Femto-UP 2020-21 School

Femtosecond Pulse Generation

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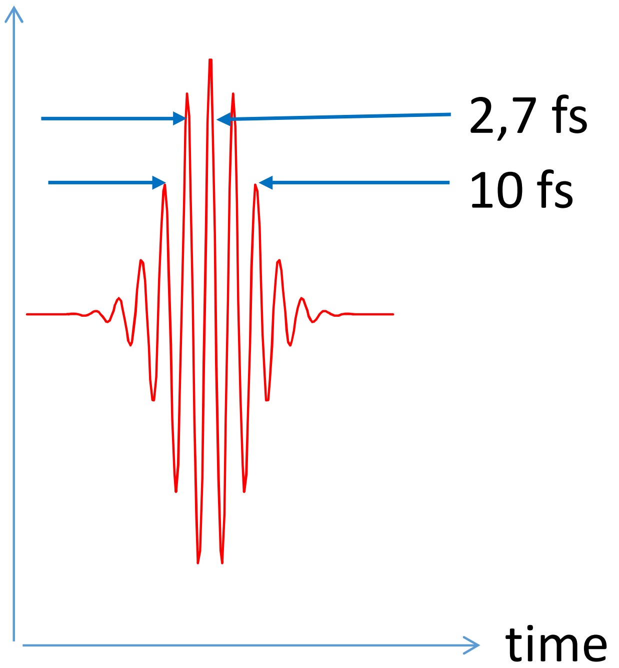
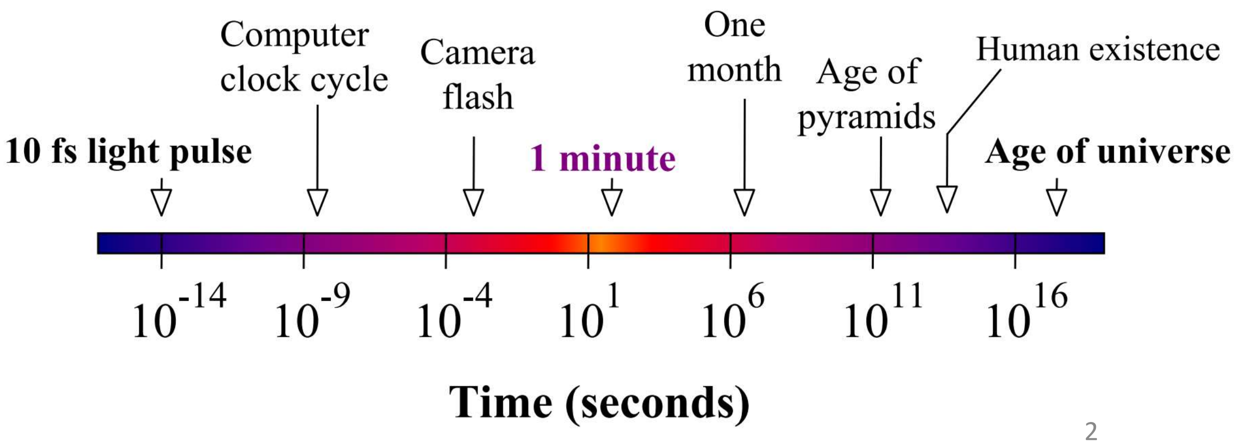
Definitions

Electric field of a 10-fs 800-nm pulse

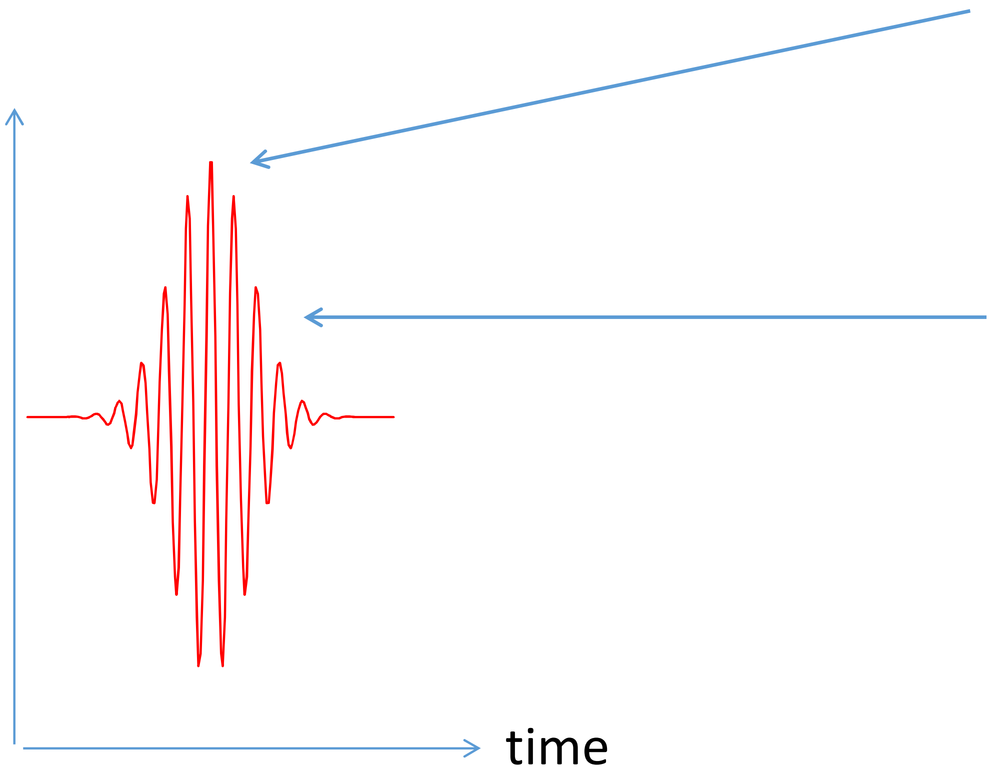


nano		10^{-9}	sec
pico		10^{-12}	
femto		10^{-15}	
atto		10^{-18}	



Many properties

Electric field of a 10-fs 800-nm pulse



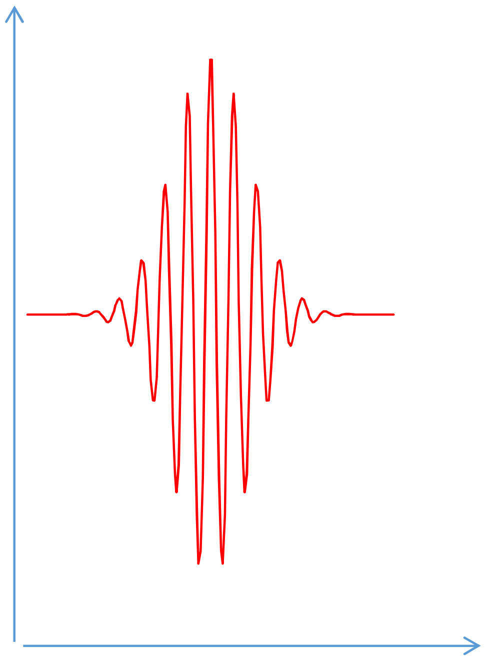
High peak power
(Energy /Duration)

Ultrashort Duration

Spectral Properties
(Frequency Comb)

Time-resolved spectroscopy

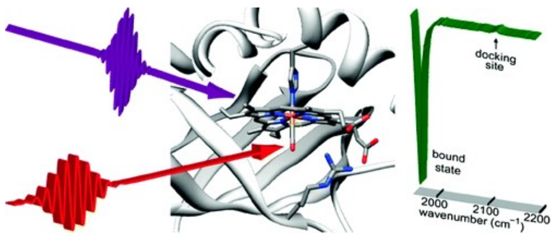
Electric field of a 10-fs 800-nm pulse

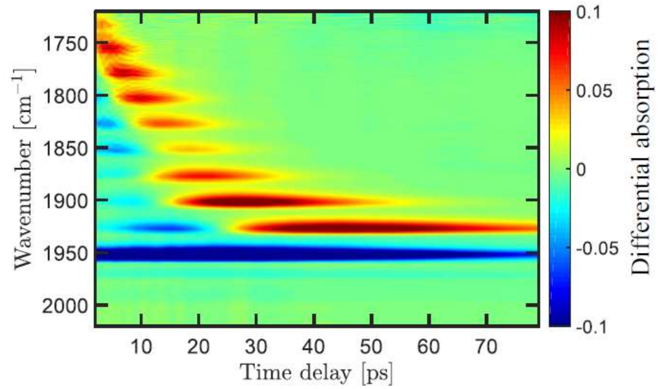


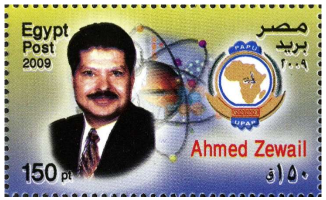
time

Ultrashort Duration

Time-resolved spectroscopy
Direct observation of ultrafast motions



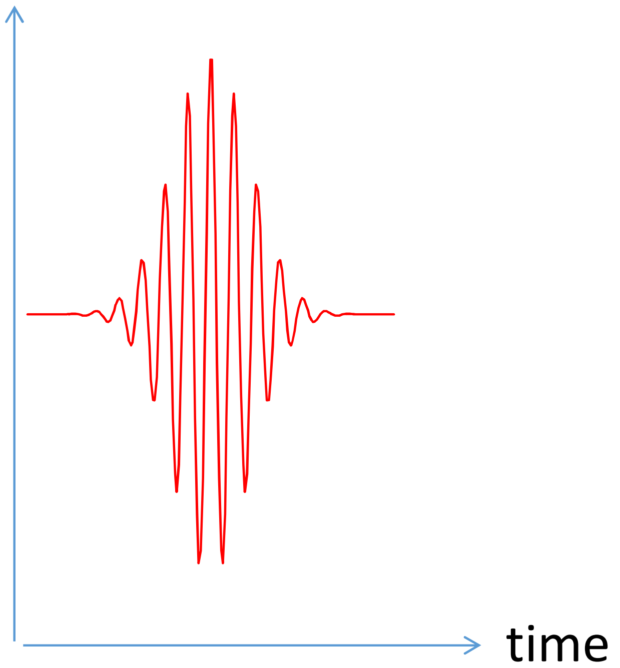




Ahmed Zewail, Nobel Prize in chemistry 1999, femtochemistry

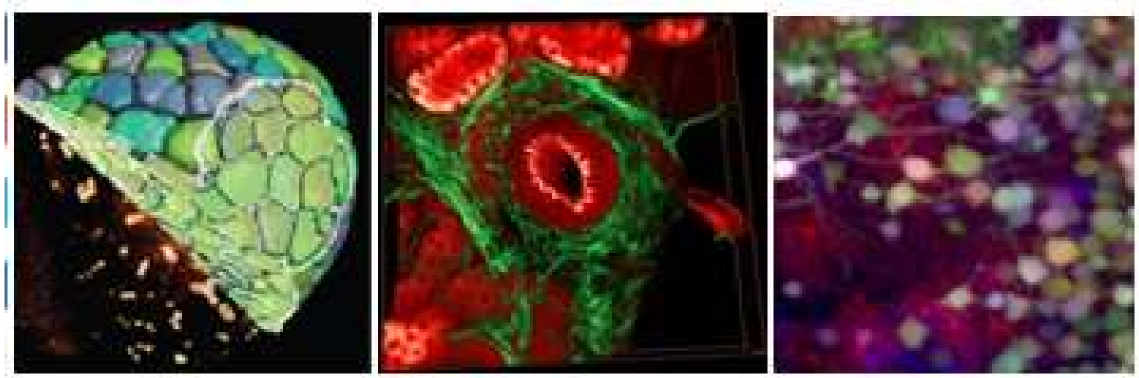
Imaging

Electric field of a 10-fs 800-nm pulse



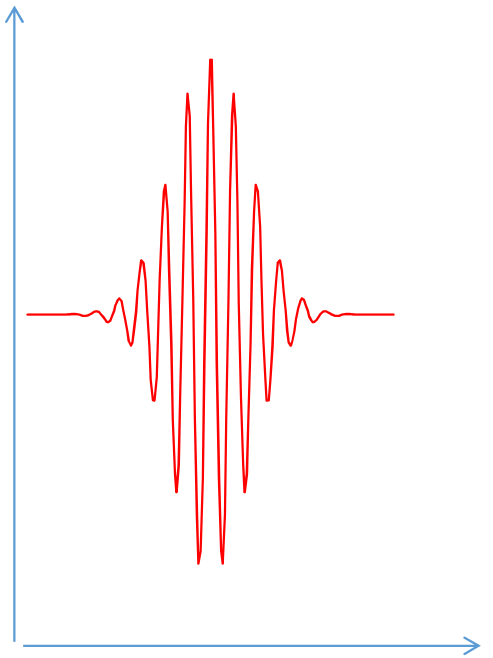
High peak power
(Energy /Duration)

Nonlinear microscopy



Material processing

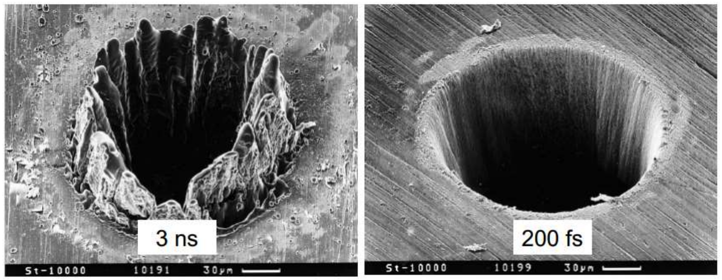
Electric field of a 10-fs 800-nm pulse



High peak power
(Energy /Duration)

Laser matter interaction

Drilling, cutting, etching,…

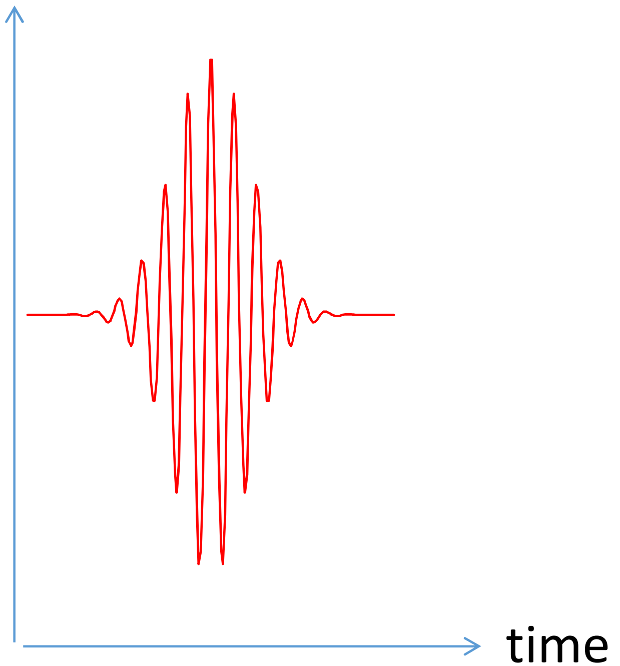


B. Chichkov *et al*, *Appl. Phys. A.* **63**, 109 (1996)

Areas of applications : aeronautics, electronics, medical, optics…

Light matter interaction

Electric field of a 10-fs 800-nm pulse



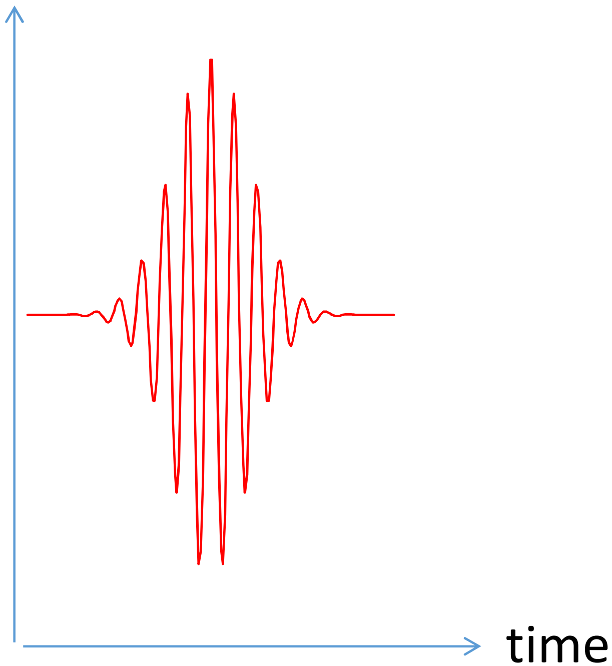
High peak power
(Energy /Duration)

Ability to reach extreme conditions (amplified system)

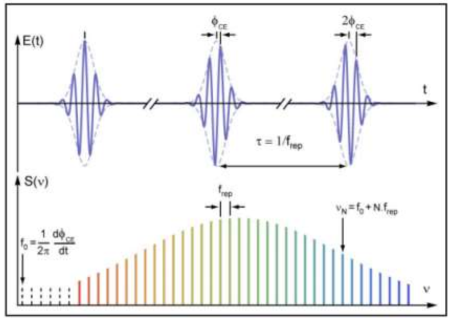
Applications : Sources of intense particles beams, X-rays, high energy density science, laboratory astrophysics ...

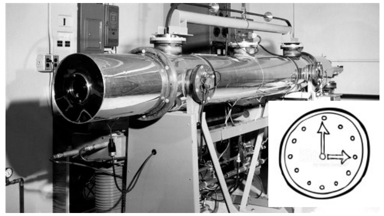
Metrology

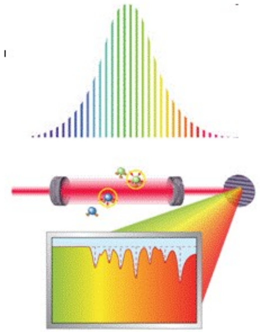
Electric field of a 10-fs 800-nm pulse



Spectral Properties
(Frequency Comb)







J.L. Hall

T.W. Hänsch

Nobel Prize 2005
"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique."

Outline

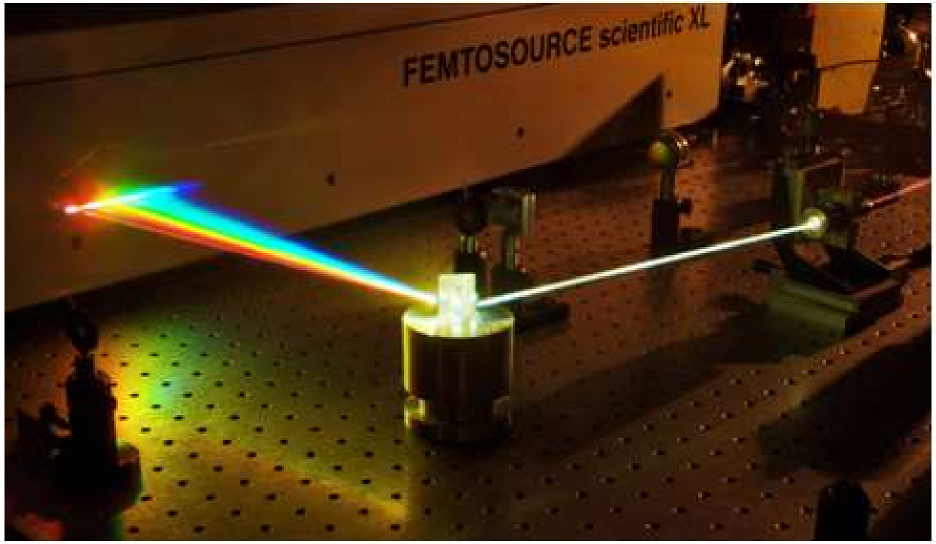
Introduction

1. Description of ultrashort light pulses

2. Generation of femtosecond laser pulses via mode locking

3. Femtosecond oscillator technology

Introduction



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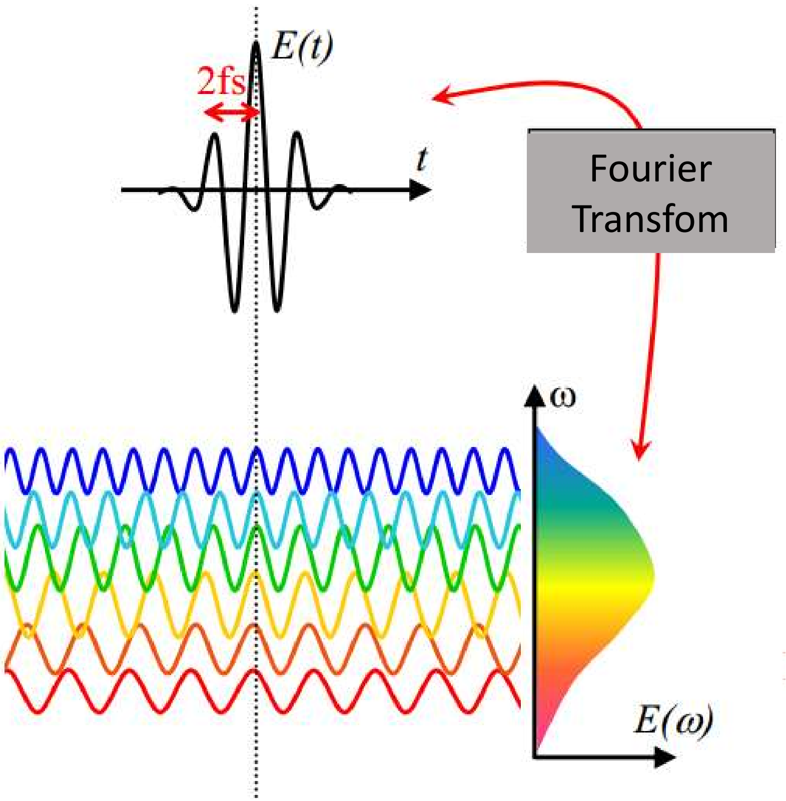
Ultrashort pulse = broad spectrum

What makes the difference between white light and femtosecond pulses ?

Definitions : Electric fields

$E(t)$ Real electric field

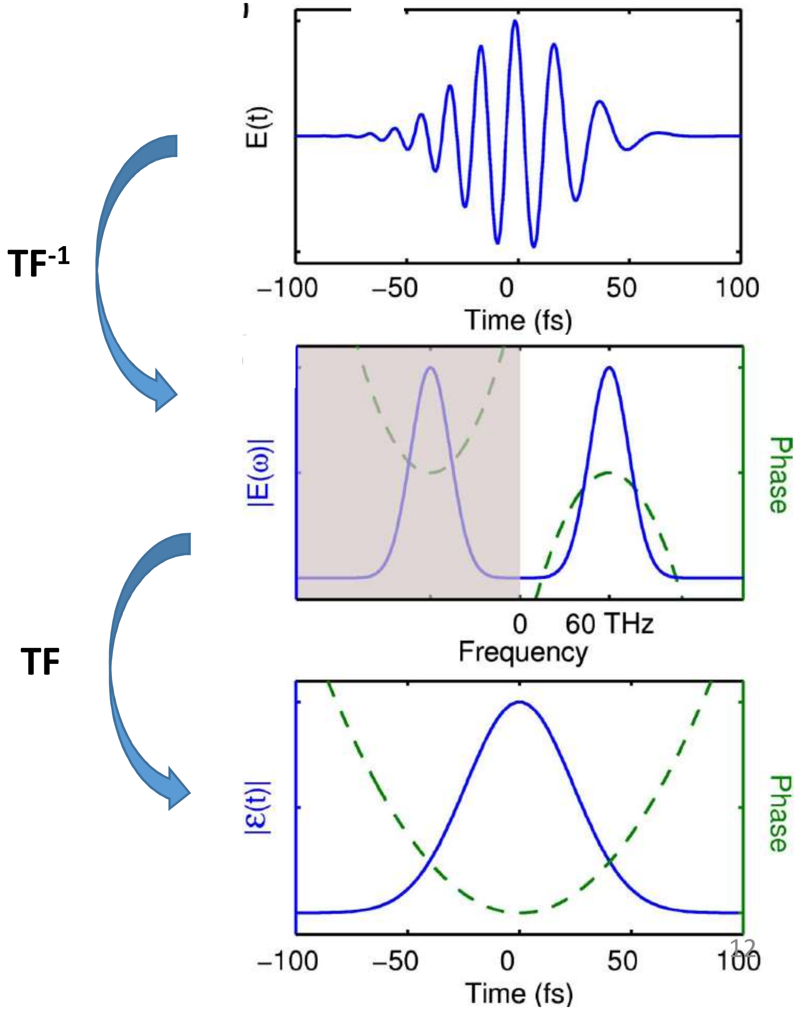


Ultrashort pulse
=
sum of monochromatic waves

$$E(t) = \int_{-\infty}^{\infty} E(\omega)\exp(-i\omega t)\frac{d\omega}{2\pi} = TF\left[E(\omega)\right]$$

$$E(\omega) = \int_{-\infty}^{\infty} E(t)\exp(i\omega t)dt = TF^{-1}\left[E(t)\right]$$

Definitions : Complex electric fields



Real electric field

Complex spectral field

$$\varepsilon(\omega) = \left|\varepsilon(\omega)\right| \exp(i\varphi(\omega))$$

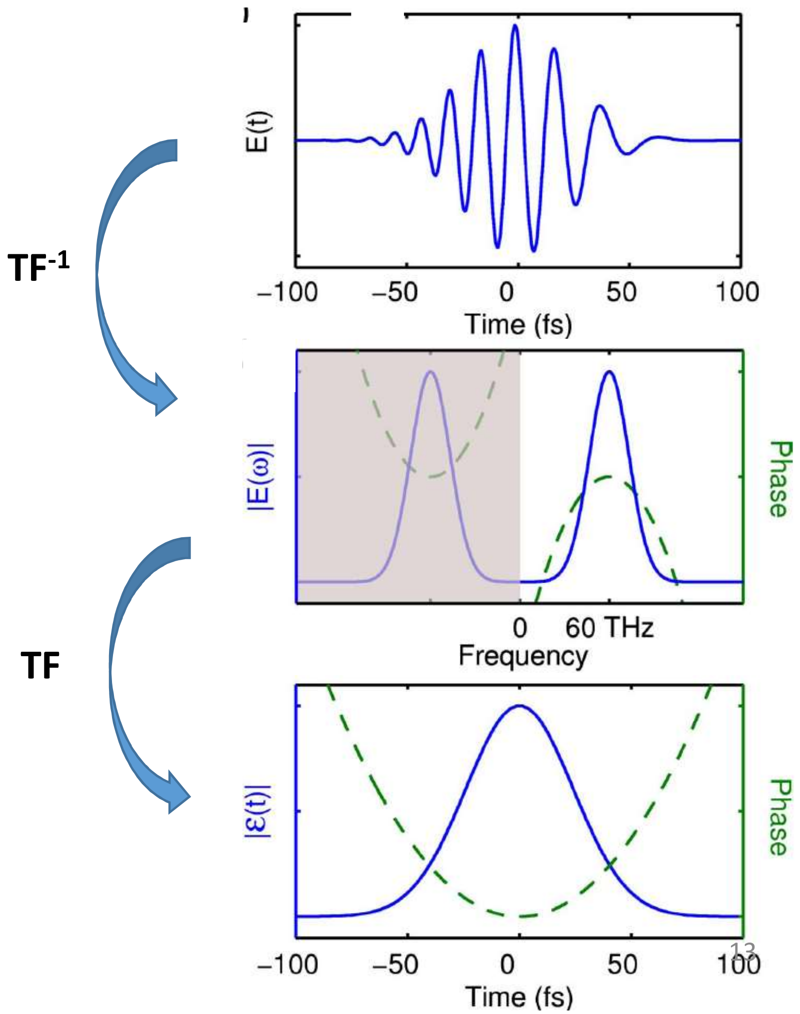
Spectral phase

Complex temporal field

$$\varepsilon(t) = \left|\varepsilon(t)\right| \exp(i\phi(t))$$

Temporal phase

Definitions : Complex electric fields



Real electric field

Complex spectral field

$$\varepsilon(\omega) = |\varepsilon(\omega)| \exp(i\varphi(\omega))$$

Complex temporal field

$$\varepsilon(t) = |\varepsilon(t)| \exp(i\phi(t))$$

$$\varepsilon(t) = TF(\varepsilon(\omega))$$

Definitions : Intensity

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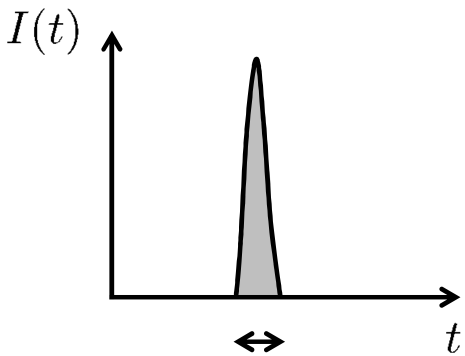
Temporal Intensity

$$I(t) = n\frac{\varepsilon_0 c}{2}\left|\varepsilon(t)\right|^2$$

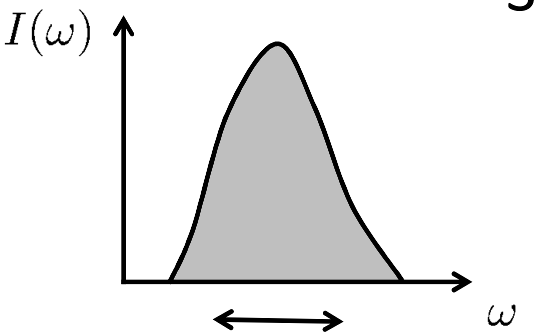


Time width

$$\Delta t = \sqrt{\left\langle (t - t_0)^2 \right\rangle}$$

Spectral Intensity

$$I(\omega) = n\frac{\varepsilon_0 c}{2}\left|\varepsilon(\omega)\right|^2$$



Spectral width

$$\Delta\omega = \sqrt{\left\langle (\omega - \omega_0)^2 \right\rangle}$$

$$\Delta t \Delta \omega \geq \frac{1}{2}$$

Short pulse = broad spectrum

Gaussian pulse

Temporal field

$$\mathscr{E}(t) = \exp(-\frac{t^2}{2a^2})\exp(-i\omega_0 t)$$

Gaussian envelope

Carrier wave

FT^{-1}

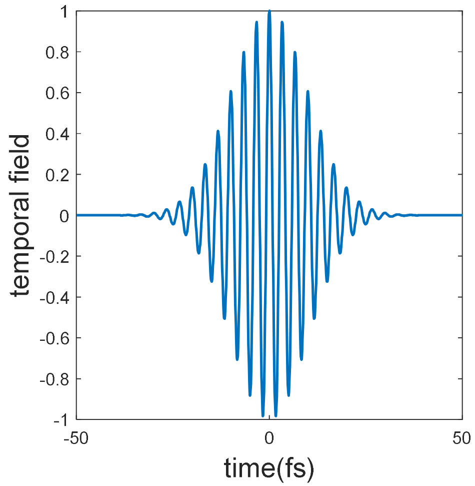
$$TF^{-1}(f(t)g(t)) = \frac{1}{2\pi} f(\omega) \otimes g(\omega)$$

Spectral field

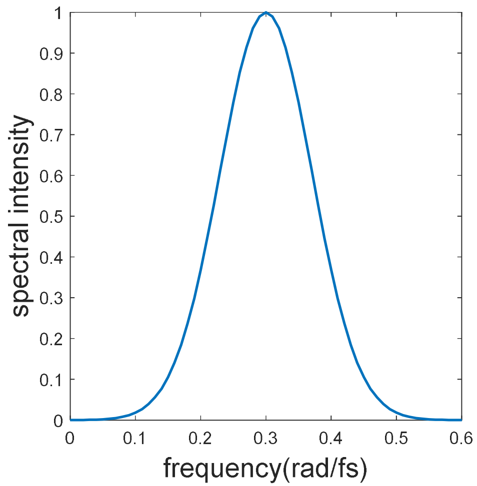
$$\mathscr{E}(\omega) = a\sqrt{2\pi}\exp(-\frac{a^2}{2}(\omega-\omega_0)^2)$$

Gaussian envelope centered on the carrier frequency

Temporal field



Spectral field



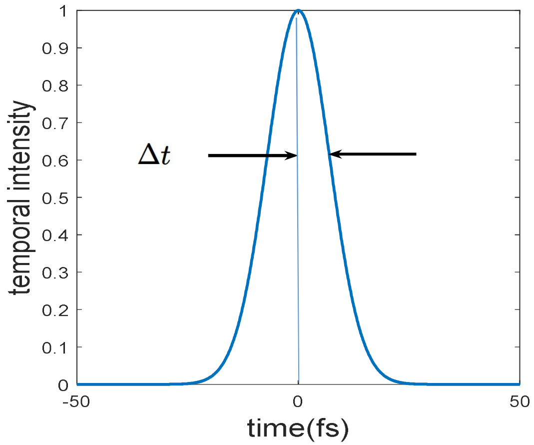
Gaussian pulse

Temporal intensity

$$I(t) = \exp(-\frac{t^2}{a^2})$$

RMS width

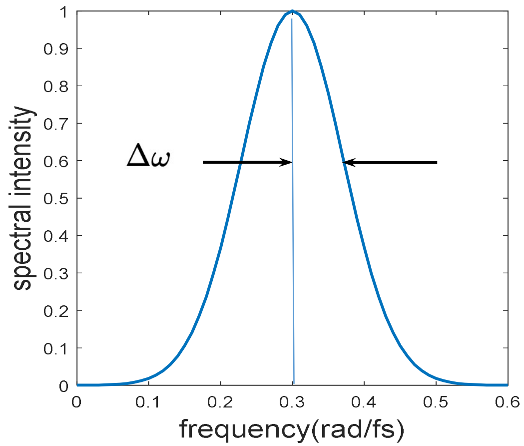
$$\Delta t = a/\sqrt{2}$$



Spectral intensity

$$I(\omega) = \exp(-a^2(\omega - \omega_0)^2)$$

$$\Delta\omega = 1/a\sqrt{2}$$



Gaussian pulse

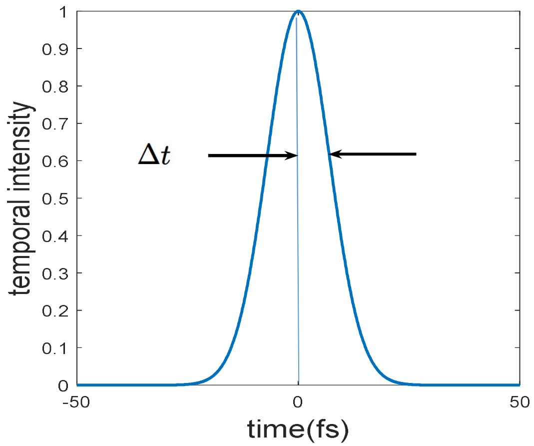
Temporal intensity

$$I(t) = \exp(-\frac{t^2}{a^2})$$

RMS width

$$\Delta t = a/\sqrt{2}$$

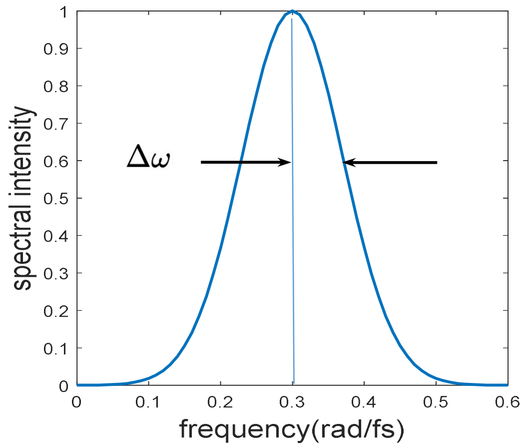
$$\Delta t \Delta \omega = 1/2$$



Spectral intensity

$$I(\omega) = \exp(-a^2(\omega - \omega_0)^2)$$

$$\Delta \omega = 1/a\sqrt{2}$$



Gaussian pulse

Temporal intensity

$$I(t) = \exp(-\frac{t^2}{a^2})$$

RMS width

$$\Delta t = a/\sqrt{2}$$

$$\Delta t \Delta \omega = 1/2$$

Spectral intensity

$$I(\omega) = \exp(-a^2(\omega - \omega_0)^2)$$

$$\Delta \omega = 1/a\sqrt{2}$$

$$\Delta t \Delta \omega = 1/2$$

The uncertainty limit is only reached for Gaussian pulses

↓

for a given spectral width, the Gaussian pulse has the shortest possible duration

Gaussian pulse

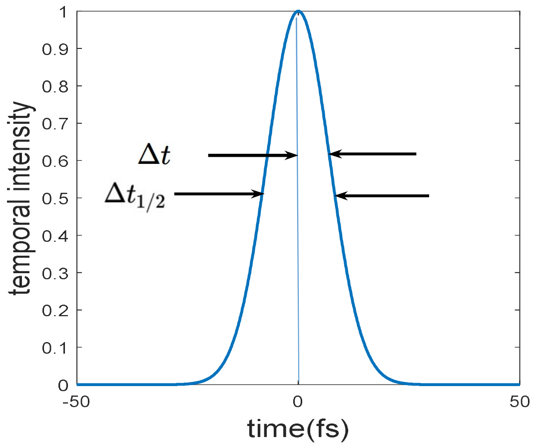
Temporal intensity

$$I(t) = \exp(-\frac{t^2}{a^2})$$

FWHM

Full Width at Half Maximum

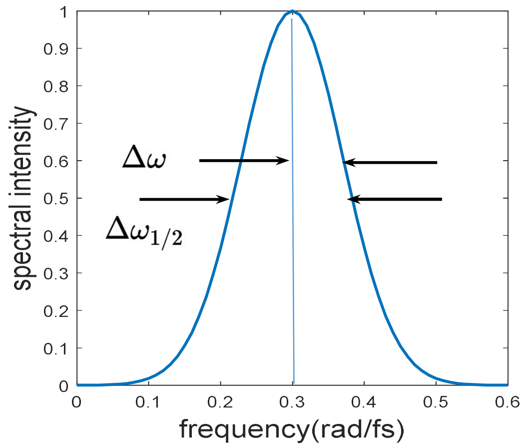
$$\Delta t_{1/2} = \sqrt{8ln2}\Delta t = 2.355\Delta t$$



$$\Delta t_{1/2}\Delta\omega_{1/2} = 4ln2$$

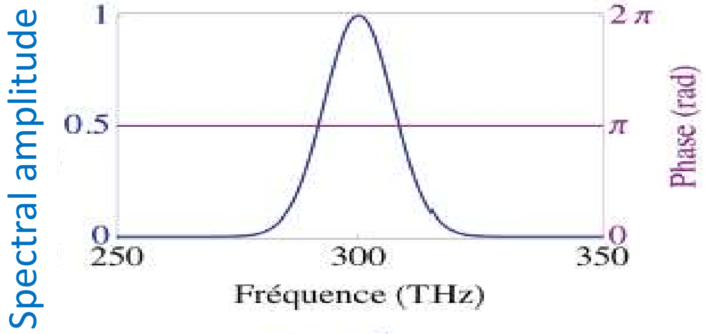
Spectral intensity

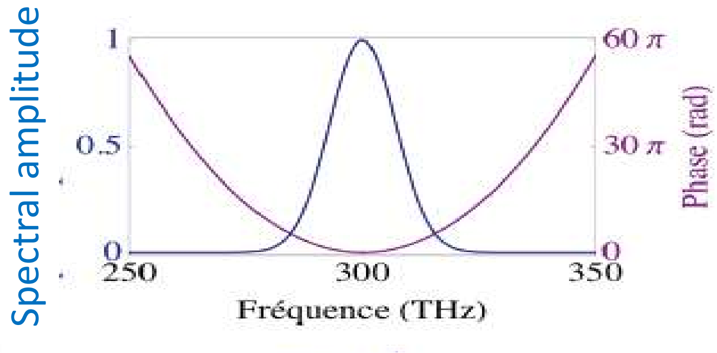
$$I(\omega) = \exp(-a^2(\omega-\omega_0)^2)$$



For λ=1 μm   Pulse duration = 100 fs   /   Spectral bandwidth = 14,6 nm

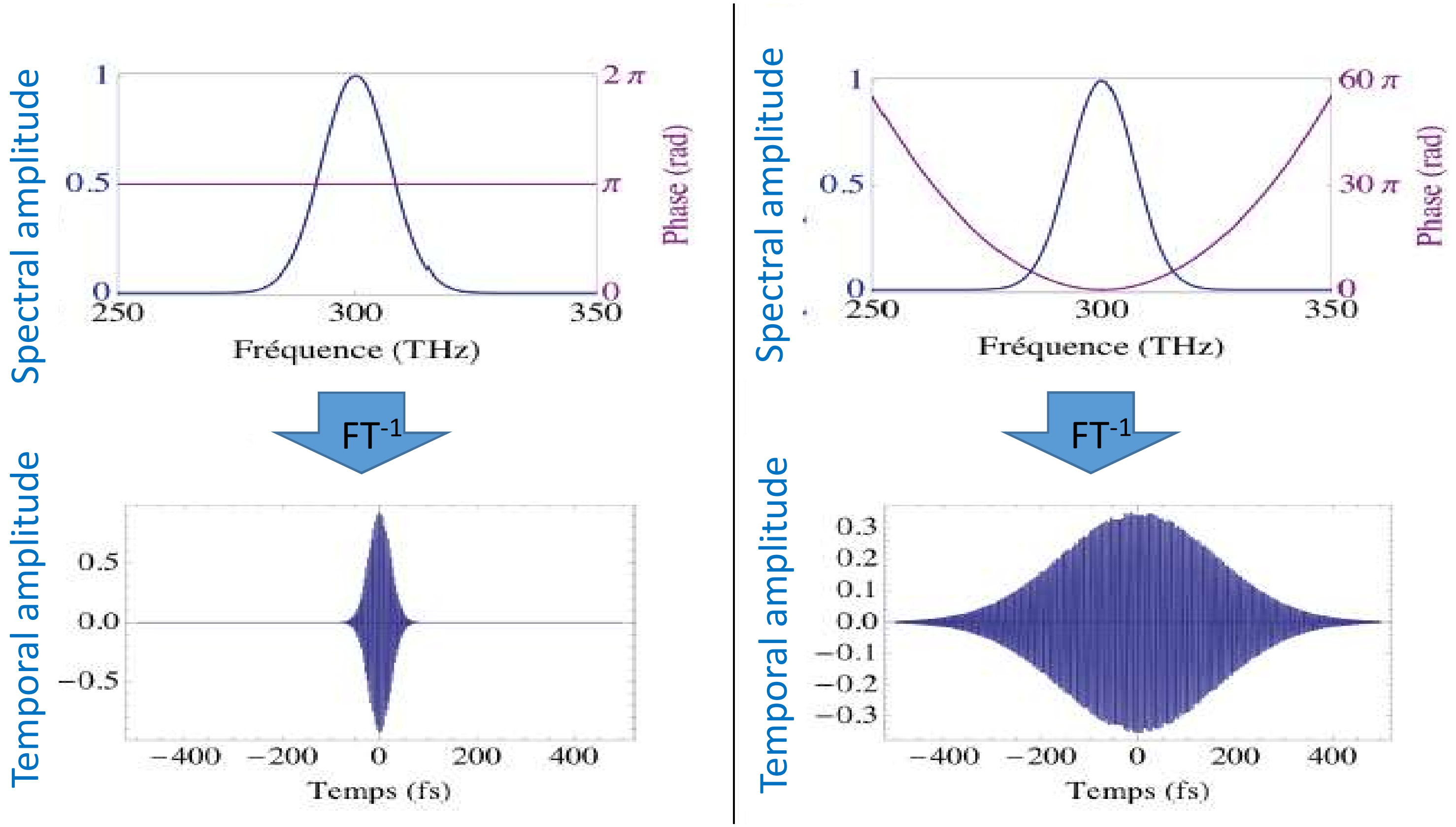
Temporal profile and spectral phase





$$\varepsilon(\omega) = |\varepsilon(\omega)| \exp(i\varphi(\omega))$$

Temporal profile and spectral phase



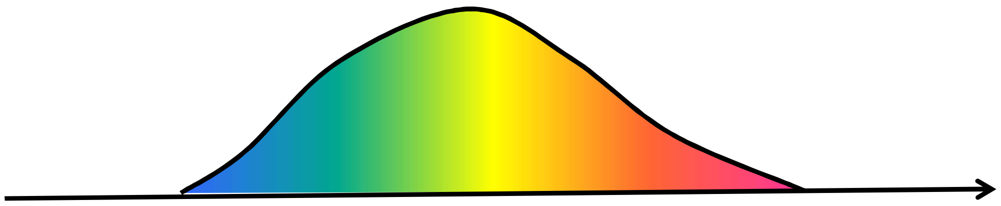
Effects of the spectral Phase

$$\mathscr{E}(\omega) = |\mathscr{E}(\omega)| \exp(i\varphi(\omega))$$

$$\varphi(\omega) = \varphi(\omega_0) + \varphi'(\omega_0)(\omega - \omega_0) + \frac{1}{2}\varphi''(\omega_0)(\omega - \omega_0)^2 + \frac{1}{6}\varphi'''(\omega_0)(\omega - \omega_0)^3 + \ldots$$

$$\tau_g(\omega) = \varphi'(\omega)$$

Group delay = relative delay of a spectral component



Effects of the spectral Phase

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$$\mathscr{E}(\omega) = |\mathscr{E}(\omega)| \exp(i\varphi(\omega))$$

$$\varphi(\omega) = \varphi(\omega_0) + \varphi'(\omega_0)(\omega - \omega_0) + \frac{1}{2}\varphi''(\omega_0)(\omega - \omega_0)^2 + \frac{1}{6}\varphi'''(\omega_0)(\omega - \omega_0)^3 + \ldots$$

Constant

Temporal translation of the envelope

The first two terms have no impact on the temporal shape

Effects of the spectral Phase

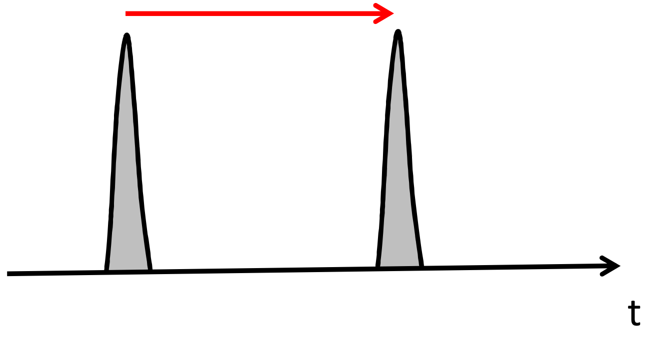
$$\mathscr{E}(\omega) = |\mathscr{E}(\omega)| \exp(i\varphi(\omega))$$

$$\varphi(\omega) = \varphi(\omega_0) + \varphi'(\omega_0)(\omega - \omega_0) + \frac{1}{2}\varphi''(\omega_0)(\omega - \omega_0)^2 + \frac{1}{6}\varphi'''(\omega_0)(\omega - \omega_0)^3 + \ldots$$

Constant

Temporal translation of the envelope

$$\tau_g = \varphi'(\omega_0)$$



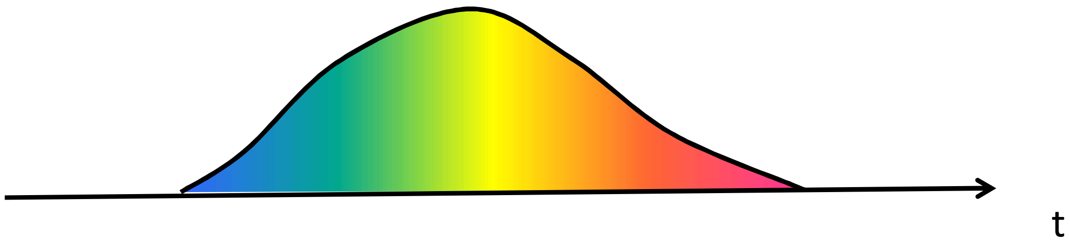
Effects of the spectral Phase

$$\mathscr{E}(\omega) = |\mathscr{E}(\omega)| \exp(i\varphi(\omega))$$

$$\varphi(\omega) = \varphi(\omega_0) + \varphi'(\omega_0)(\omega - \omega_0) + \frac{1}{2}\varphi''(\omega_0)(\omega - \omega_0)^2 + \frac{1}{6}\varphi'''(\omega_0)(\omega - \omega_0)^3 + \dots$$

$$\tau_g(\omega) = \varphi''(\omega_0)(\omega - \omega_0)$$

The group delay varies linearly with the frequency



Parabolic spectral phase

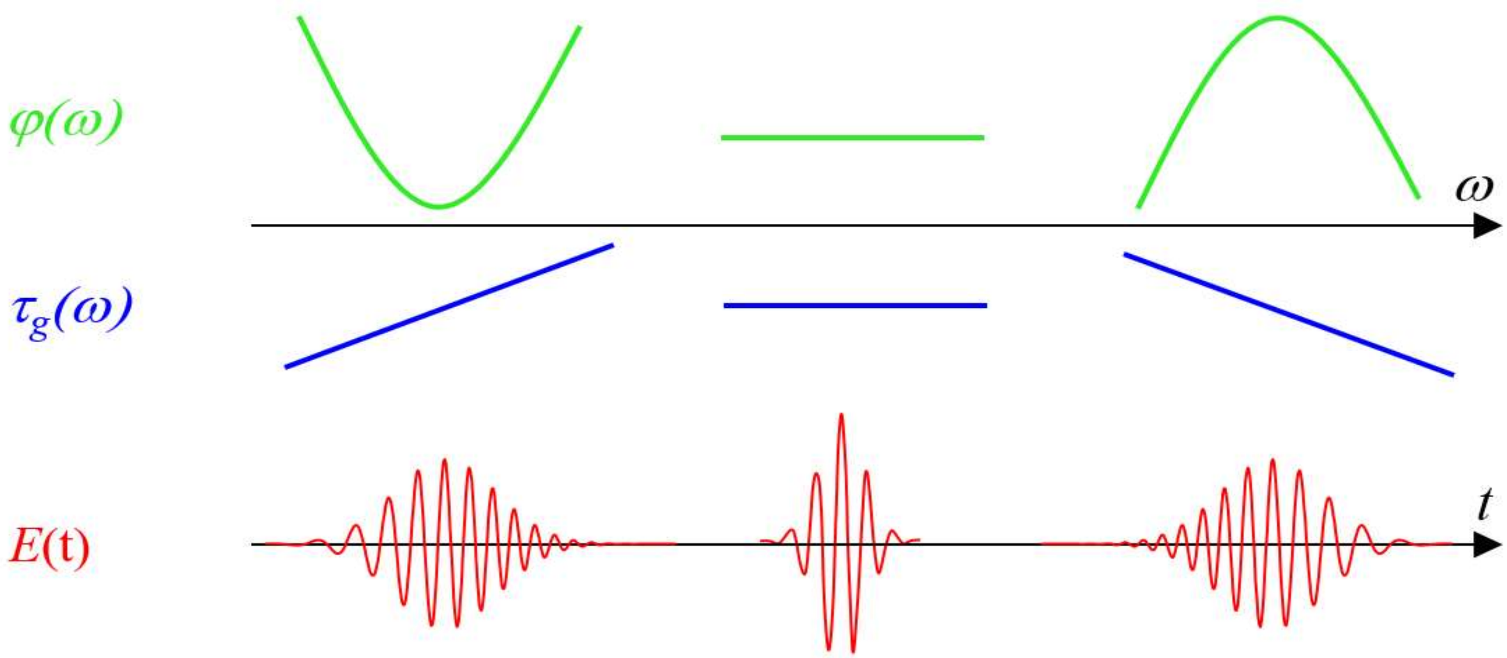
$$\tau_g(\omega) = \varphi''(\omega_0)(\omega - \omega_0)$$

$\varphi''(\omega_0) > 0$ | $\varphi''(\omega_0) = 0$ | $\varphi''(\omega_0) < 0$

Spectral Phase

Group delay

Temporal field



up-chirped | FT limited | down-chirped

Propagation effects

Spectral phase accumulated by propagation :

$$\varphi(z,\omega) = \varphi(0,\omega) + k(\omega)z \qquad k(\omega) = n(\omega)\omega/c$$

$$\tau_g(z,\omega) = \tau_g(0,\omega) + k'(\omega_0)z + (\omega - \omega_0)k''(\omega_0)z + \dots$$

Propagation effects

Spectral phase accumulated by propagation :

$$\varphi(z,\omega) = \varphi(0,\omega) + k(\omega)z \qquad k(\omega) = n(\omega)\omega/c$$

$$\tau_g(z,\omega) = \tau_g(0,\omega) + k'(\omega_0)z + (\omega - \omega_0)k''(\omega_0)z + \dots$$

Constant delay

$$V_g(\omega) = 1/k'(\omega)$$

Group velocity
(velocity of the envelope)

Propagation effects

Spectral phase accumulated by propagation :

$$\varphi(z,\omega) = \varphi(0,\omega) + k(\omega)z \qquad k(\omega) = n(\omega)\omega/c$$

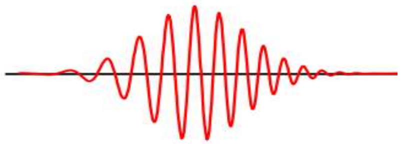
$$\tau_g(z,\omega) = \tau_g(0,\omega) + k'(\omega_0)z + (\omega-\omega_0)k''(\omega_0)z + \dots$$

Constant delay

$$V_g(\omega) = 1/k'(\omega)$$

Group velocity
(velocity of the envelope)

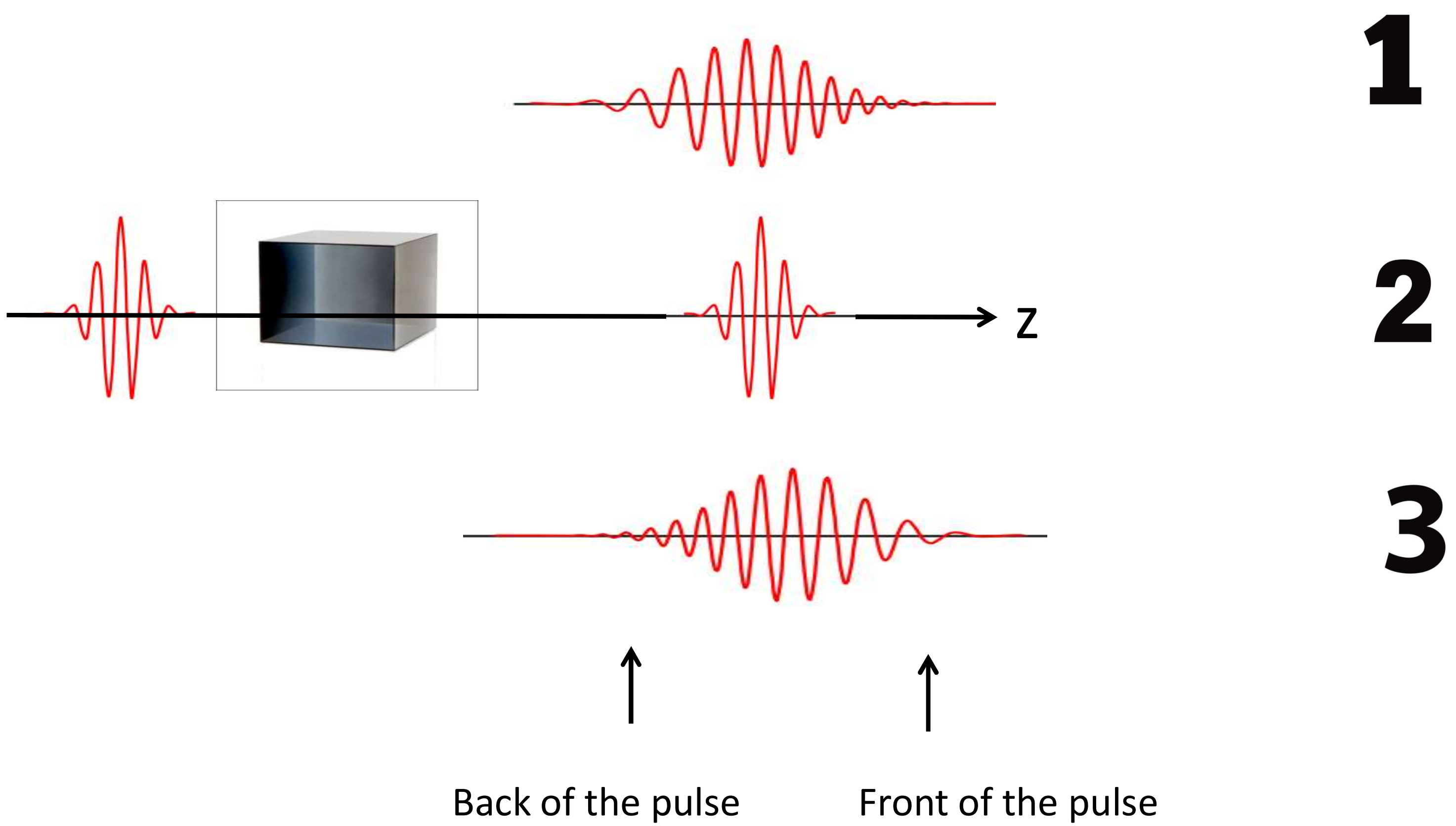
Group Delay Dispersion
(GDD)



The pulse is chirped

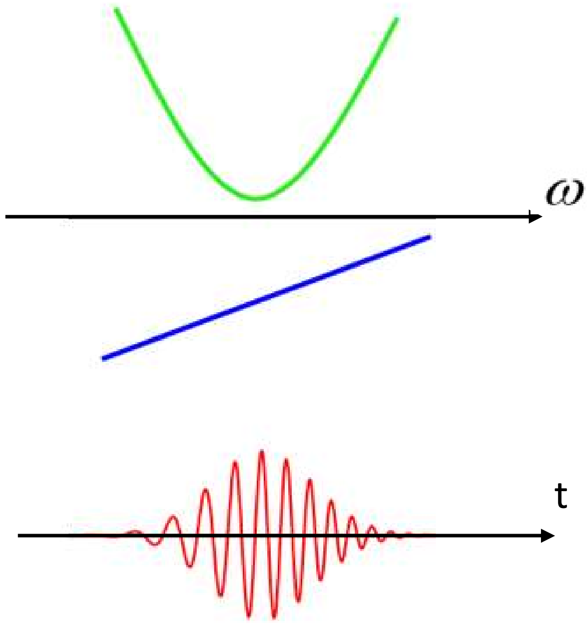
Quizz

What is the output pulse after propagation in a material with k''>0?



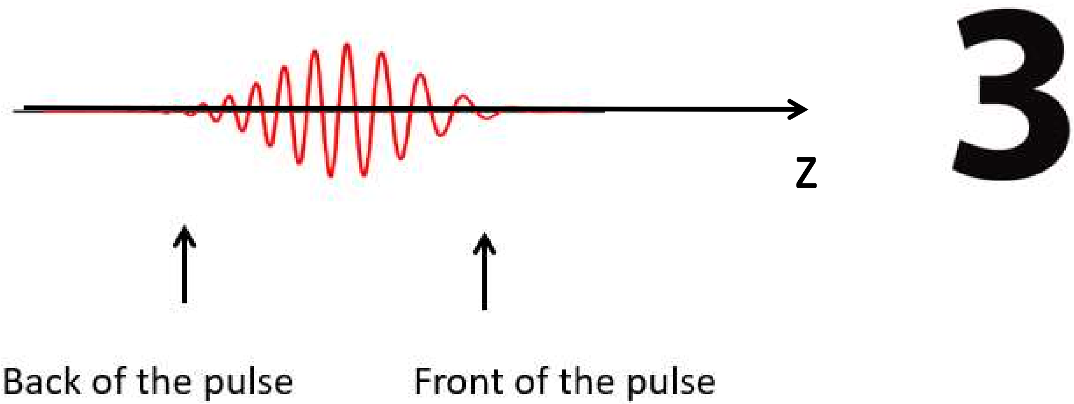
Quizz

$$\varphi''(\omega_0) > 0$$



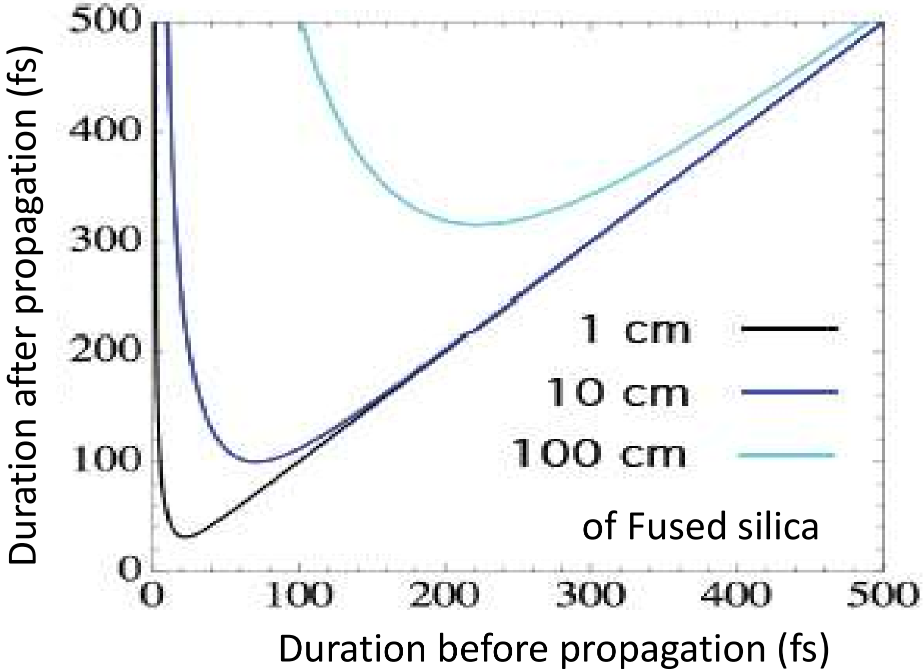
up-chirped

The high frequency components present a higher group delay, they are at the back of the pulse



Duration after propagation in a dispersive material

Materials transparent in the visible : k’’>0



Dispersive effects higher for shorter pulses

$$\tau_g(z,\omega) = \tau_g(0,\omega) + k'(\omega_0)z + (\omega-\omega_0)k''(\omega_0)z + \dots$$

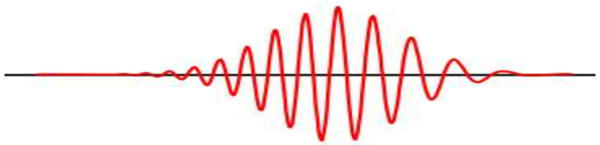
Summary 1

$$\varepsilon(\omega) = \left|\varepsilon(\omega)\right| \exp(i\varphi(\omega))$$

- ✓ Short Pulse = broad spectrum

$$\boxed{\Delta t \Delta \omega \geq \frac{1}{2}}$$

- ✓ The spectral phase governs the temporal shape
- ✓ Non linear spectral phase = group velocity dispersion
- ✓ Propagation in transparent material = up chirped pulse



Outline

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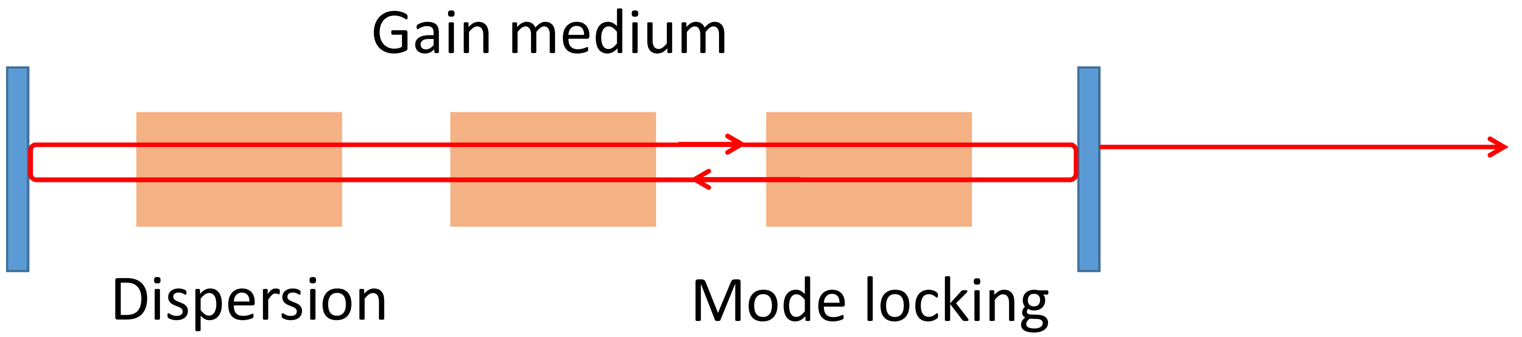
Introduction

1. Description of ultrashort light pulses

2. Generation of femtosecond laser pulses via mode locking

3. Femtosecond oscillator technology

Fundamental of mode locking

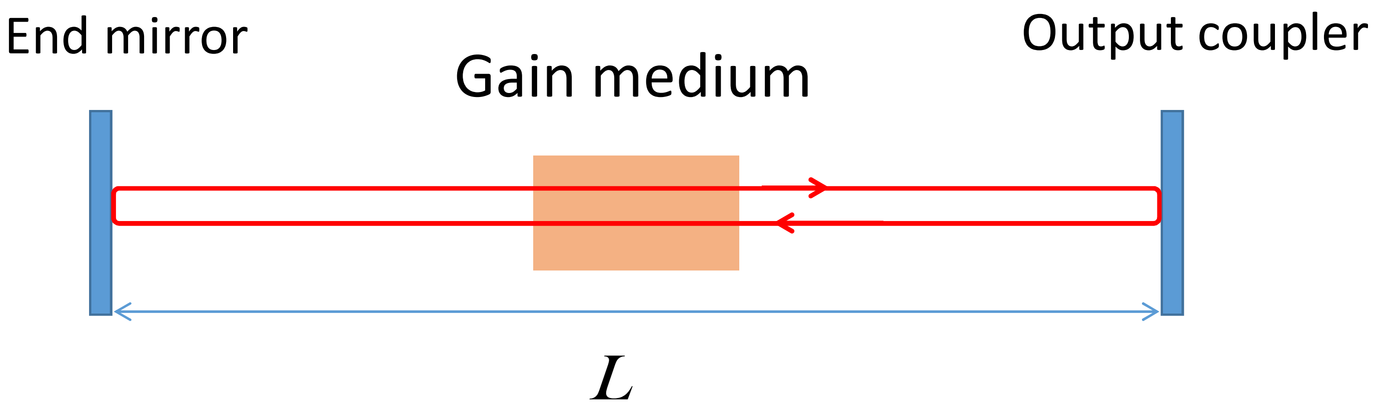


✓Compensation of the dispersion
- Prisms
- Gratings
- Chirped mirrors

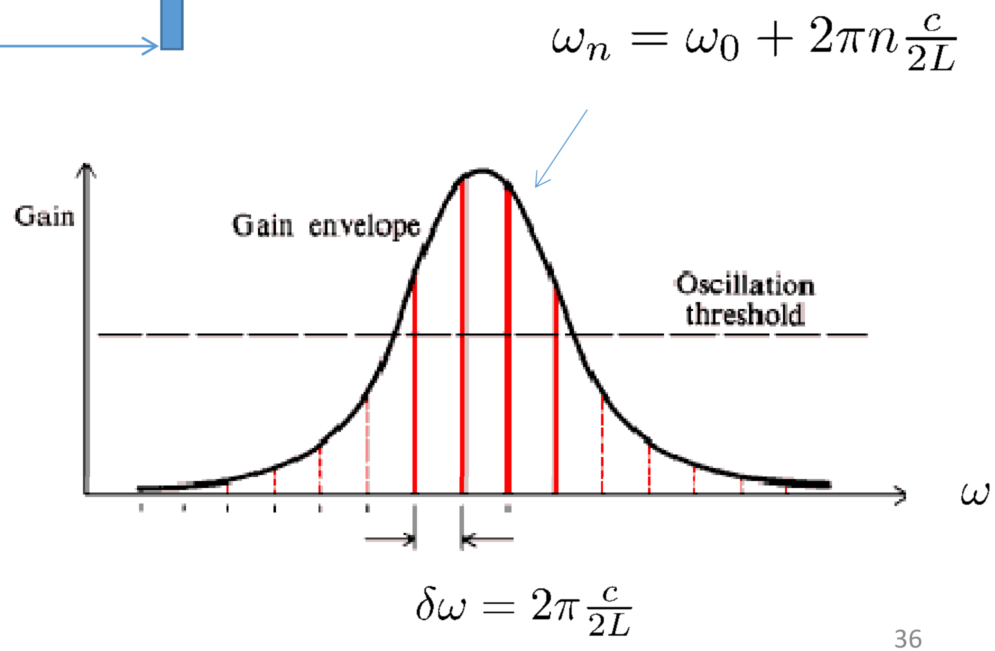
✓Gain medium
- Gain
- Wavelength
- Pulse duration
- Pumping

✓Non linear effect for mode locking
- AOM
- Kerr-lens
- Saturable absorber

Gain medium



Longitudinal modes in the frequency domain



Longitudinal modes

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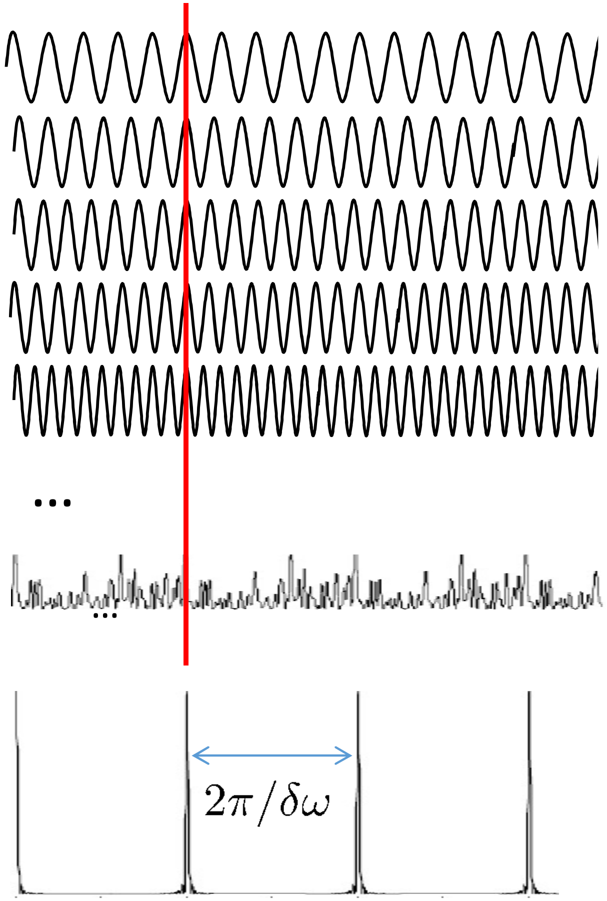
in time domain



ω_n $\phi_n(t)$

ω_{n+1} $\phi_{n+1}(t)$

ω_{n+2} $\phi_{n+2}(t)$

ω_{n+3} $\phi_{n+3}(t)$

ω_{n+4} $\phi_{n+4}(t)$

Example :

$\lambda = 800nm$

$\Delta\lambda = 80nm$

N modes >100 000

Random phase modes

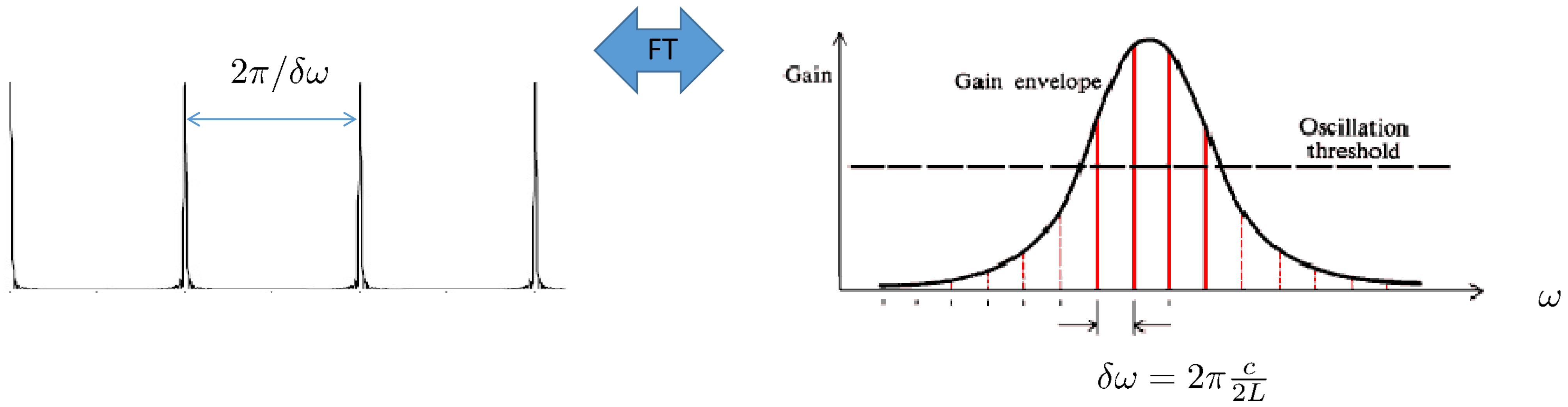
In-phase modes : $\phi_n(t) = 0$

$$I(t) = I_0 \left[\frac{\sin(N\delta\omega t/2)}{\sin(\delta\omega t/2)} \right]^2$$

$$\delta\omega = 2\pi \frac{c}{2L}$$

Mode locking

time domain | frequency domain



Mode locking = phases locked $\phi_n = n\alpha$

Train pulses separated by the round trip time

Spectral width increases with *N*

Duration decreases with *N* $T = 2\pi/\delta\omega = 2L/c$

Mode locking

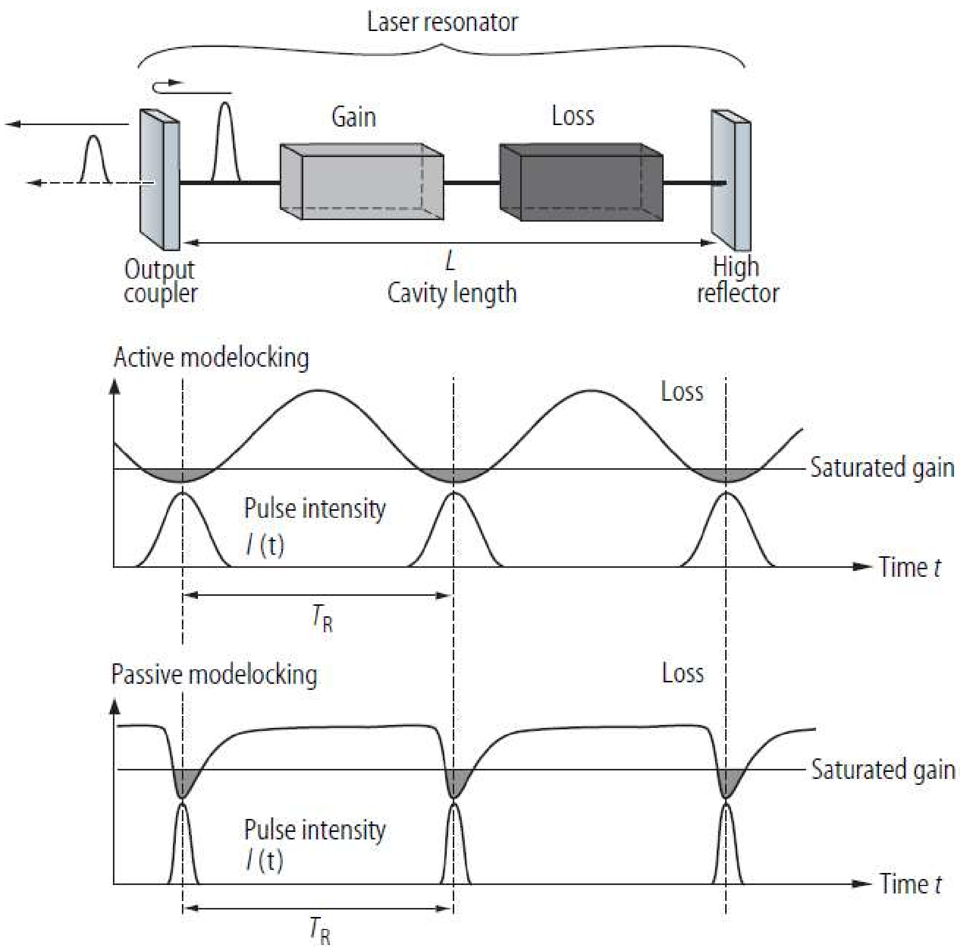


Fig. 2.1.3. Schematic laser cavity setup for active and passive mode-locking.

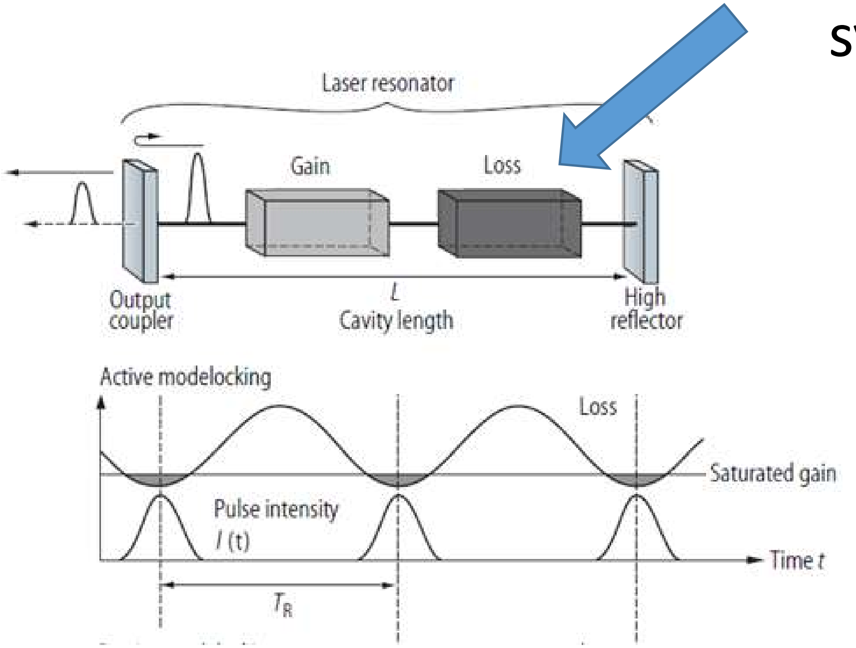
Idea :to favor pulsed regime over continous one

➡ Loss modulation

- Active modelocking
  - Acousto-optic modulator
  - Electro-optic modulator
- Passive modelocking
  - KLM
  - SESAM

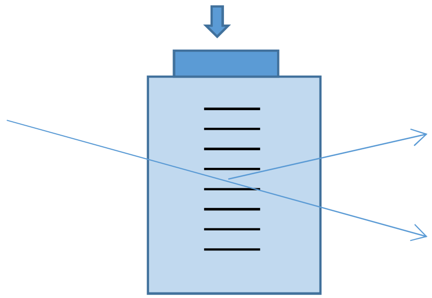
Figure from book chapter *Ultrafast solid-state lasers*, Ursula Keller

Active modelocking



Acousto-optic (or electro-optic) modulator synchronized with the resonator round trip

Piezo + RF modulator $\Omega = \pi c/L$



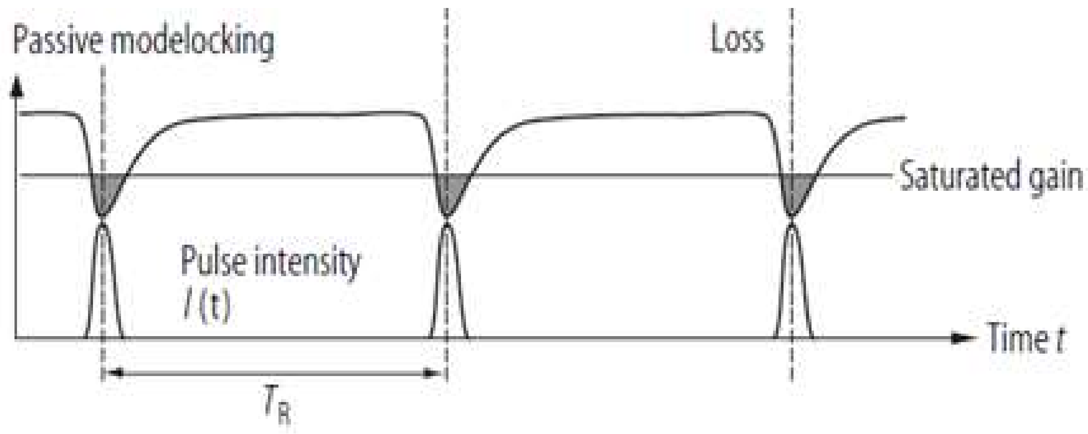
Diffracted and frequency shift beam

Generation of a grating that turns ON and OFF at a frequency $2\Omega = c/2L$

Passive modelocking

Self amplitude modulation of the light by **fast** loss saturation

Shorter pulse
Starting with noise fluctuations



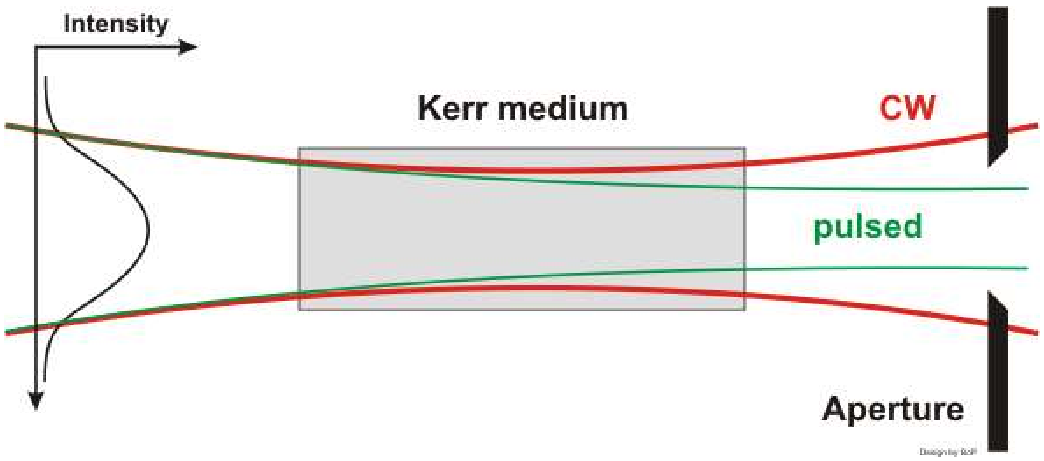
Cavity round-trip time

- Kerr Lens
- Saturable absorber

Kerr lens modelocking

Kerr effect: Nonlinear change in refractive index $n(r) = n_0 + n_2 I(r)$

Fast (few fs) and broadband



KLM = Kerr Lens Modelocking

Self focusing + hard or « soft » aperture

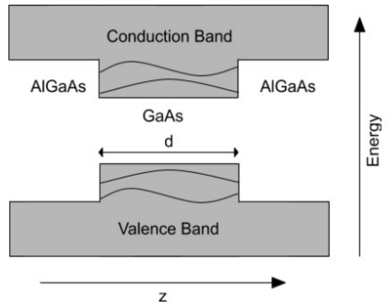
Not self starting : vibrating mirror or saturable absorber

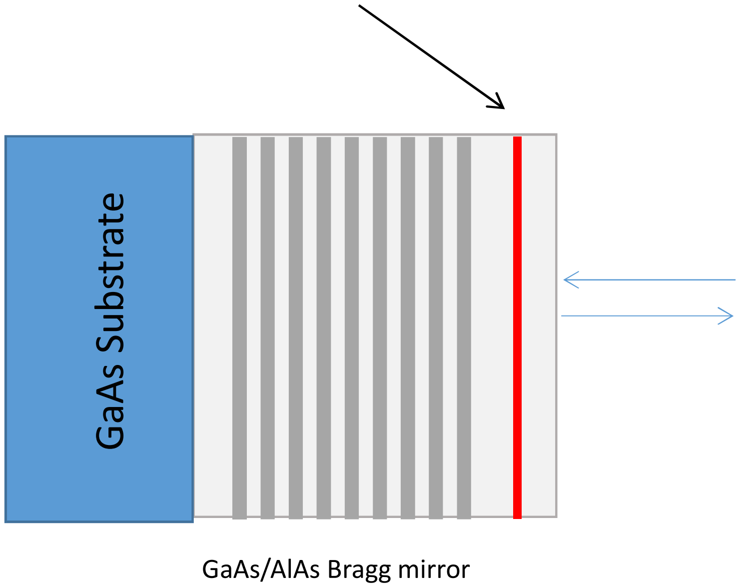
Saturable absorber

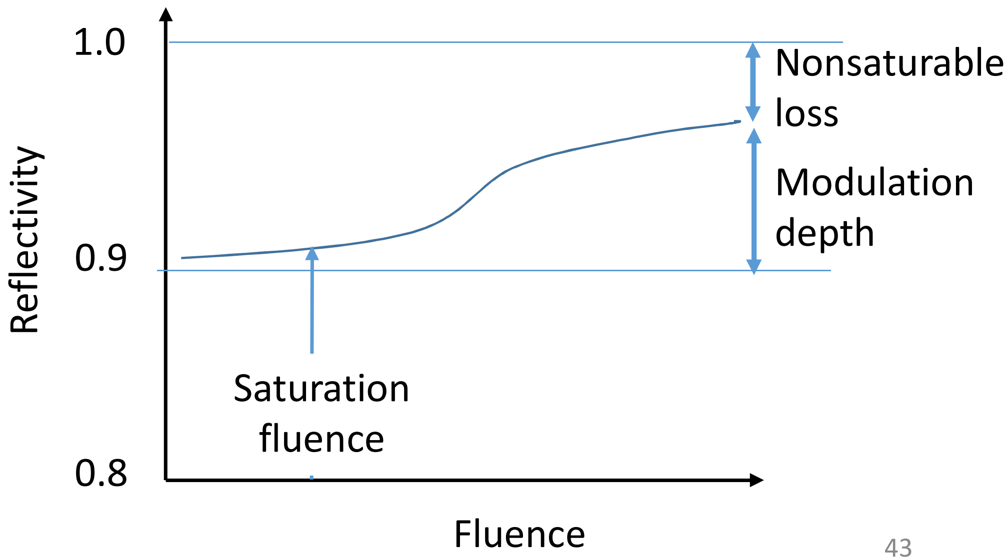
Saturable absorber : component with losses reduced by high intensities

SESAM : Semiconductor Saturable Absorber Mirror

InGaAs quantum well absorber on a Bragg mirror

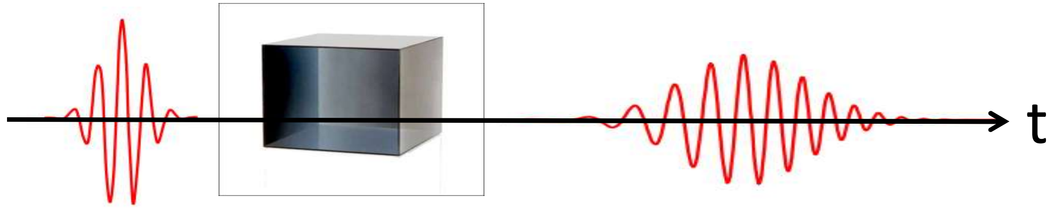






Dispersion management

How to compensate for the dispersion in the cavity?



DVG >0 in the visible

✓Prisms

✓Gratings

✓Chirped mirrors

Dispersion management with prisms

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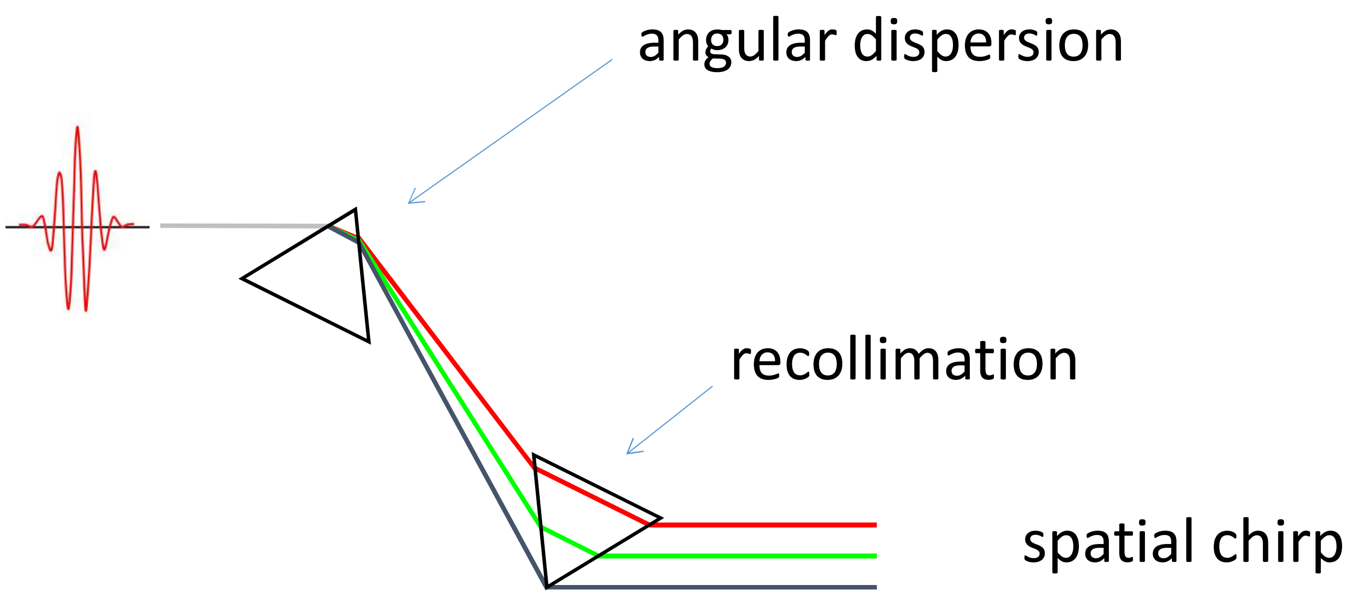
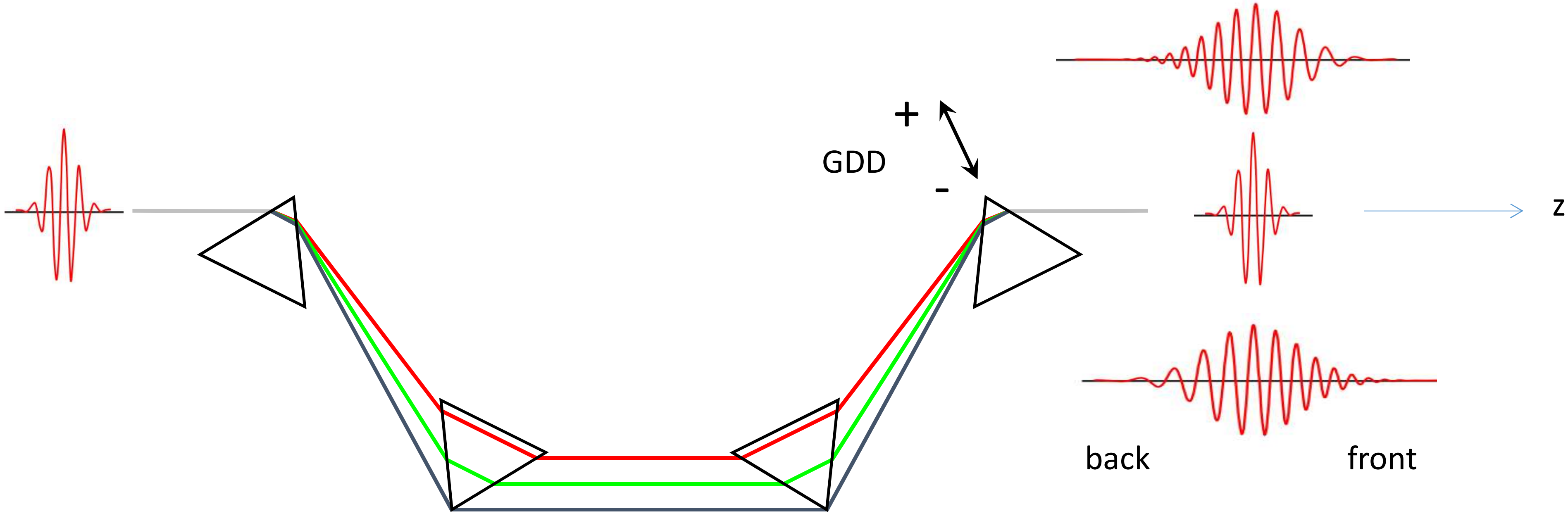
Prism sequence for adjustable group delay dispersion.



Dispersion management with prisms

Prism sequence for adjustable group delay dispersion.



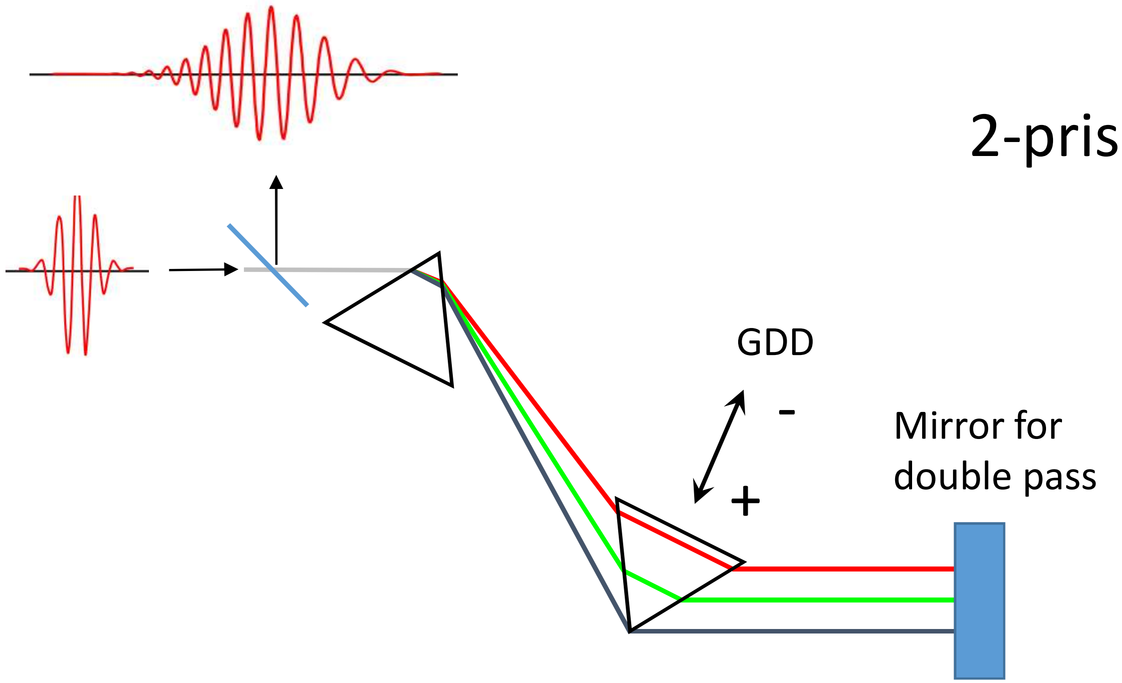
GDD
$$\frac{d^2\phi_{fourprisms}}{d\omega^2} \approx \frac{d^2\phi_m}{d\omega^2} + \frac{d^2\phi_p}{d\omega^2} = \frac{\lambda^3 L}{2\pi c^2}\frac{d^2 n}{d\lambda^2} - \frac{4 l_p \lambda^3}{\pi c^2}\left(\frac{dn}{d\lambda}\right)^2$$

TOD
$$\frac{d^3\phi_{fourprisms}}{d\omega^3} \approx \frac{d^3\phi_m}{d\omega^3} + \frac{d^3\phi_p}{d\omega^3} = \frac{-\lambda^4 L}{4\pi^2 c^3}\left(3\frac{d^2 n}{d\lambda^2} + \lambda\frac{d^3 n}{d\lambda^3}\right) + \frac{6 l_p \lambda^4}{\pi^2 c^3}\frac{dn}{d\lambda}\left(\frac{dn}{d\lambda} + \lambda\frac{d^2 n}{d\lambda^2}\right).$$

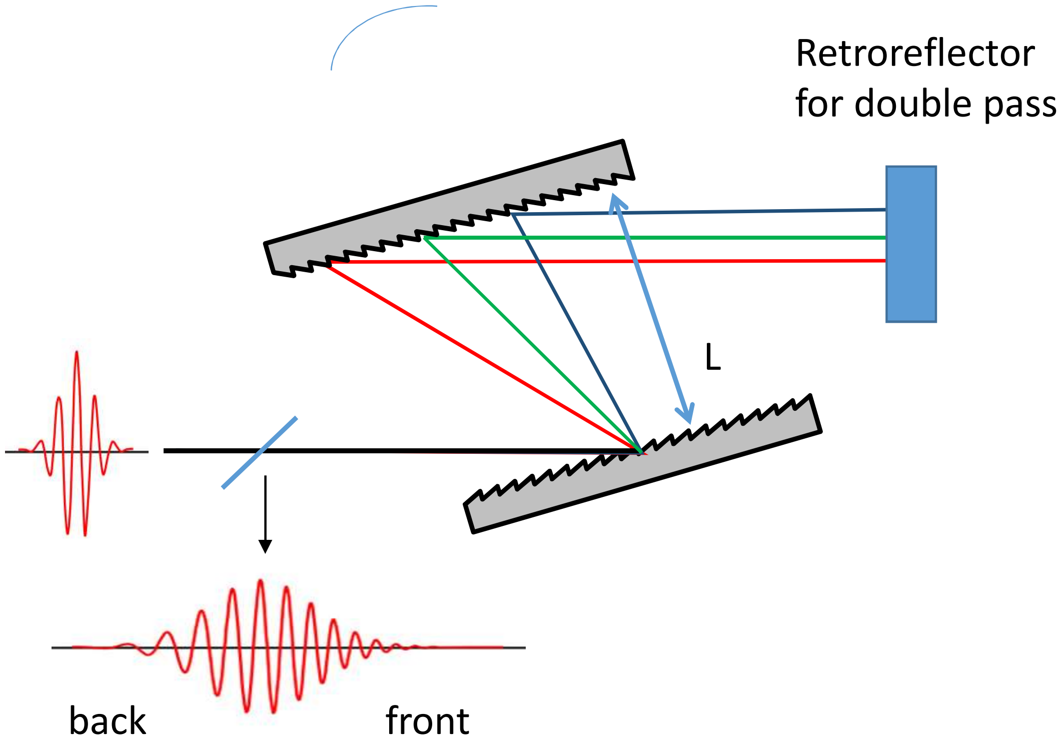
lp distance between prisms
L mean glass pass

Dispersion management with prisms

2-prism sequence in double pass



Dispersion management with gratings

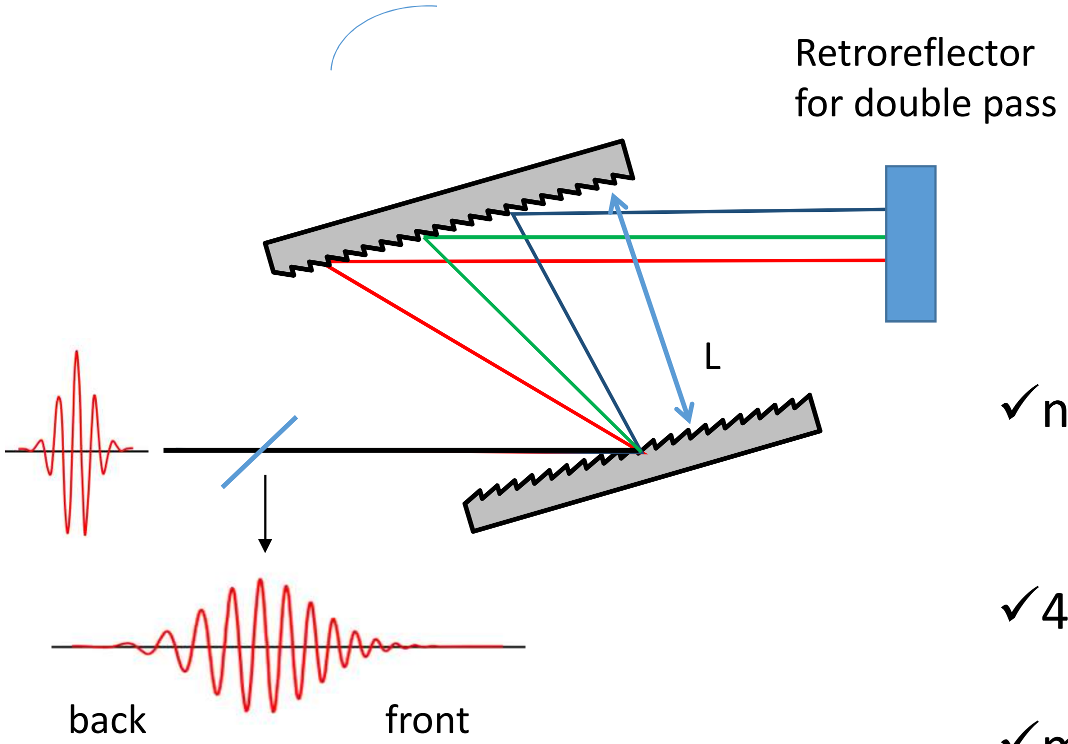


p diffraction order
d grating pitch
I angle of incidence
θ angle of the reflected wavelength

$$\frac{d^2\varphi}{d\omega^2} = \frac{-8\pi^2 cL}{\omega^3 d^2 \cos^3\theta} < 0 \qquad (p = 1)$$

$$\frac{d^3\varphi}{d\omega^3} = \frac{12\pi^2 cL}{\omega^4 d^2} \frac{1 + \frac{2\pi c}{\omega d}\sin i - \sin^2 i}{\cos^5\theta} > 0$$

Dispersion management with gratings

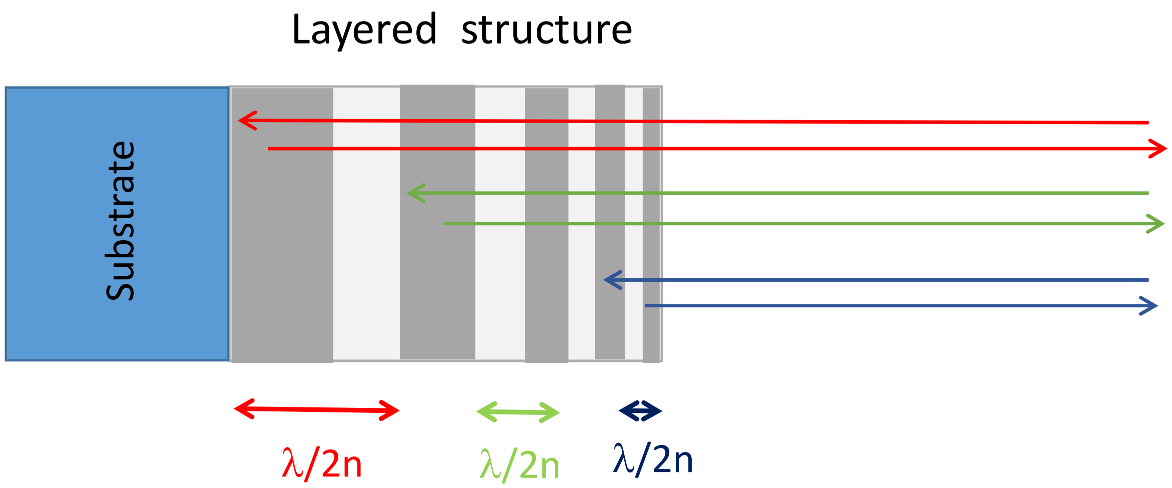


- ✓negative group delay
  - ✓Distance between gratings
  - ✓Gratings pitch
- ✓4 gratings or 2 gratings in double pass

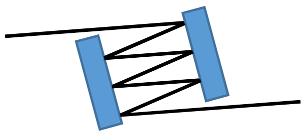
- ✓much more dispersive than prisms but introduces higher losses

Dispersion management with chirped mirror

Bragg mirror with variable layer thickness values



- ✓Compact
- ✓High reflectivity
- ✓Can compensate for higher orders
- ✓Fixed GDD -> multiple reflections



Quizz

The repetition rate of a femtosecond oscillator is related to:

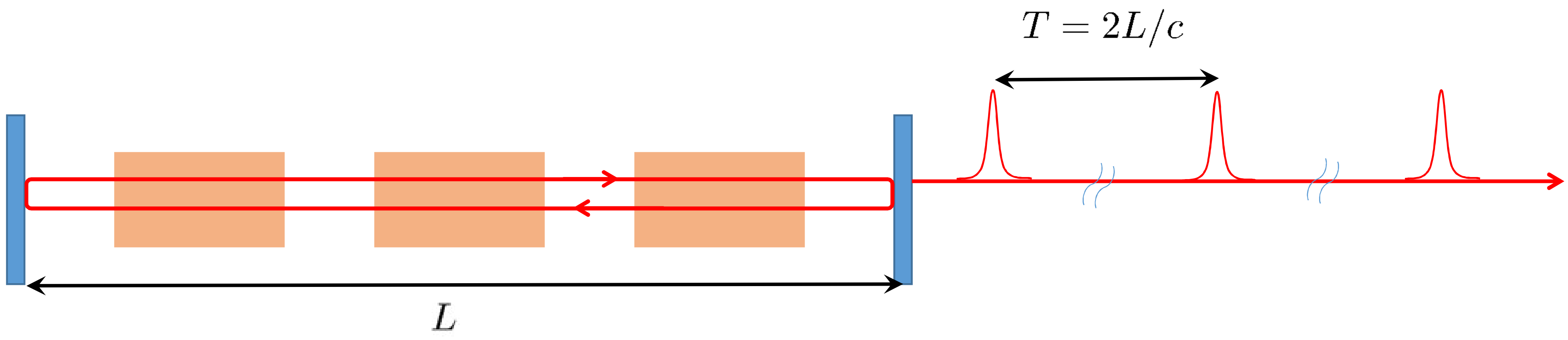
- The acousto-optic modulator **1**
- The length of the cavity **2**
- the pulse width **3**

Quizz

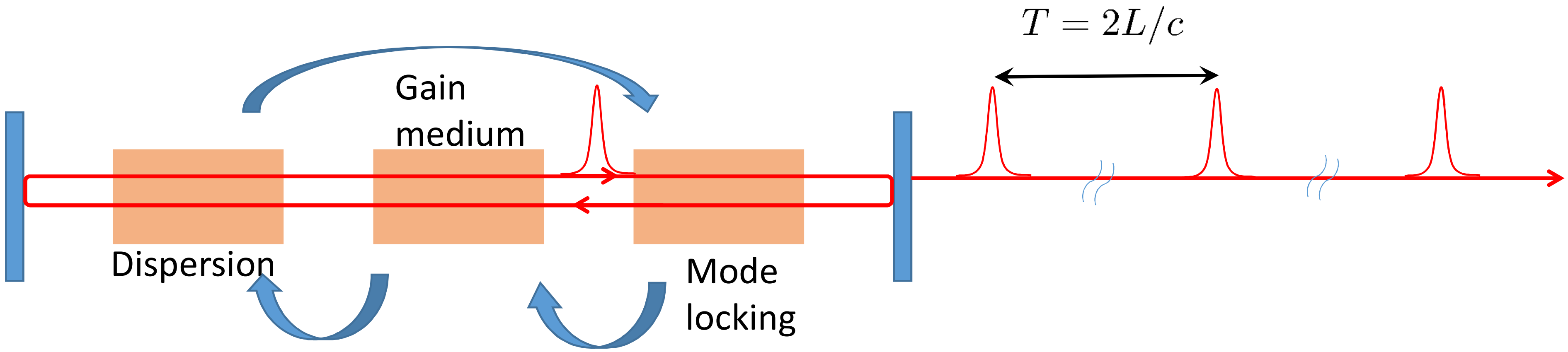
The repetition rate of a femtosecond oscillator is related to:

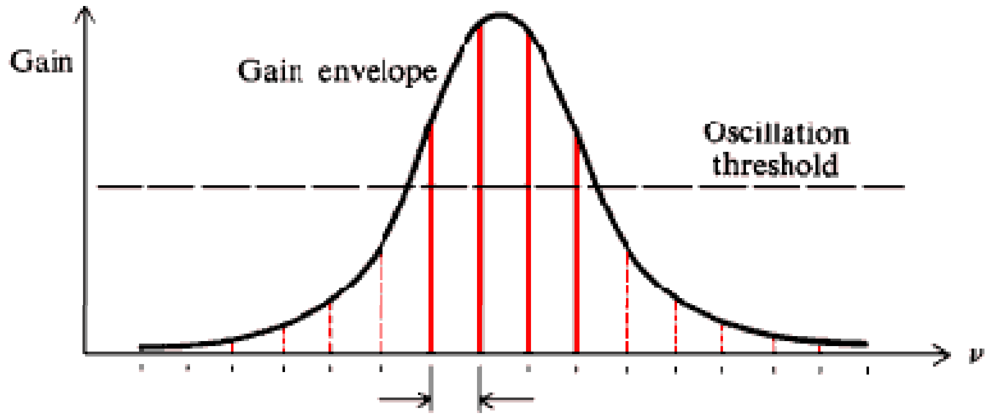
- The length of the cavity

2



Summary 2

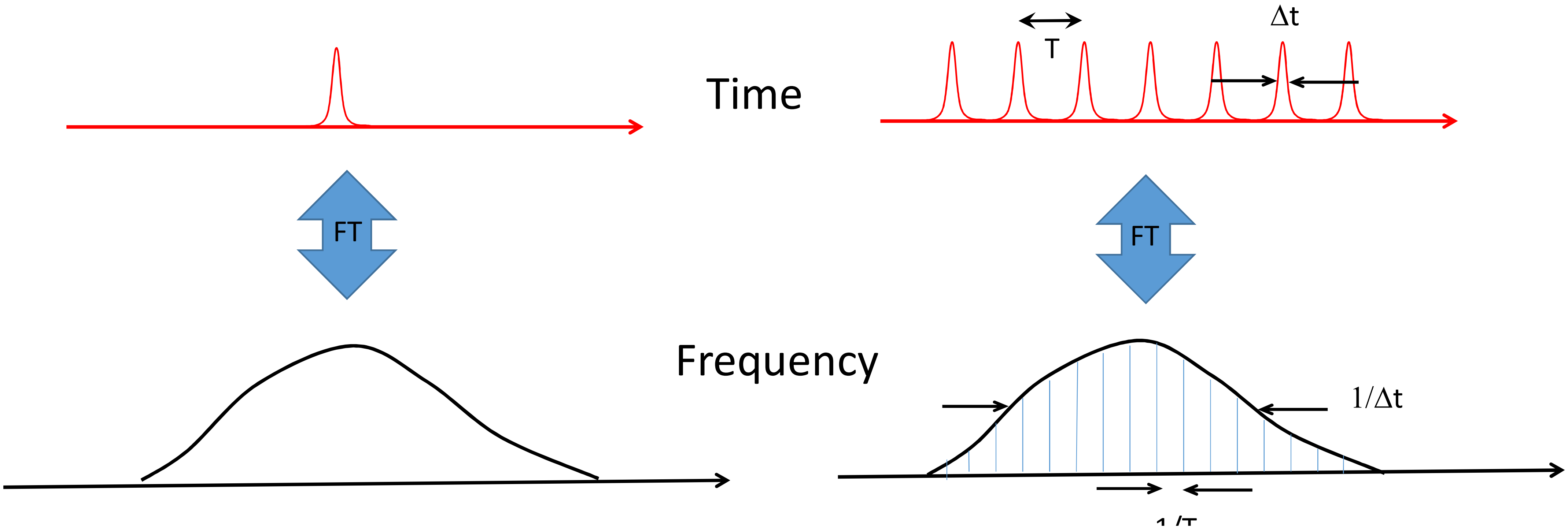




$$\Delta\omega = 2\pi \frac{c}{2L}$$

Mode locking is a balance between dispersion and NL effects. It allows **exact** adjustment of the phase of the modes.

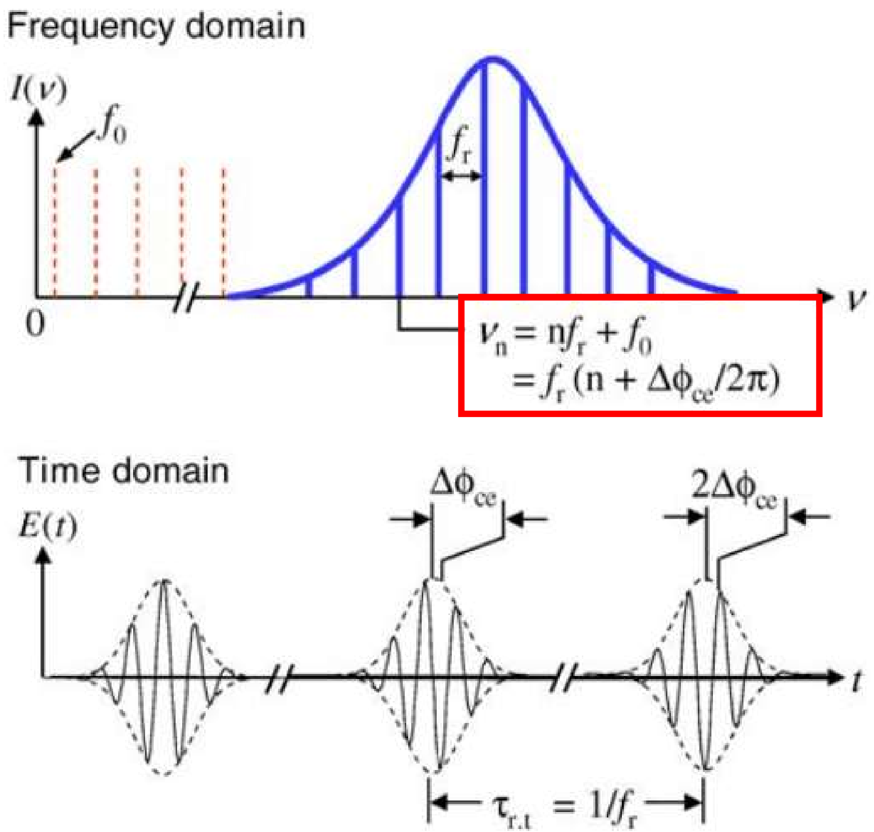
Frequency comb



Discrete and perfectly equally spaced frequency lines

➢ **frequency etalon**

The carrier enveloppe phase



f_r Repetition rate 100MHz-GHz

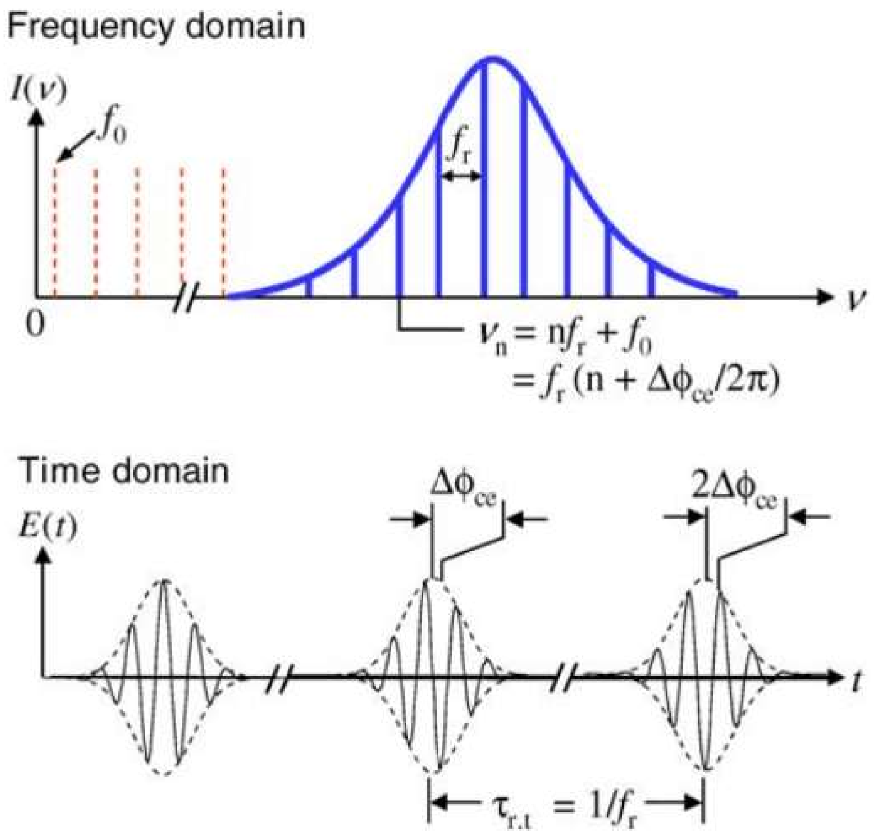
f_0 Carrier Enveloppe Offset (CEO)

For very short pulse, difference between phase and group velocities matters

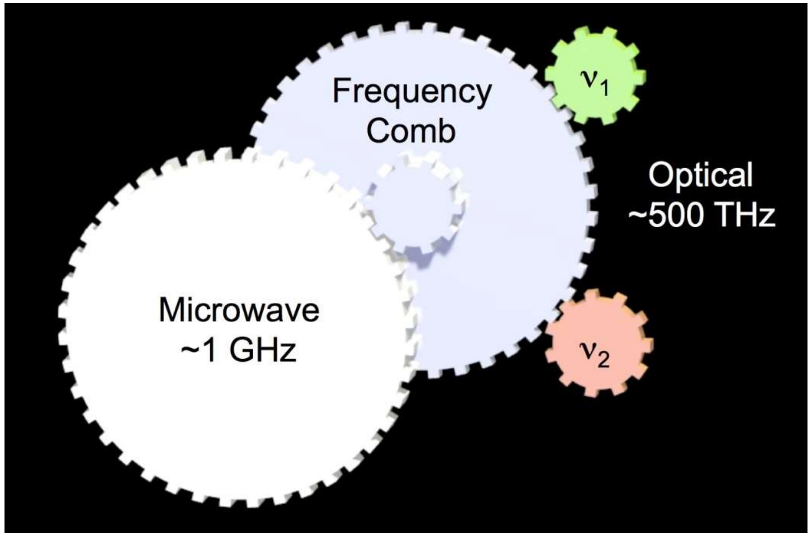
$$f_0 = \frac{\Delta\phi_{CE}}{2\pi} f_r$$

$$\Delta\phi_{CE} = L\omega_0 \left(\frac{1}{v_g} - \frac{1}{v_\varphi}\right)$$

Frequency comb for optical clock



f_r and f_0 are
Microwave frequencies (100MHz-GHz)
linked to **optical frequencies** (THz)



https://www.nist.gov/programs-projects/femtosecond-laser-frequency-combs-optical-clocks

➡ Optical clock

A revolution in the measure of time/frequency

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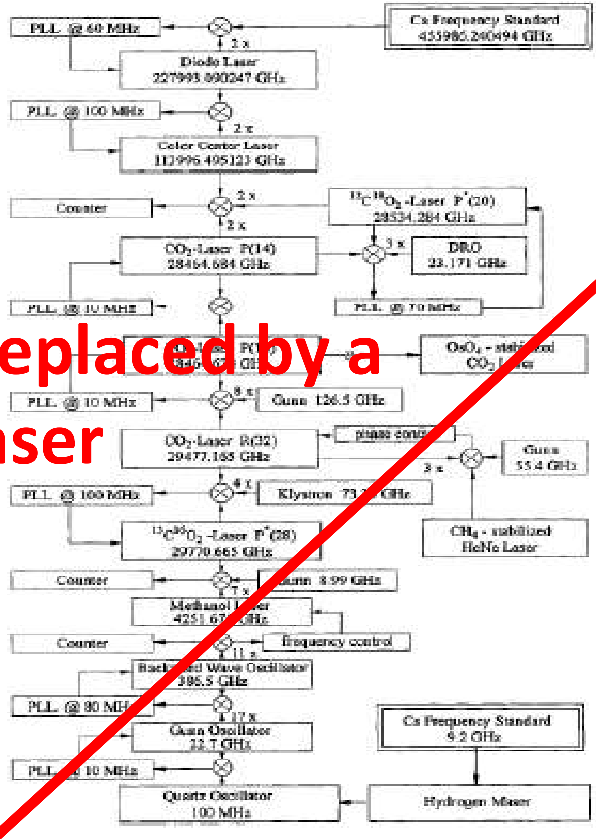
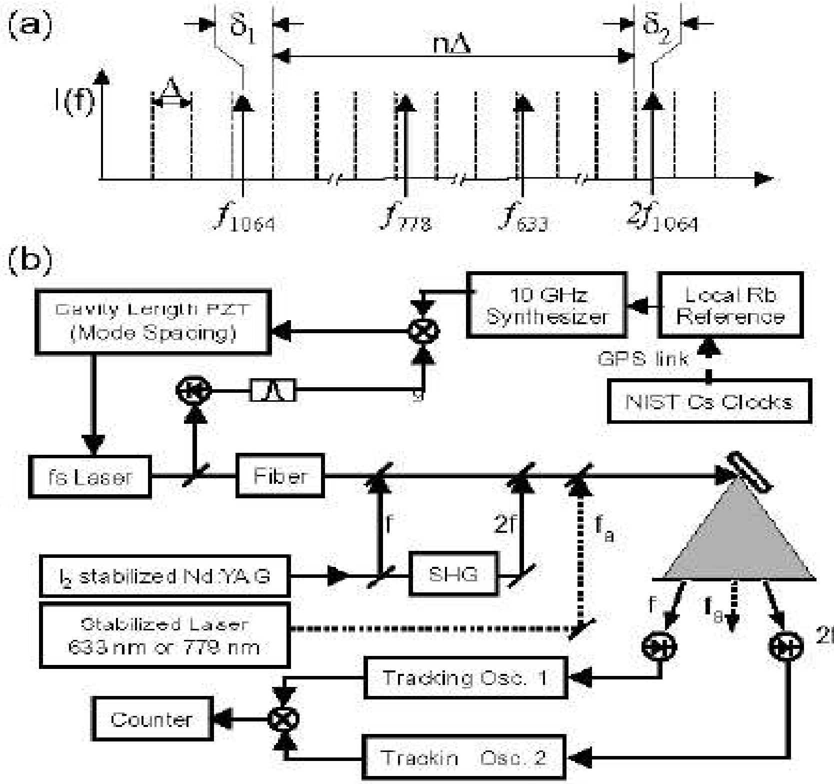


Replaced by a laser

Phys. Rev. Lett. **76**, 18 (1996)

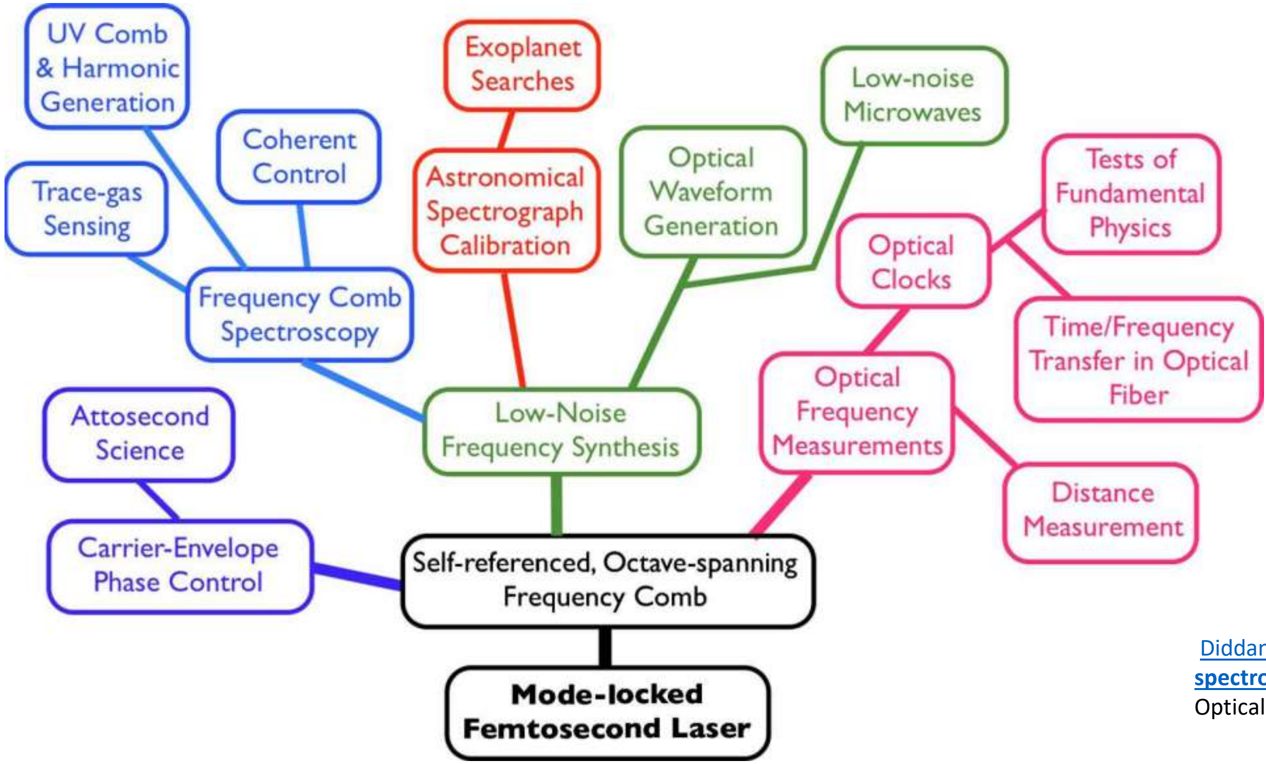


Phys. Rev. Lett. **84**, 5102 (2000)

Précision : 2×10^{-13} (50 Hz pour une fréquence de 282 THz)

Frequency comb evolutionary tree

fs oscillator = « comb generator »



Diddams SA. 2008. **Direct frequency comb spectroscopy**. Advances in Atomic, Molecular, and Optical Physics. 55:1–6

Outline

Introduction

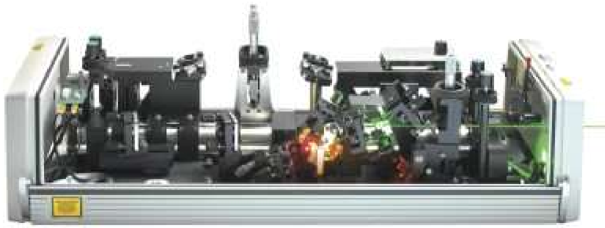
1. Description of ultrashort light pulses

2. Generation of femtosecond laser pulses via mode locking

3. Femtosecond oscillator technology

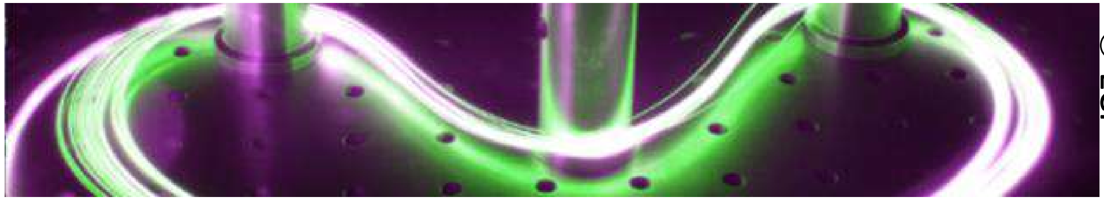
Femtosecond oscillator technology

✓Ti:Sapphire oscillators



✓Yb:bulk oscillators

✓Fiber-based oscillators



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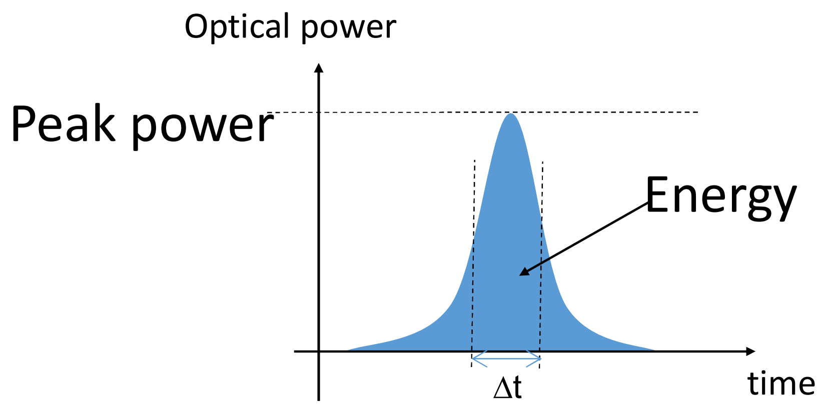
Laser specifications

Energy	Energy per pulse	Joule
Average power	Energy per unit time	Watt
Peak power	Maximum power	Watt
Intensity (irradiance)	Peak power per unit area	Watt/cm2



Quizz

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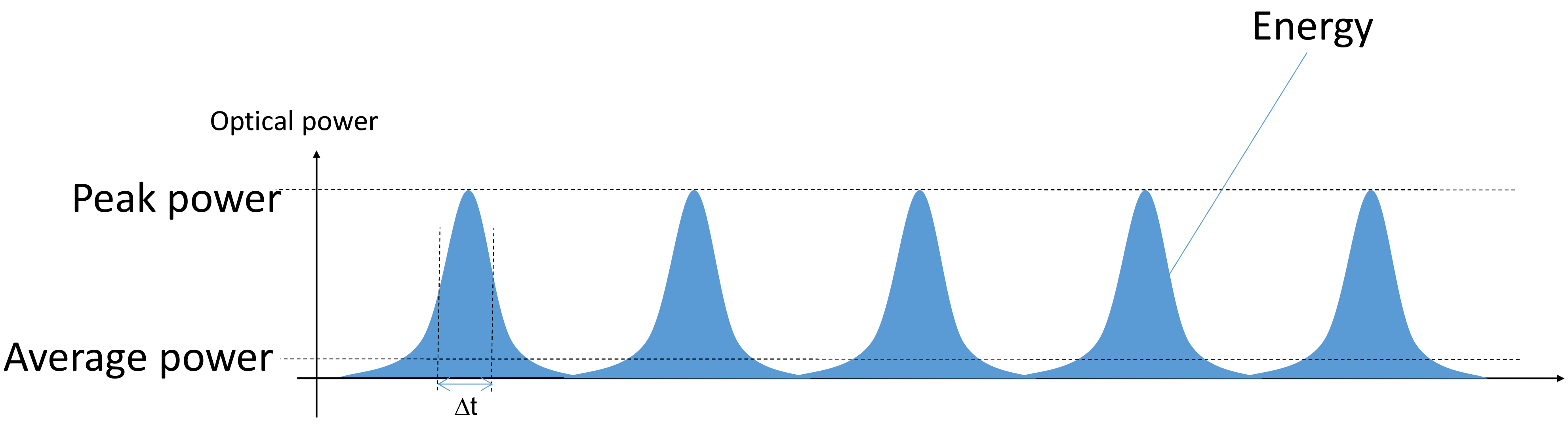
Pulse width	10 fs
Energy	10 nJ
Repetition rate	100 MHz
Average power?	
Peak power?	

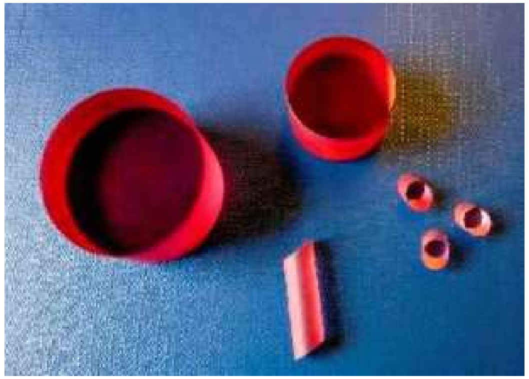
Quizz

Pulse width	10 fs
Energy	10 nJ
Repetition rate	100 MHz
Average power?	1 W = 10 nJ x 100 MHz
Peak power?	1 MW = 10 nJ / 10fs

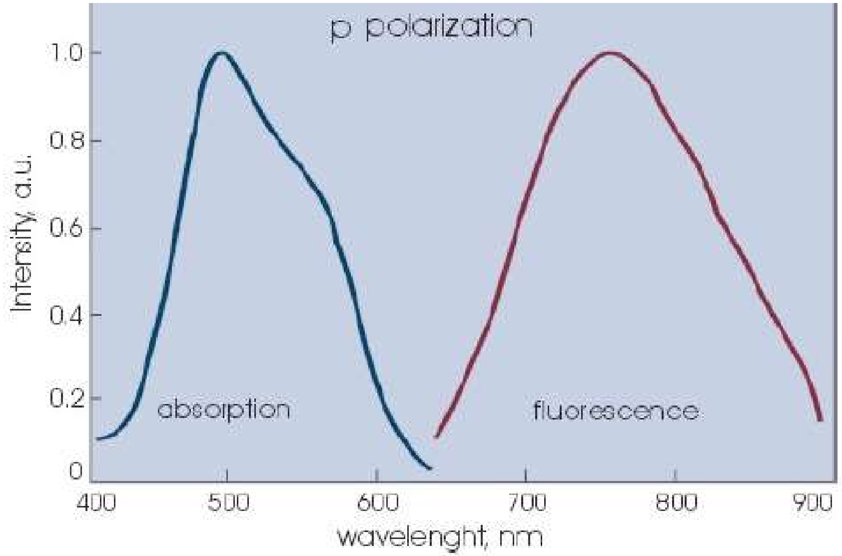


Ti:Sapphire oscillator

Sapphire crystals doped with ions Ti3+



Ti:Sa emission and absorption spectra



Good thermal conductivity

Very broad gain bandwidth from 650 nm to 1100 nm

Large emission cross section (41. 10^{-20} m2 @ 780 nm)

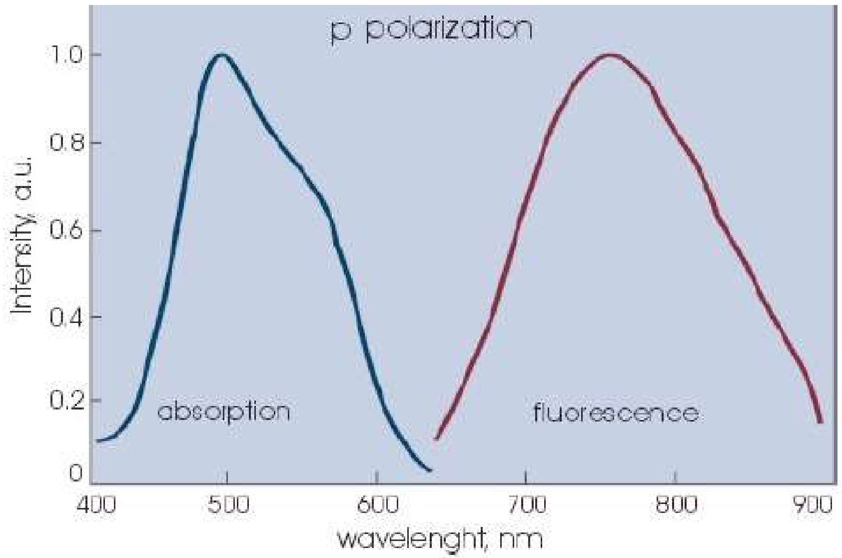
→ Extreme tunability and short duration

Ti:Sapphire oscillator

Large quantum defect (energy difference between pump and laser photons)

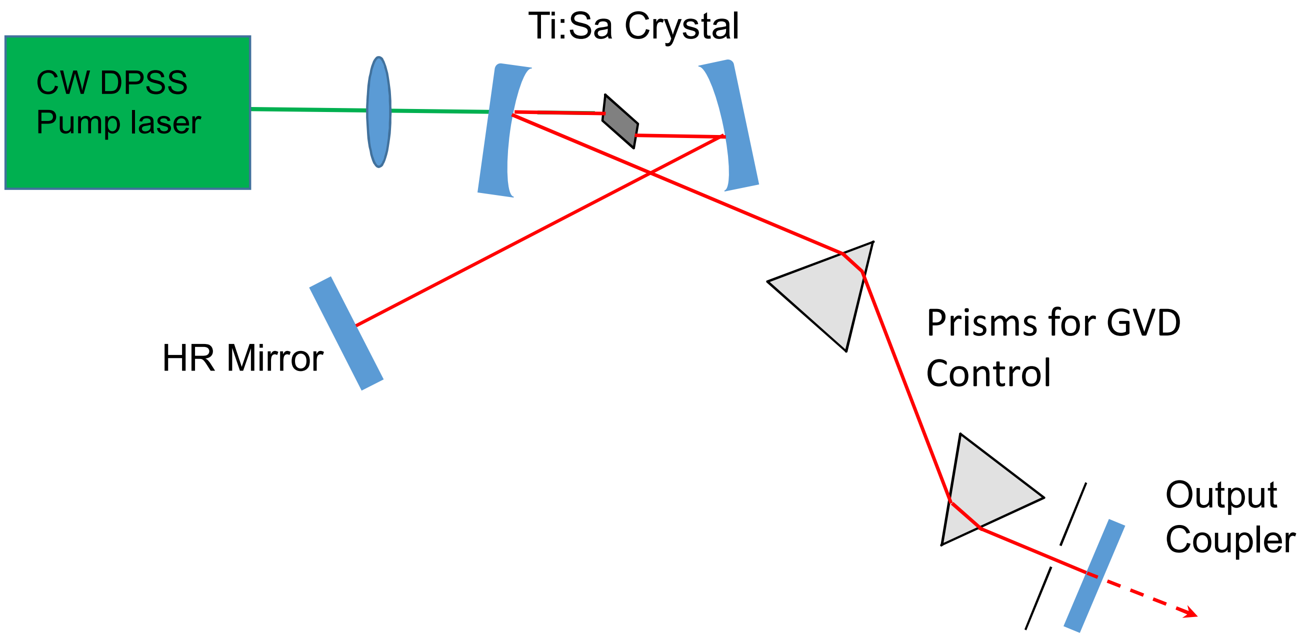
Pump : green CW laser (DPSS :frequency doubled diode-pumped laser)

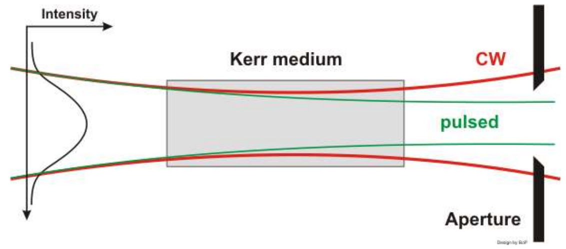
Ti:Sa emission and absorption spectra



→ Energetically inefficient, complex and expensive

Ti :Sapphire cavity





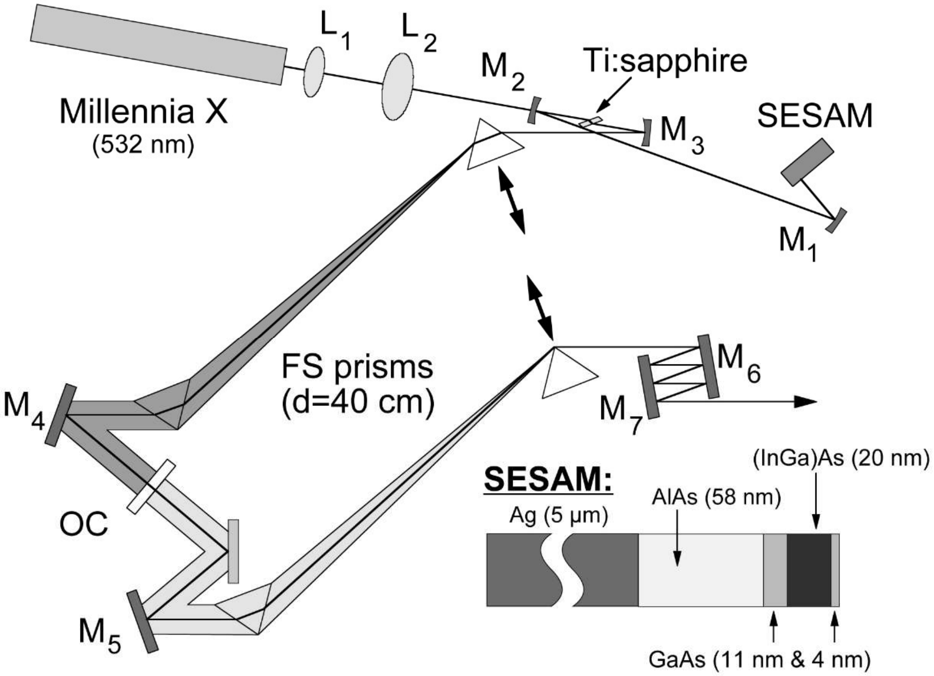
Pulse width : 15 fs
Repetition rate : 80 MHz
Energy : 10 nJ

✓KLM

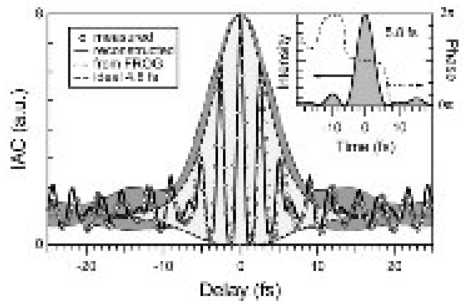
✓Prisms or chirped mirrors

✓vibrating mirror or AO or SESAM

Pulses in the two-cycle regime



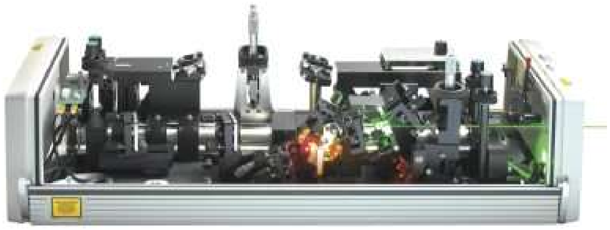
Interferometric autocorrelation



Pulse duration ~5fs

D. H. Sutter, G. Steinmeyer, L. Gallmann, N. Matuschek, F. Morier-Genoud, U. Keller, V. Scheuer, G. Angelow, and T. Tschudi, "Semiconductor saturable-absorber mirror–assisted Kerr-lens mode-locked Ti:sapphire laser producing pulses in the **two-cycle regime**," Opt. Lett. **24**, 631-633 (1999)

Ti:Sapphire commercial lasers



0,7 W, 700-1080 nm, <100fs

0,6 W, 800nm, <8fs

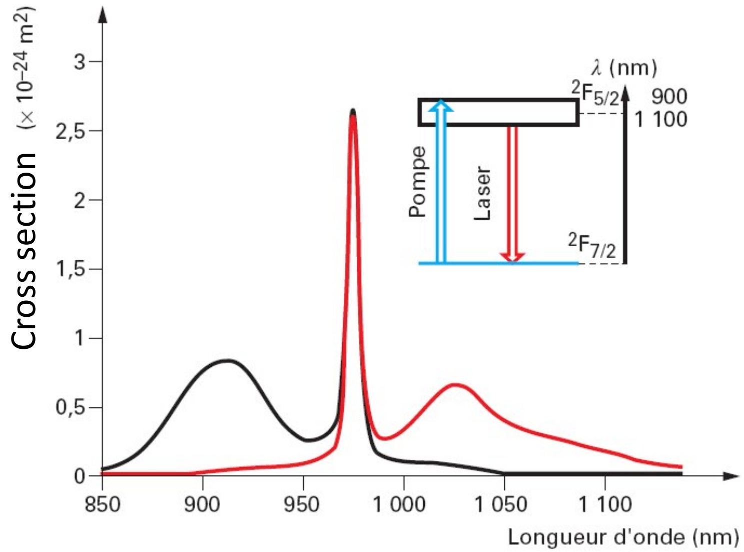
2,5 W, 690nm- 1020 nm, 140fs

Repetition rate : 80MHz

Ti:Sa today :

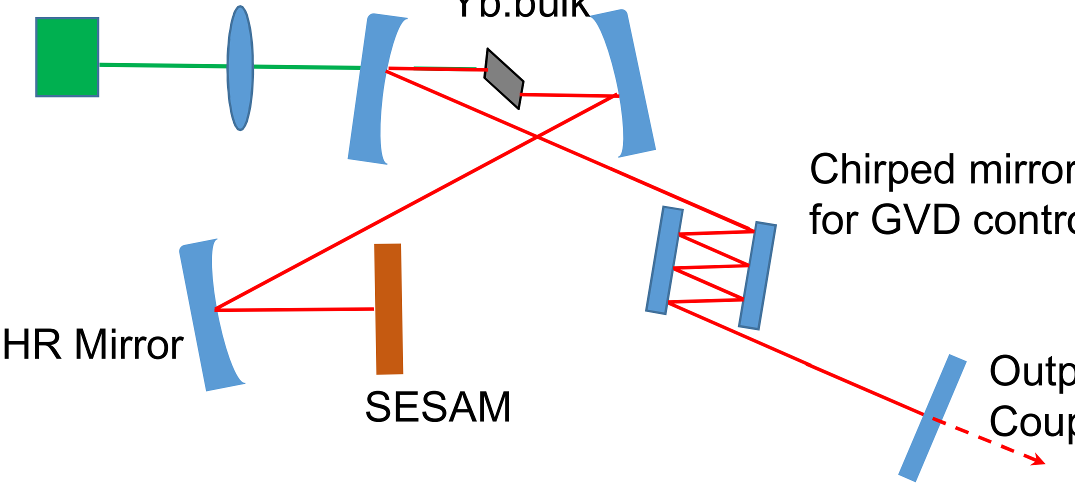
- Expensive and not very effective but reliable, **tunable**, and **very short pulsewidth**
- Many applications : bio-imaging, ultrafast spectroscopy, high field physics, amplifier seeding,…

Ytterbium : bulk oscilllator



Many different hosts for Ytterbium ions : YAG, glass, KYW, CaF2, …
Low quantum defect : high power efficiency, reduced thermal effects
Great advantage : **diode pumping** at 980 nm

Ytterbium : bulk oscilllator



Pulse width : 300 fs
Repetition rate : 50 MHz
Energy : a few 100s nJ
High average power

✓SESAM

✓Prisms or chirped mirrors

Ytterbium : bulk oscilllator

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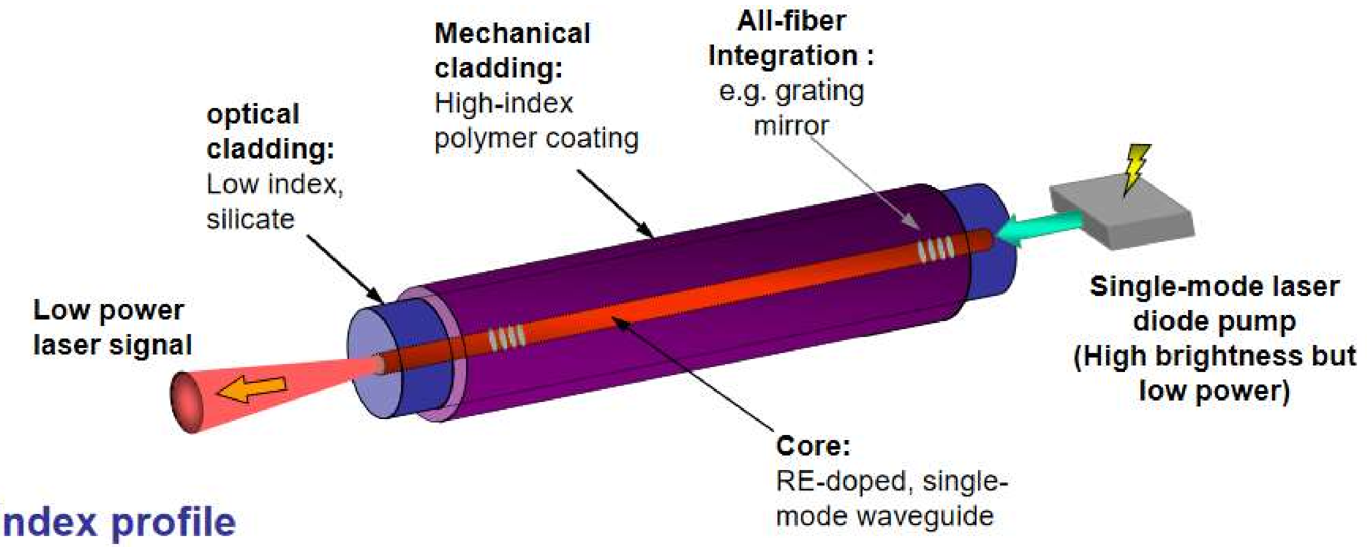
- ✓ High average power
- ✓ Low cost per watt
- ✓ Compact
- ✓ Pulse duration 300fs

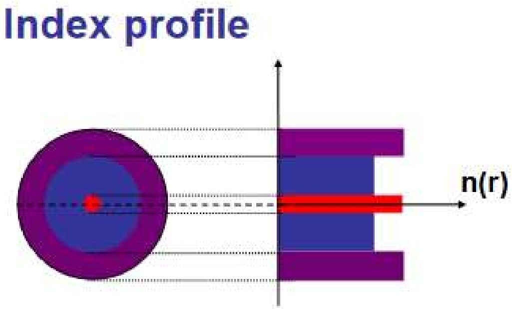
Average Power	> 1,3 W
Energy Per Pulse	> 24 nJ
Pulsewidth	< 250 fs
Repetition Rate	54 MHz
Central Wavelength	1025 +/- 5 nm

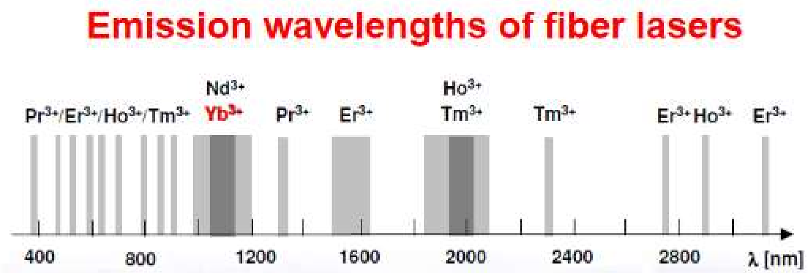
Average Power	>1.5 W
Wavelength	1045 ±8.0 nm
Repetition Rate	63 MHz
Pulse Width (FWHM)	<250 fs
Pulse Energy	>24 nJ
Peak Power	>80 kW

Fiber-based oscillators

Gain media : fiber doped with Rare Earth ions (Large gain bandwidth)

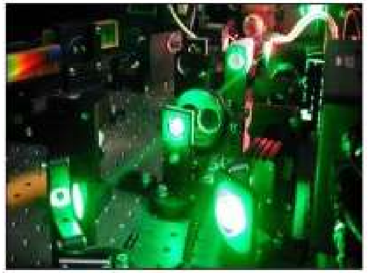


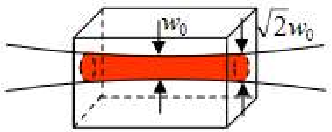




Fiber-based oscillators

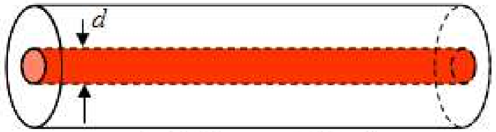
Conventional laser





L_c (100µm – 10 cm)

Fibre laser



L_f (10 cm – 300 m)

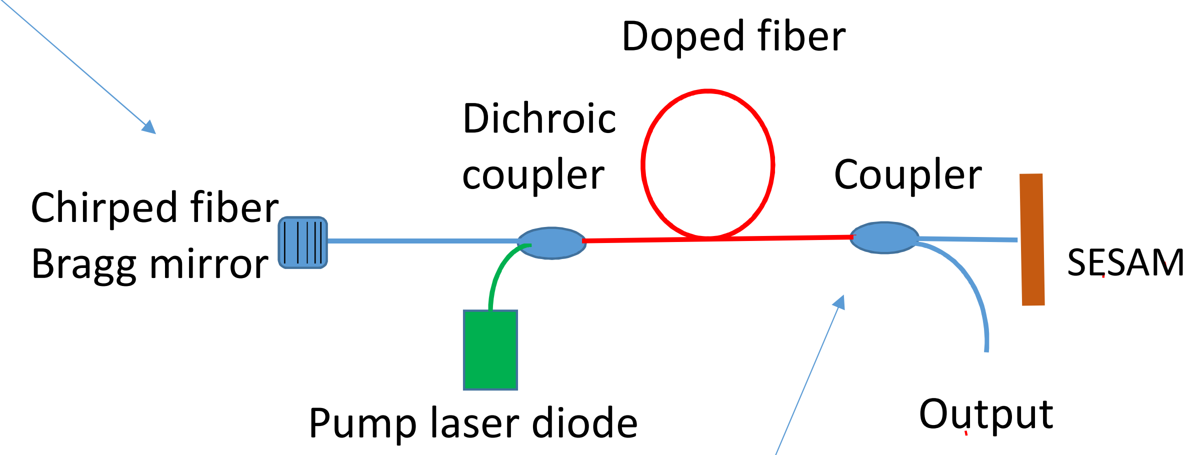
Large surface area
Guided mode
Heat resistance of silica

→ Low thermal effects

Simple cavity of fiber-based oscillators

Bragg mirrors in the core of the fiber

High gain efficiency of active fibers
Low thermal effect



Passive modelocking

High beam quality

Diode pumping

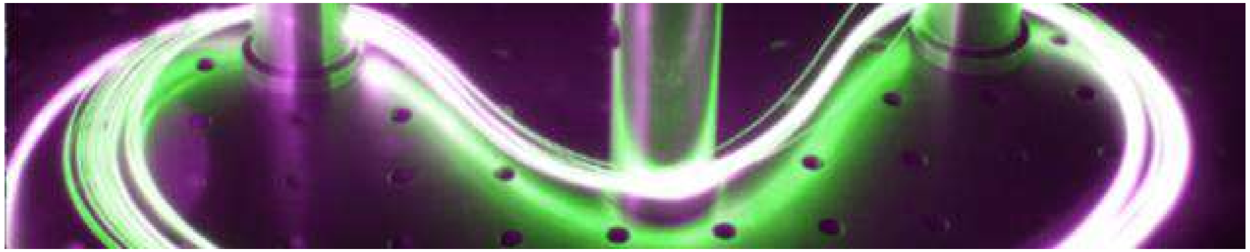
Fiber couplers

Fiber-based oscillators

✓Long propagation distance : High gain, low thermal effects
✓Spatial quality
✓Stability
✓Compactness
✓Cost effective

500 mW, 90fs, 1560nm, 100MHz

Large variety of designs and specifications



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1 W , 200fs , 1045 nm , 50 MHz
fs pulses delivered by optical cable

Summary

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✓Ultrashort pulses = broad spectra -> Large dispersion effects

✓Description in both time and frequency domain

✓Generation via modelocking thanks to nonlinear effects

✓Wide variety of femtosecond lasers