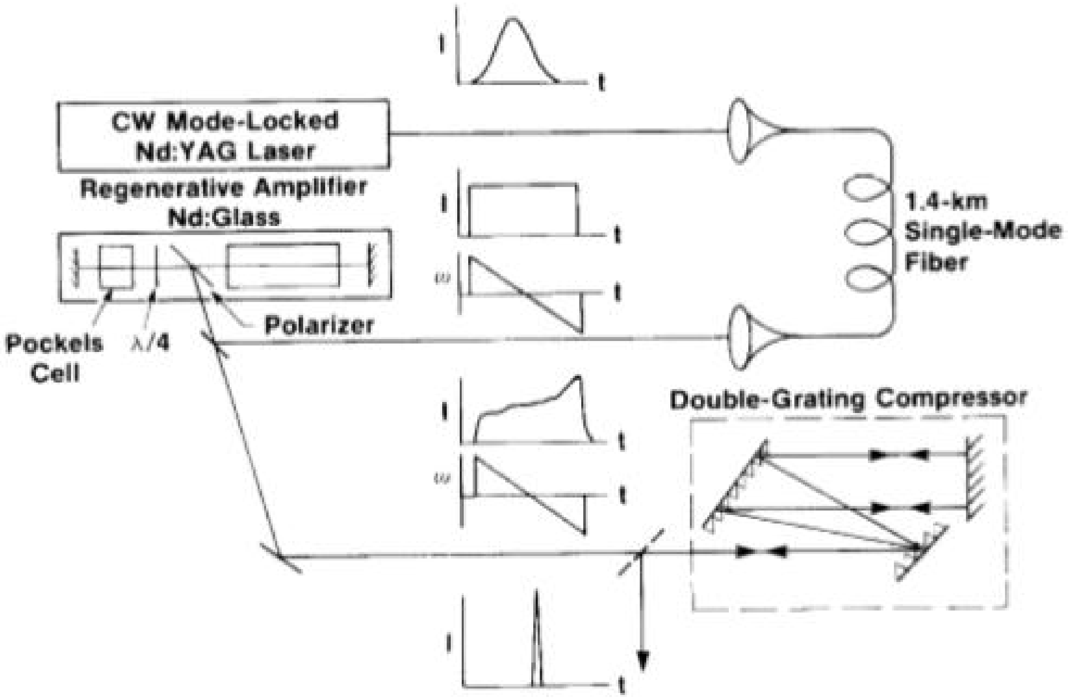



Fig. 1. Amplifier and compression system configuration.

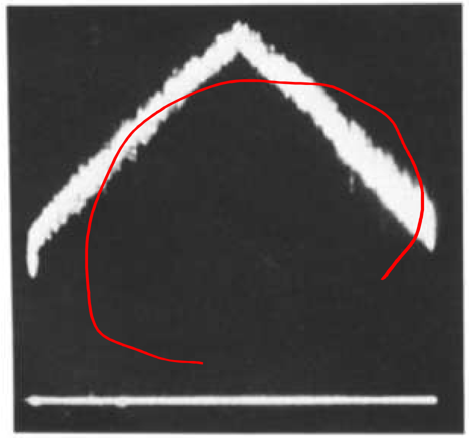


Fig. 2. Autocorrelation of stretched pulse at output of fiber. The pulse is rectangular in shape with a 300 ps pulsewidth.

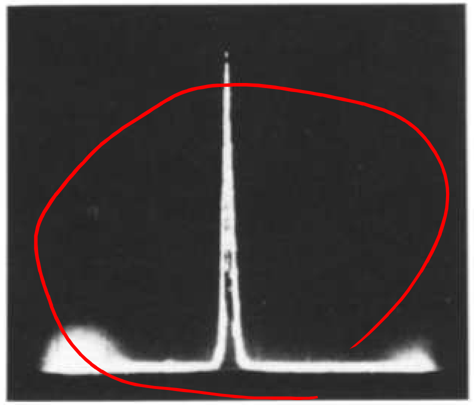


Fig. 3. Autocorrelation of 1.5 ps compressed pulse.

Google

compression of amplified chirped optical pulses citation

전체 이미지 뉴스 동영상 지도 더보기 설정 도구

검색결과 약 125,000개 (0.52초)

**compression of amplified chirped optical pulses citation**에 대한 학술자료

… modulation and spectral broadening of **optical pulses** … - Agrawal - 1286회 인용

**Compression** of **optical pulses** to six femtoseconds by … - Fork - 1446회 인용

Nonlinear **compression** of **chirped** solitary waves with … - Moores - 146회 인용

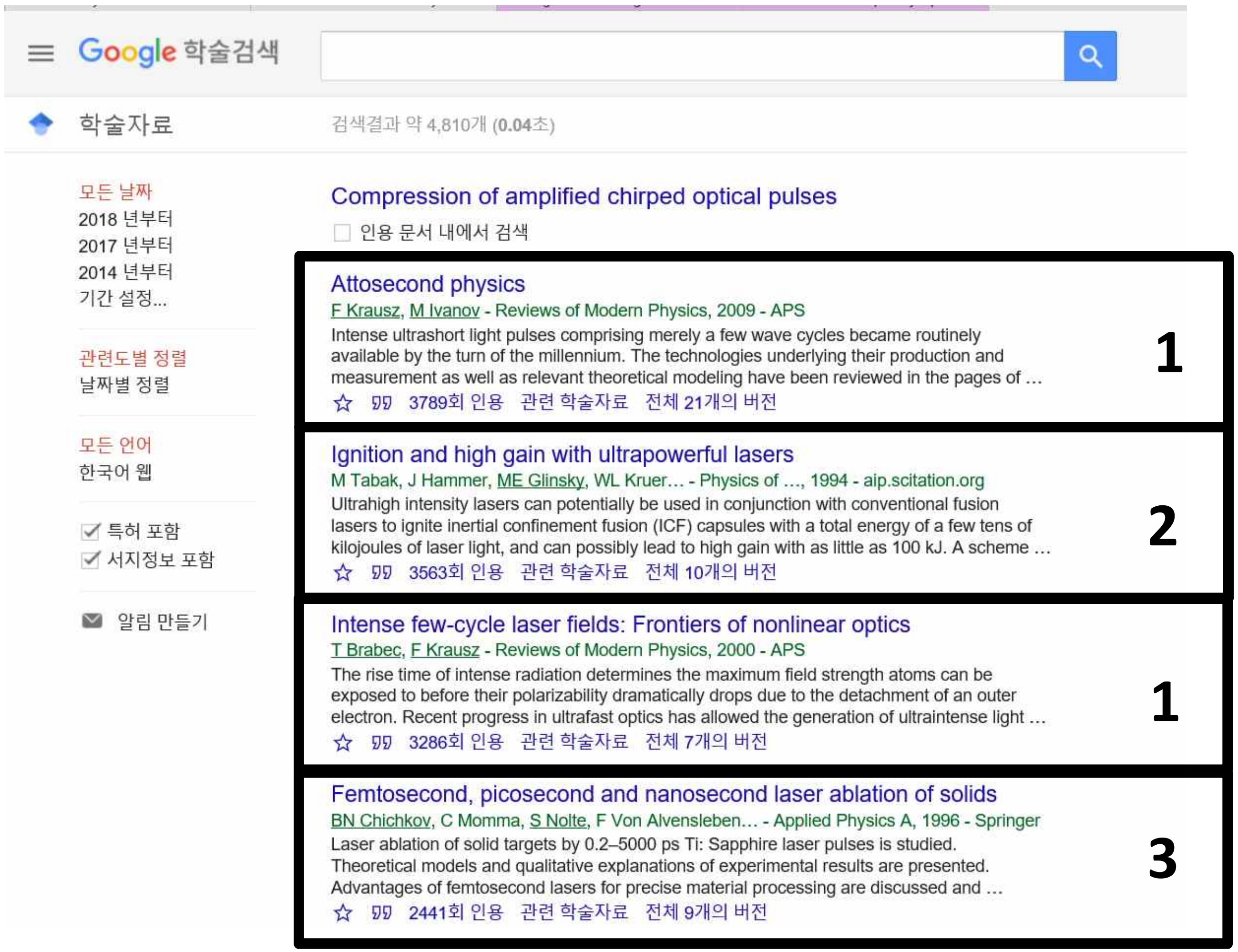
Compression of amplified chirped optical pulses - Science Direct

https://www.sciencedirect.com/science/article/.../00304018859012... - 이 페이지 번역하기

D Strickland 저술 - 1985 - 4734회 인용 - 관련 학술자료

1985. 12. 1. - **Compression of amplified chirped optical pulses**☆ ... A system which produces 1.06 µm laser **pulses** with **pulse** widths of 2 ... **Citing** articles (0) ...

# 고출력 극초단 레이저 활용 분야



# Ultrashort pulse generation

- A ultrahigh power laser can be developed using the CPA technology

- Still, ultrashort laser pulses are required
  - To achieve high intensity (I = energy / duration / area)
  - To achieve better temporal resolution (pump-probe experiment)
  - To control strong field processes

- A ti:sapphire laser can produce a laser pulse with a duration of 30 fs.

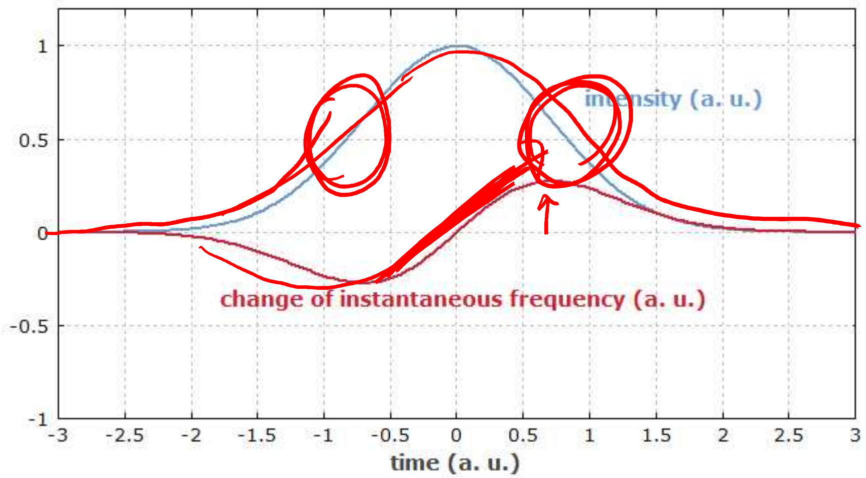
- Ultrashort pulse generation
  - Super-continuum generation
  - Dispersion control

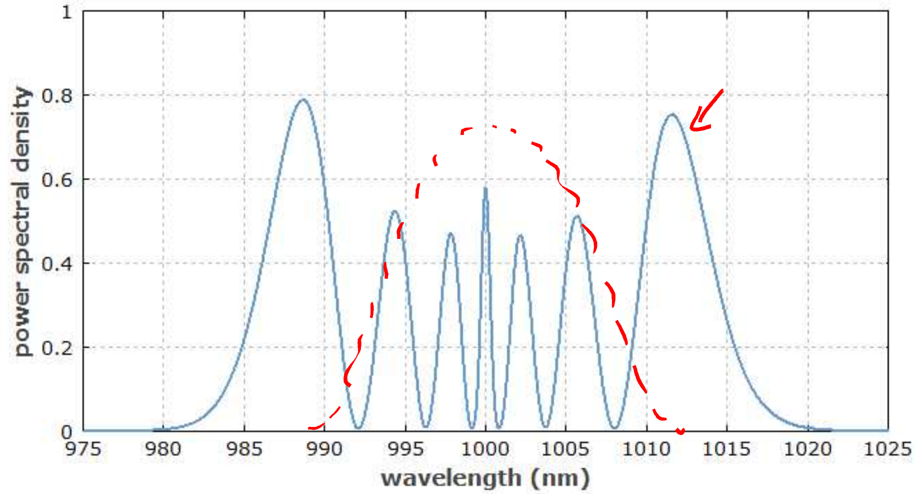
# Suercontinuum generation - self phase modulation

Kerr effect

$$n = n_0 + n_2 I$$

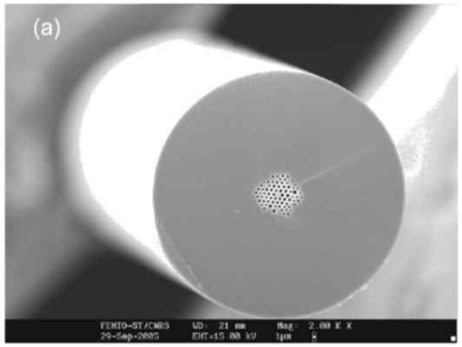
Time dependent phase (due to self phase modulation)

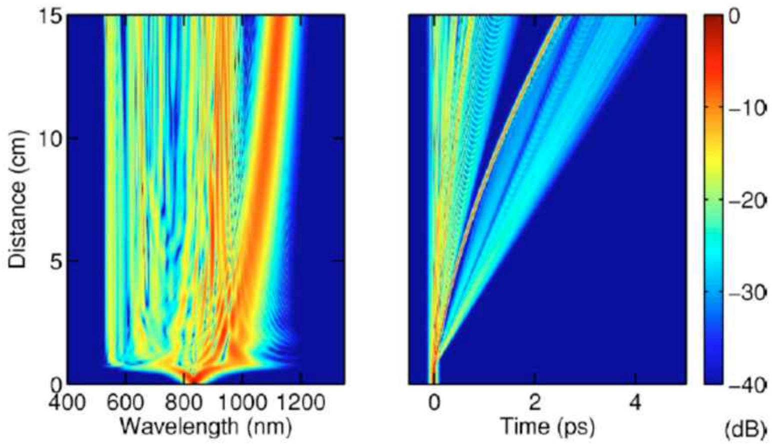


# Super continuum generation

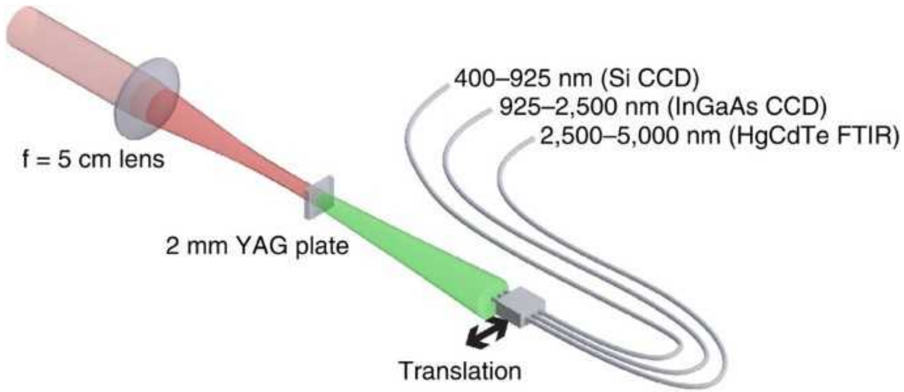
Photonic crystal fiber






J. M. Dudley et al., RMP **78**, 1135 (2006)

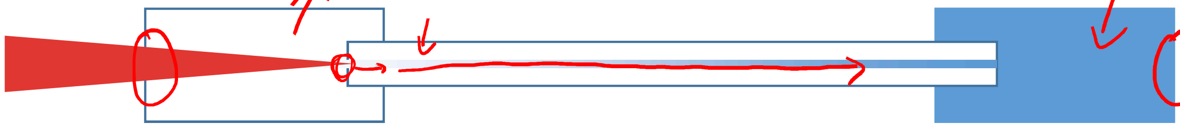
Supercontinuum generation from mid-infrared filamentation in a bulk crystal




F. Silva et al., Nat. Comm. **3**, 807 (2012)

# Super-continuum generation

Compression of high-energy laser pulses below 5 fs

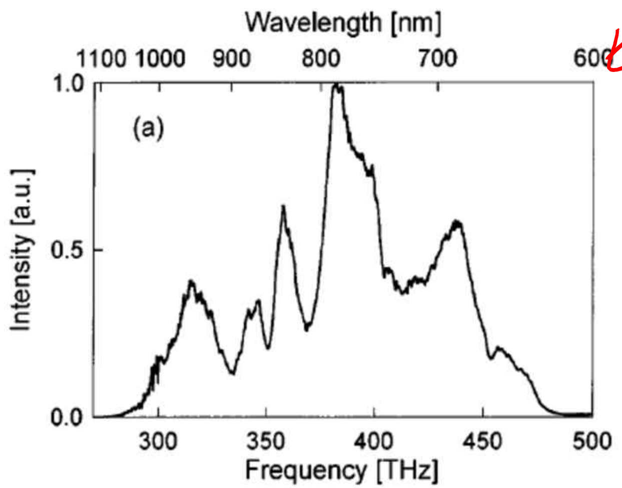


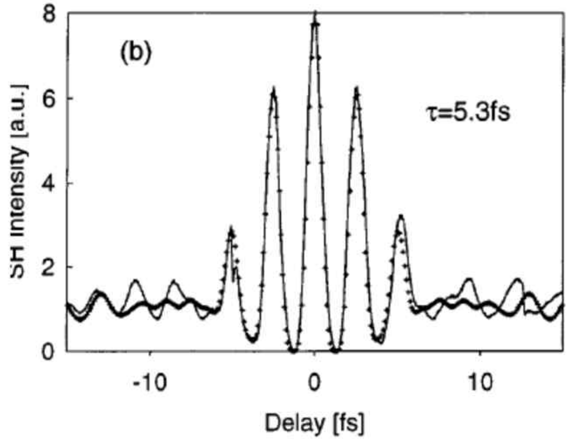
$$n_2 = \frac{3\eta_o}{n^2\epsilon_o}\chi^{(3)}. \quad (21.3\text{-}6)$$

Optical Kerr Coefficient

$$n(I) = n + n_2 I. \quad (21.3\text{-}7)$$

Optical Kerr Effect

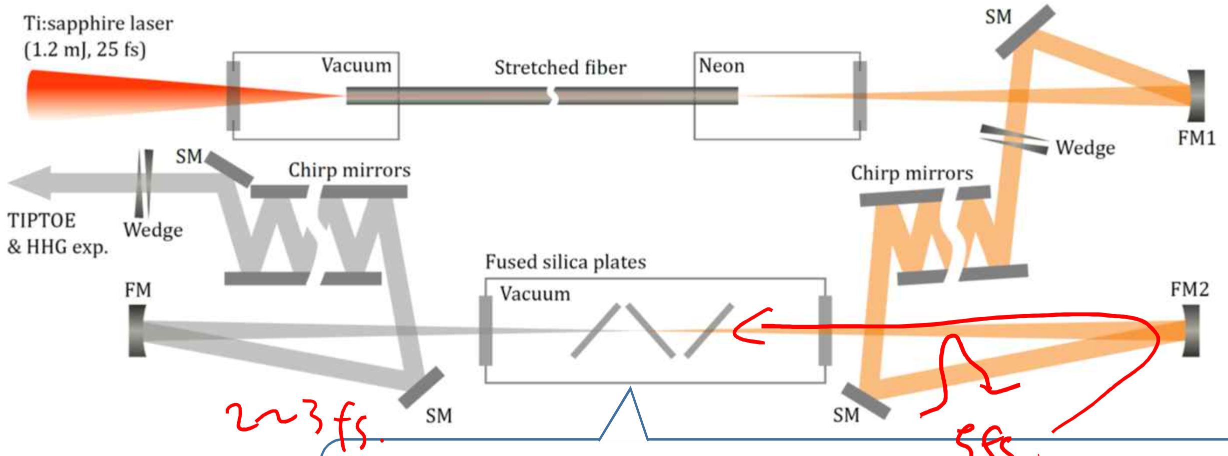


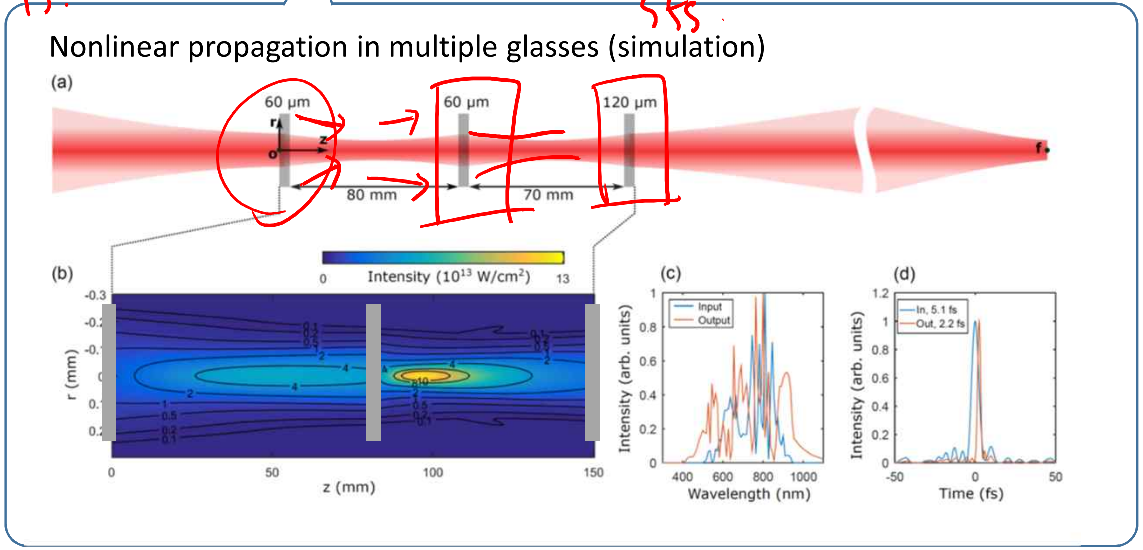




M. Nisoli et al., OL 22, 522 (1997)

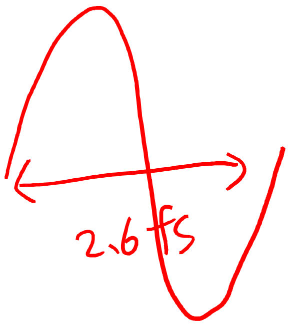
# Generation of a single-cycle pulse using a two-stage compressor

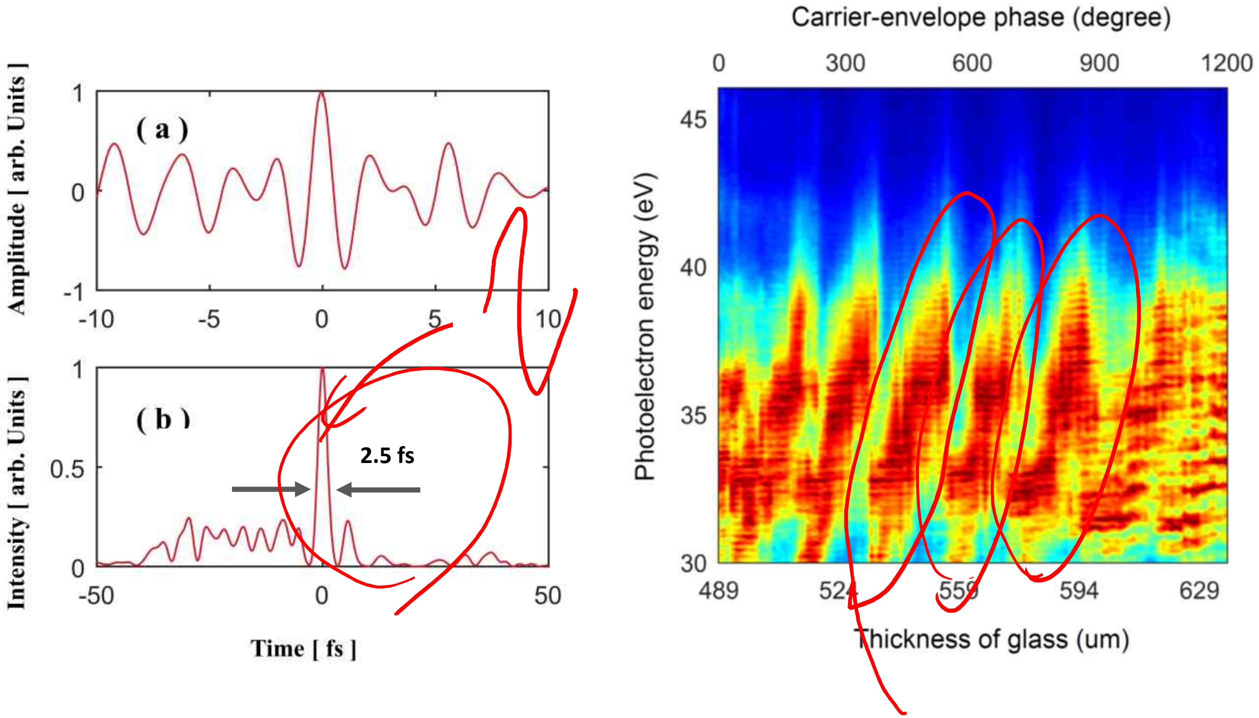
**Two stage compressor (hollow fiber + thin fused silica plates)**



# TIPTOE measurement of a single cycle pulse

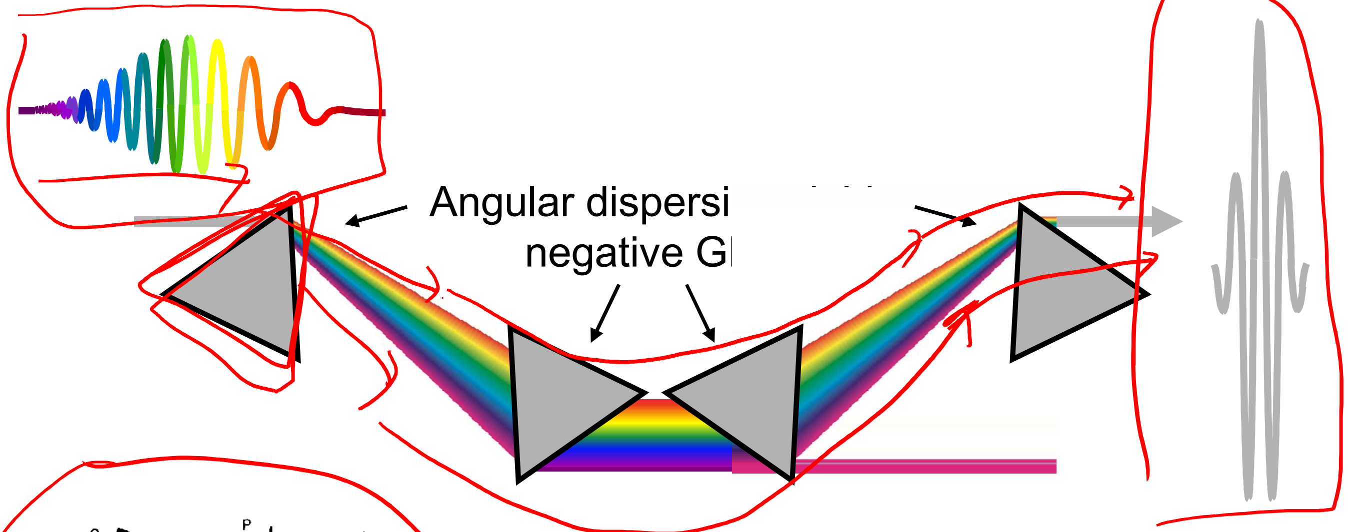


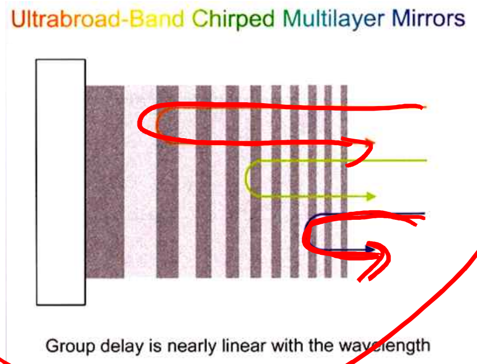

S. I. Hwang *et al.*, "Generation and characterization of single-cycle laser pulses …" Scientific report **9**, 1613 (2019)

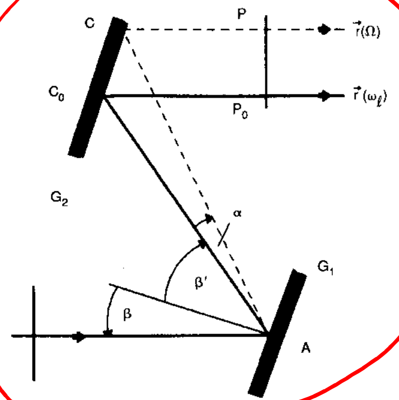
# Dispersion control – prism, grating and chirped mirror

- Conventional techniques
  - Prism compressor
  - Grating compressor



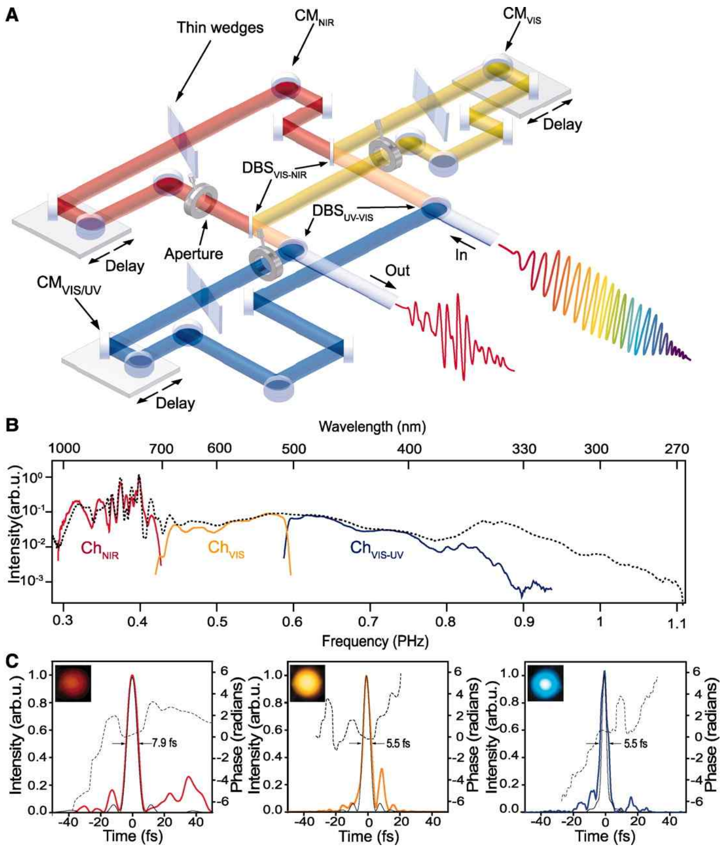

- Chirped mirror

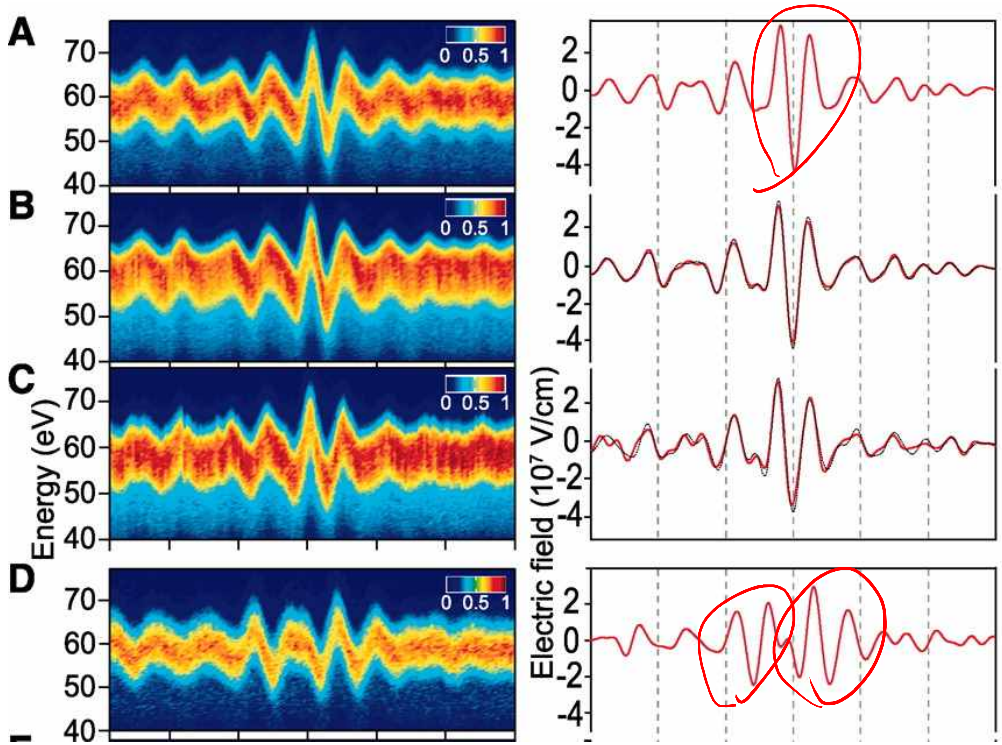


# Dispersion control - Synthesized Light Transients

- Pulse synthesizer



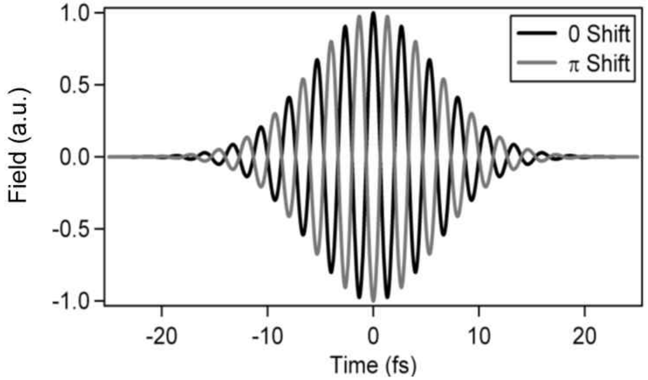

Synthesized Light Transients
A. WIRTH et al., Science 334, 195 (2011).

# CEP stabilization and measurement

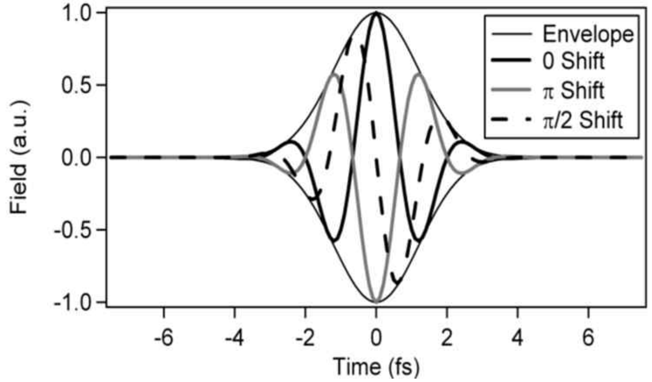
- As the pulse duration gets shorter, the CEP becomes a critical parameter.

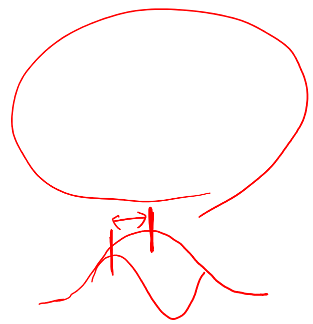
$$v_g \equiv \frac{\Delta\omega}{\Delta k} = \frac{c_0 k_1 - c_0 k_2}{n_1 k_1 - n_2 k_2}$$

Different absolute phases for a four-cycle pulse




Different absolute phases for a single-cycle pulse

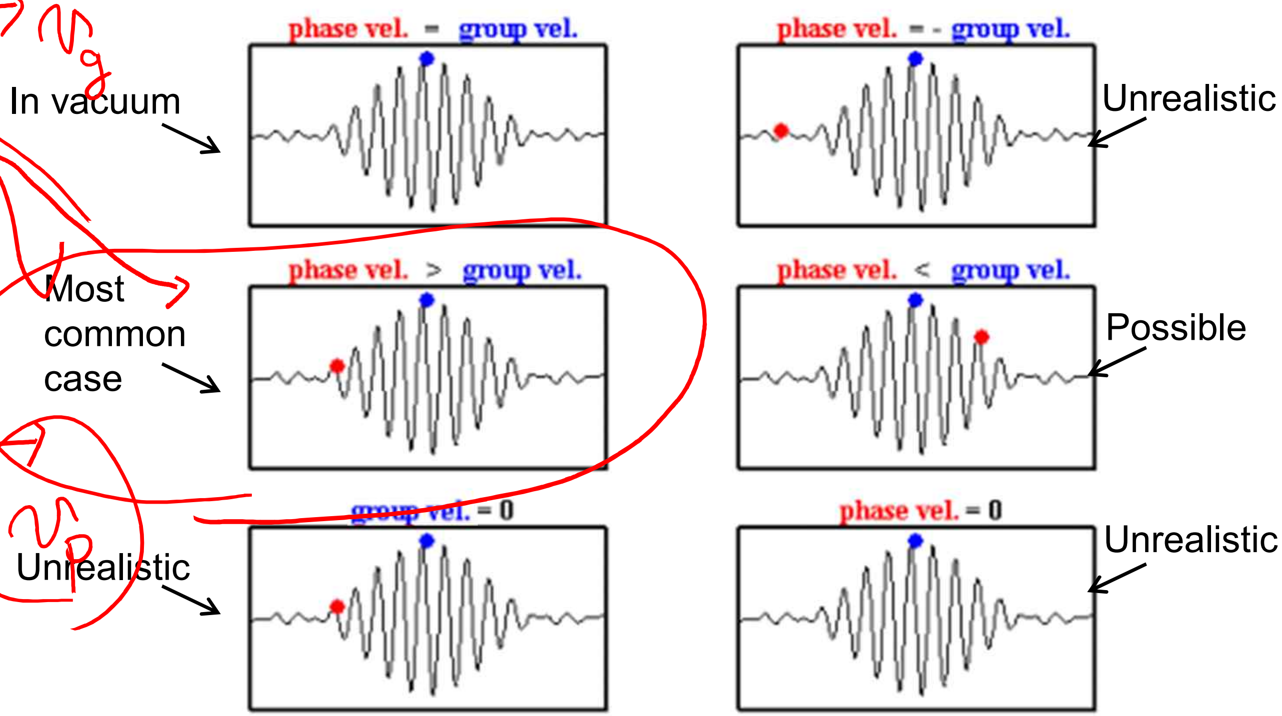


# Why does the CEP slip?

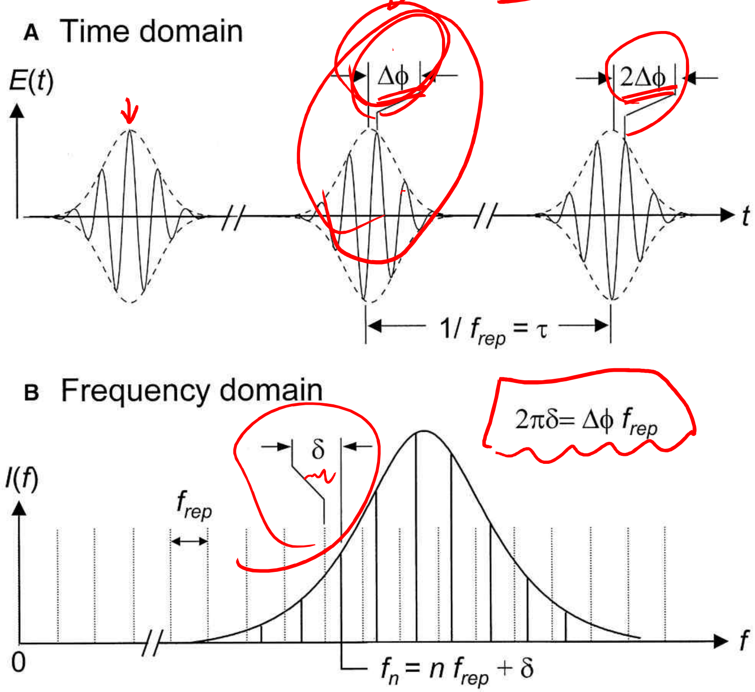
- Group velocity (speed of envelope) vs phase velocity (speed of oscillation)

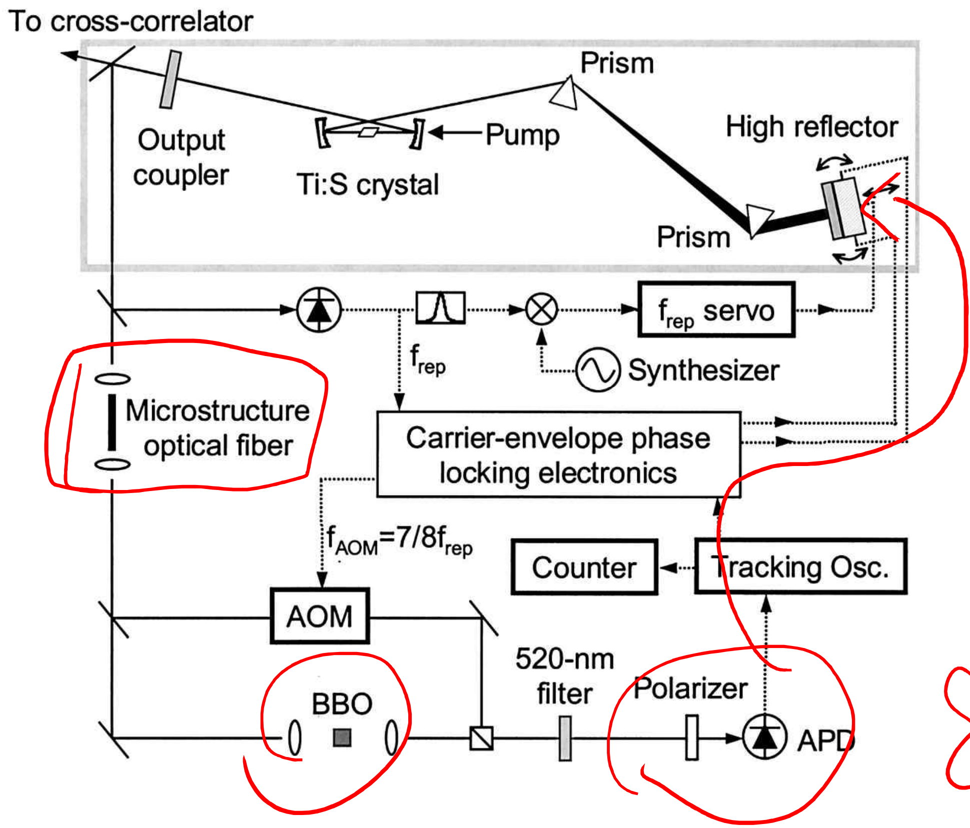
$$v_g = \frac{d\omega}{dk} \qquad v_p = \frac{\omega}{k}$$




isvr

# CEP stabilization



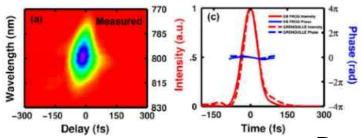




Carrier-Envelope Phase Control of Femtosecond Mode-Locked Lasers and Direct Optical Frequency Synthesis
David J. Jones et al., Science **288**, 635 (2000).

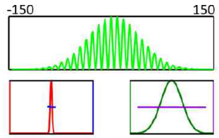
# Problems with the conventional techniques

## Conventional methods rely on SHG

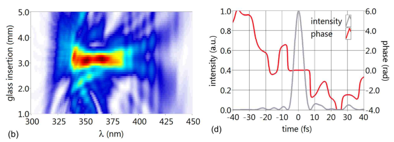
**FROG**




**SPIDER**




**D-scan**




**Advantage**

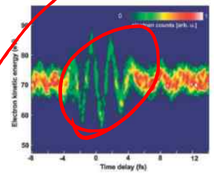
- Easy and fast implementation in air

**Disadvantage**

- Bandwidth limited
- Not a field measurement (no CEP info)
- Frequency domain techniques (short temporal range)

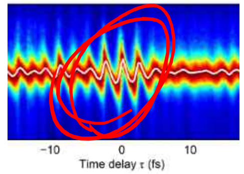
## Field measurement

**Attosecond Streak Camera**



Goulielmakis et al., Science **304** (2004).

**Petahertz Optical Oscilloscope**




K. T. Kim *et al.*, Nature Photonics **7**, 958 (2013).

**Advantage**

- Broad bandwidth (UV to INF)
- Direct measurement of an electric field

**Disadvantage**

- Complicated setup in vacuum
- Photoelectron or XUV measurement

**Advantage of TIPTOE**

- Easy and fast implementation in air
- Broad spectral range from UV to IR
- Time domain technique
- CEP (conditional)

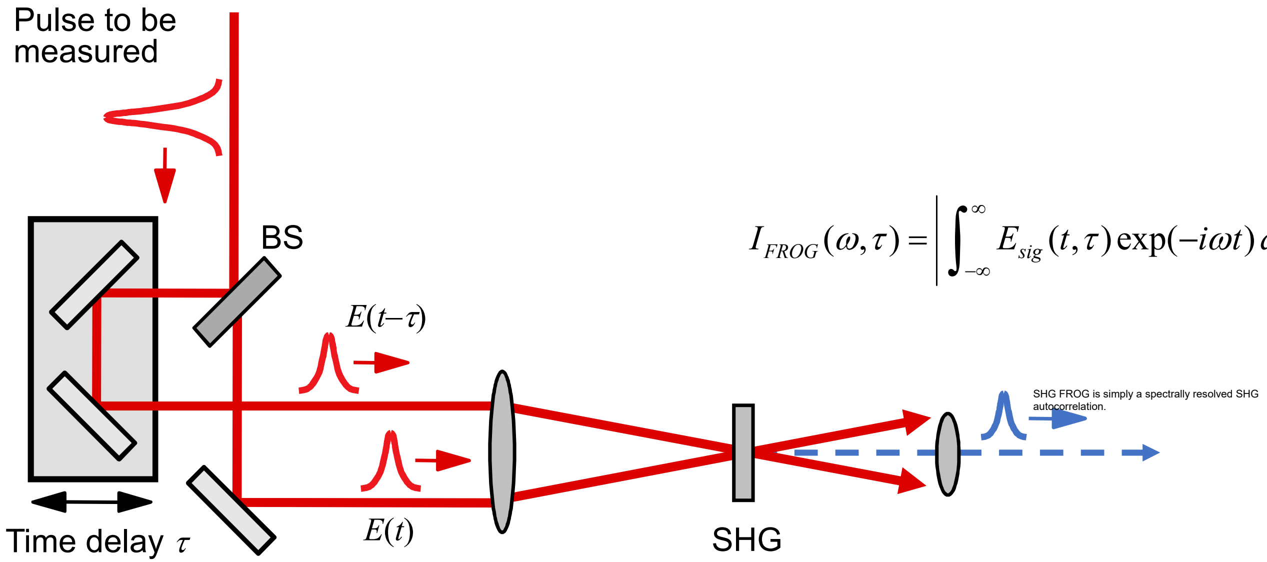
광주과학기술원
Gwangju Institute of Science and Technology

# Conventional techniques I (nonlinear response of a material)

- Pulse characterization techniques utilizes the 2nd or 3rd nonlinear effect.
  - Autocorrelation, FROG, SPIDER, WIZZLER, D-SCAN, …

- Ex) FROG (Frequency resolved optical gating)

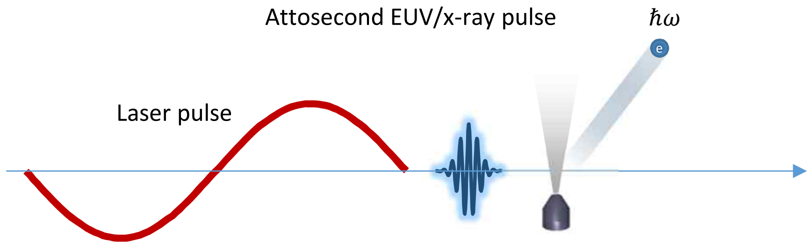
$$I_{FROG}(\omega,\tau) = \left| \int_{-\infty}^{\infty} E_{sig}(t,\tau)\exp(-i\omega t)\,dt \right|^2$$



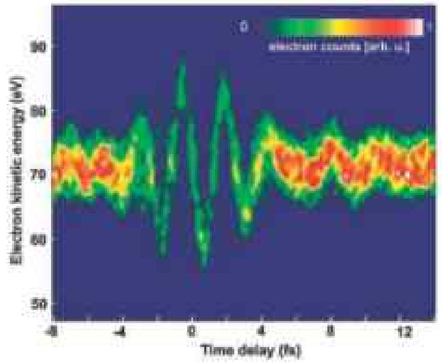
# Conventional techniques II (direct sampling of an electric field)

- Attosecond streak camera

The energy of the photoelectron is shifted due to the additional laser field.



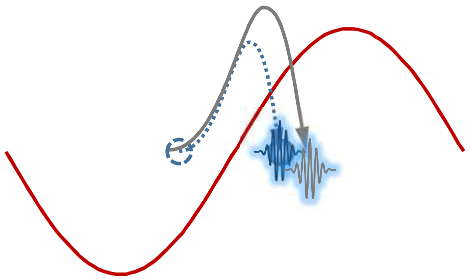

Photoelectron spectra



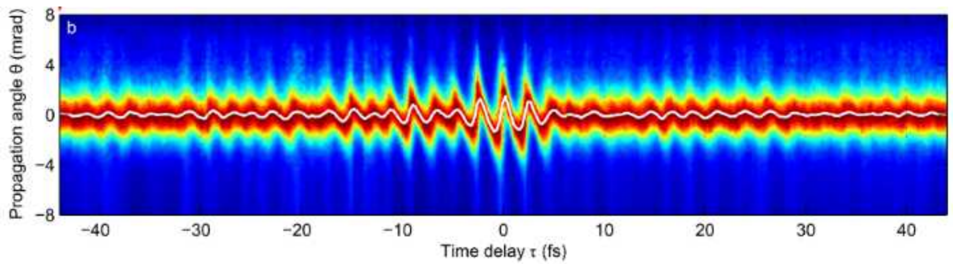

Goulielmakis et al., Science **304** (2004).

- Petahertz optical oscilloscope

The propagation direction of HHG emission is changed due to the additional laser field



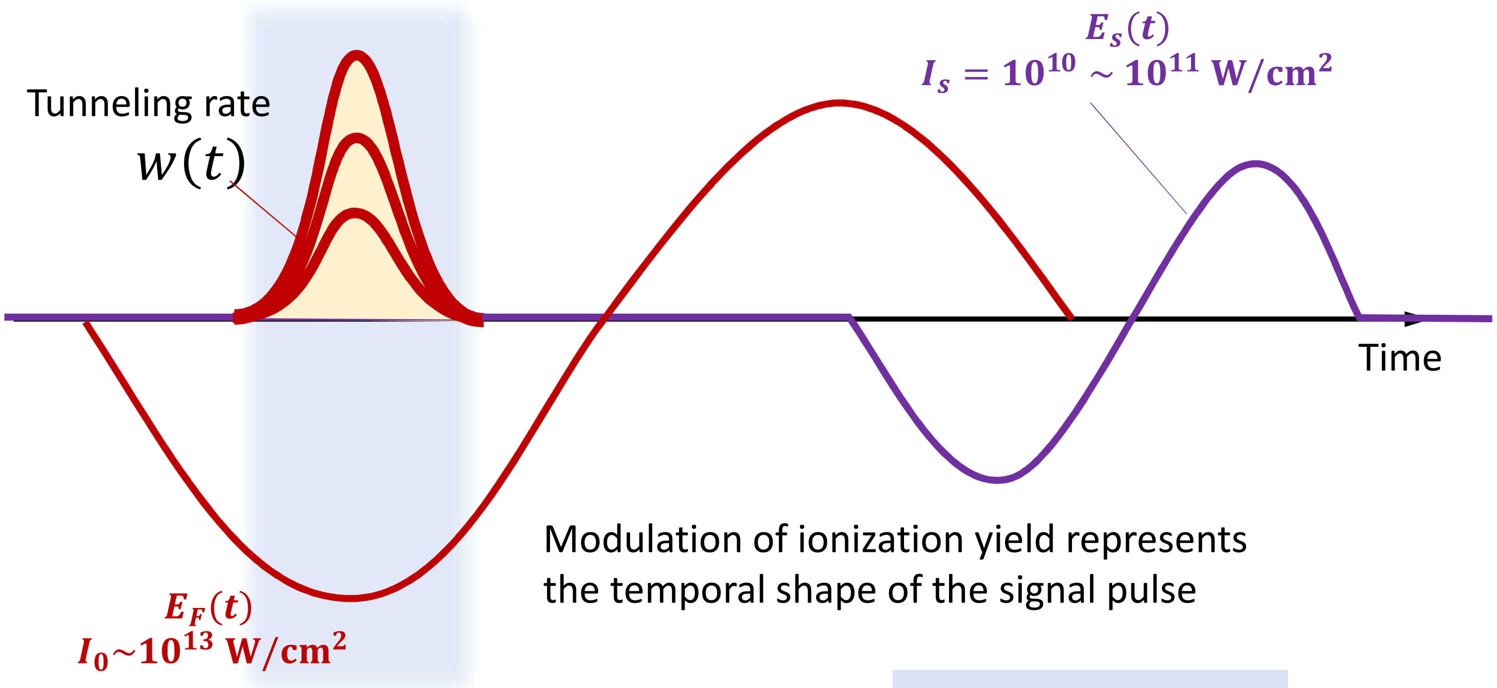
High harmonic spectra




K. T. Kim *et al.*, Nature Photonics **7**, 958 (2013).

# Basic idea of TIPTOE

**T**unneling **I**onization with a **P**erturbation for **T**ime-domain **O**bservation of **E**lectric-field

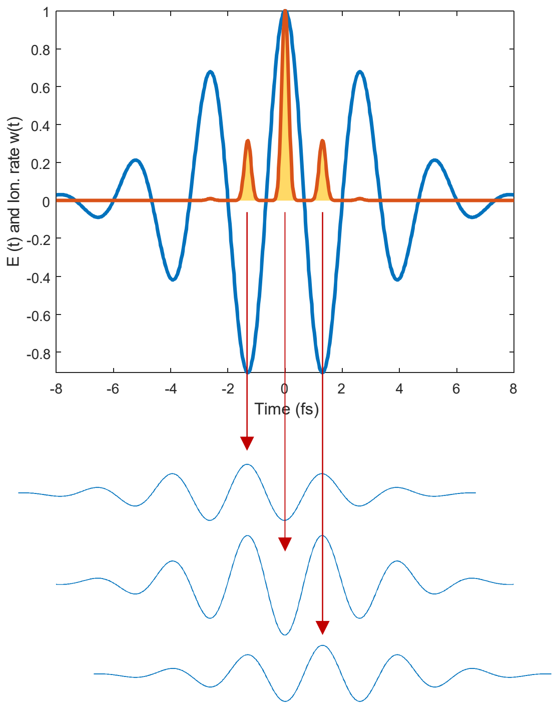



Modulation of ionization yield represents the temporal shape of the signal pulse

$$\delta N(\tau) \propto E_s(\tau)$$

# TIPTOE algorithm for multiple ionization

- Multiple ionization → convolution effect.




- Longer ionization modulation than the original pulse.
- If the pulse is badly chirped
  → too many ionizations
  → canceling the modulation
  → duration < 3 x TL duration
- These convolution effect must be considered.

- Ionization yield

$$N(\tau) = \int_{-\infty}^{+\infty} [E(t) + rE\,(t-\tau)]^n dt$$

- Find E(t) that minimize RMS error

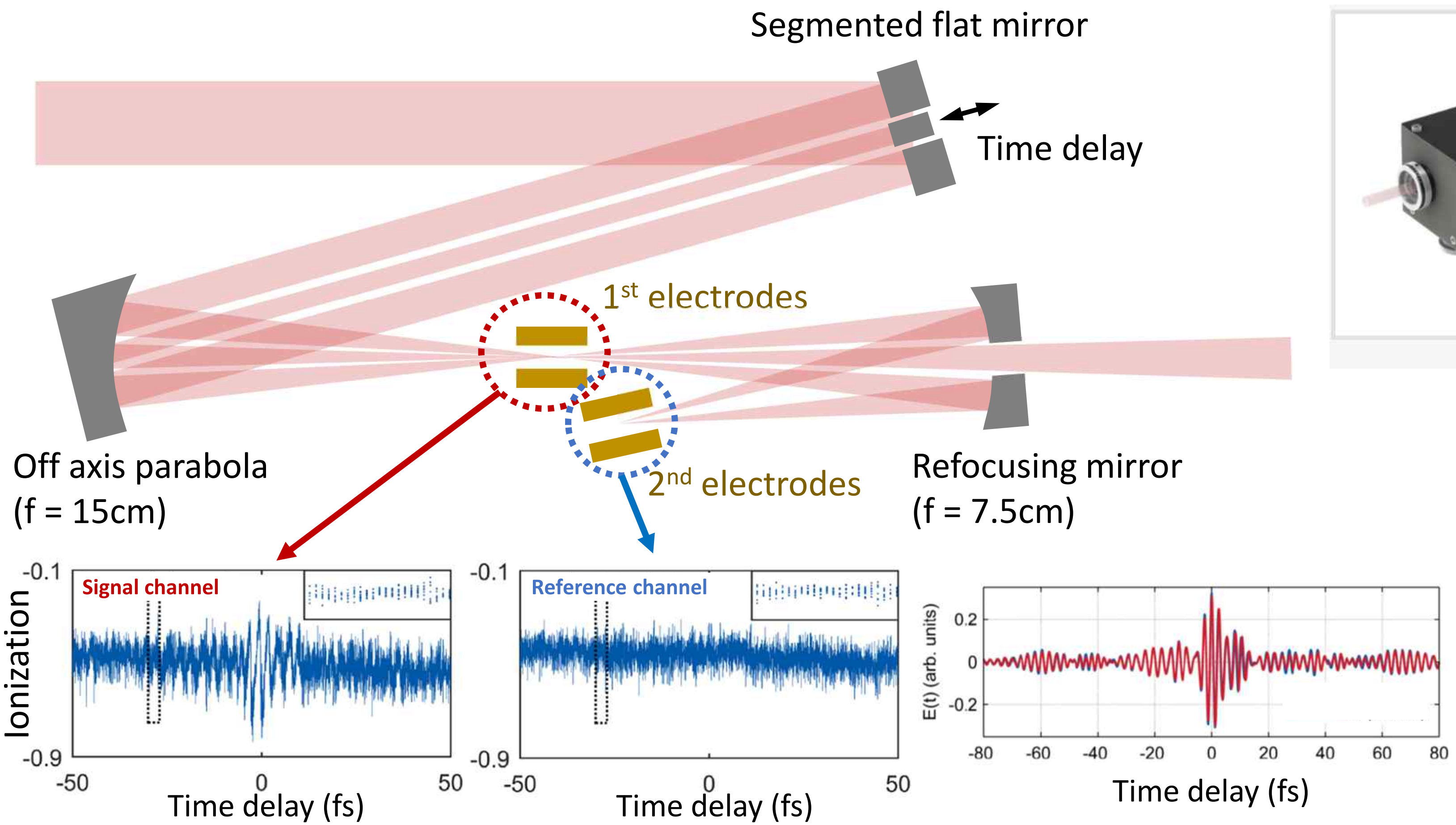
$$\varepsilon = \sqrt{\frac{\sum N_{EXP}^2 - N_{REC}^2}{N_{data}}}$$

- Gradient descent algorithm

  ADAM (adaptive momentum algorithm)

Wosik Cho *et al.*, Sci. Rep. **11**, 13014 (2021)

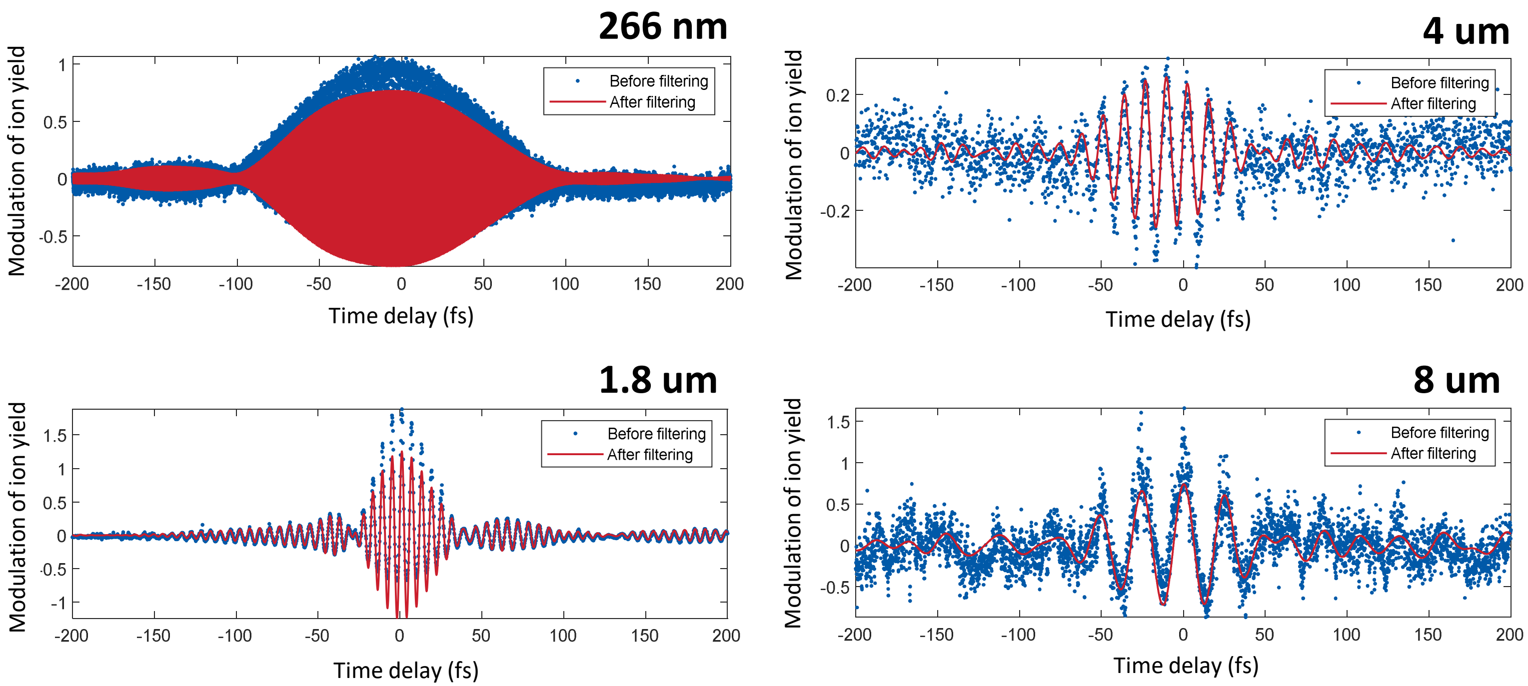
# TIPTOE experiment setup




Tiptoe

# Universal temporal characterization method

- Applied for a broad spectral range from UV to IR (at ALLS in Canada).




S. B. Park et al., Optica **5**, 402 (2018)

Wosik Cho *et al.*, Scientific report **9**, 16067 (2019)

Wosik Cho *et al.*, Sci. Rep. **11**, 13014 (2021)

# Summary

- Laser
  - Laser history
  - Principle of laser
  - Laser oscillator / mode-locking
  - Chirped pulse amplification
  - Amplifier
  - Chirped pulse amplification
  - Ultrashort pulse generation
  - Dispersion control
  - CEP measurement
  - Pulse measurement
  - Field measurement

- Strong field physics
  - Above threshold ionization
  - High harmonic generation
  - Frustrated tunneling ionization