Advanced Radiation Sources - PHSY761

Exercise 03

Summary

Laboratory demonstration:

Part 1
- Relaxation oscillations
- Passive Q-switched Nd:YAG laser

Part 2
- Ti:Sapphire Kerr-lens mode locked laser

12 October 2023

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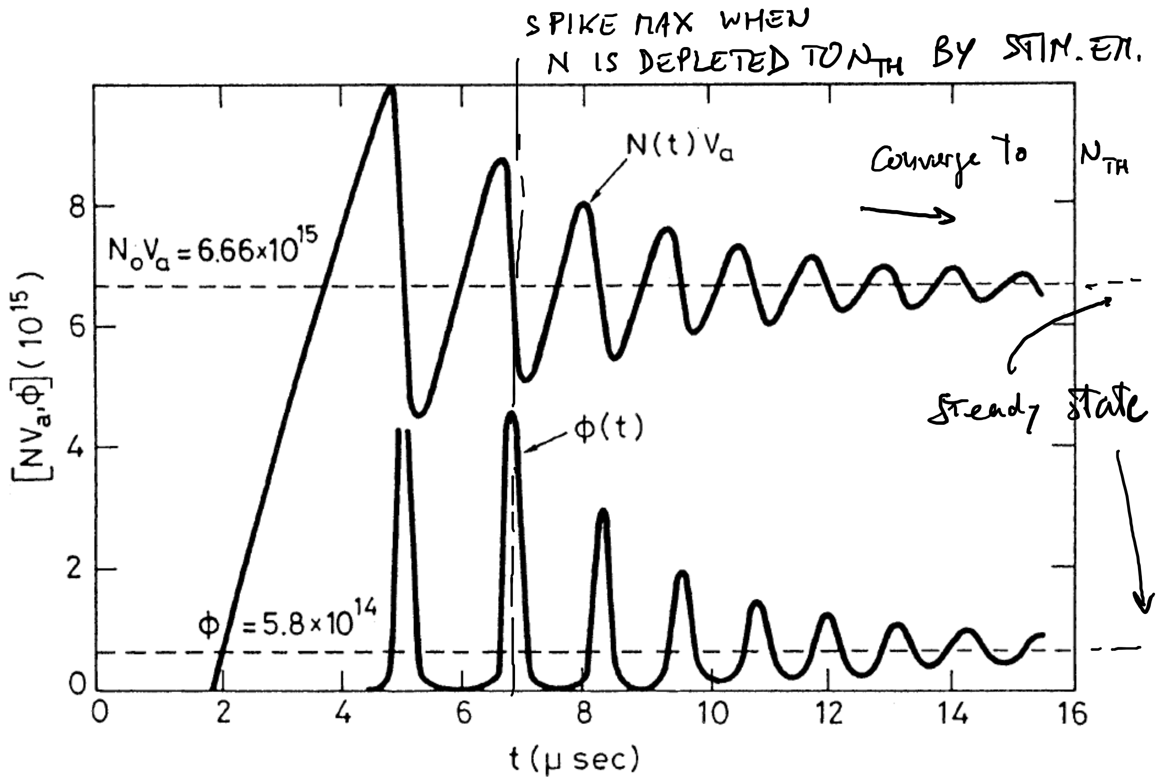
Relaxation oscillation in the Nd:YAG laser

- Pump laser sudden turned on at t=0
- The system reach the steady state inversion and photon flux in a series of relaxation oscillations

↓

REPRODUCE THIS BEHAVIOUR BY MODULATING THE PUMP DIODE



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Passive Q-Switching

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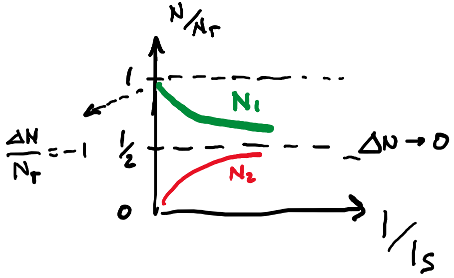
Reminder: 2 level system

$N_T = N_1 + N_2$



$$\Delta N = N_T \frac{1}{1 + 2\, I/I_s}$$

ABSORPTION COEFF. $\alpha = \sigma \Delta N$

- ΔN → INVERSION
- σ → ABS. X SECTION

USUALLY $N_2 \approx 0$ $N_1 \sim N_T$

BEER – LAMBERT

$$I(z) = I_0 e^{+\alpha z}$$

$$\alpha = -\sigma N_T$$

→ WHAT HAPPENS WHEN N_2 CANNOT BE NEGLECTED?

Simplifying assumption (steady state population has been reached)

$$\Delta N = N_T \frac{1}{1 + 2\, I/I_s}$$

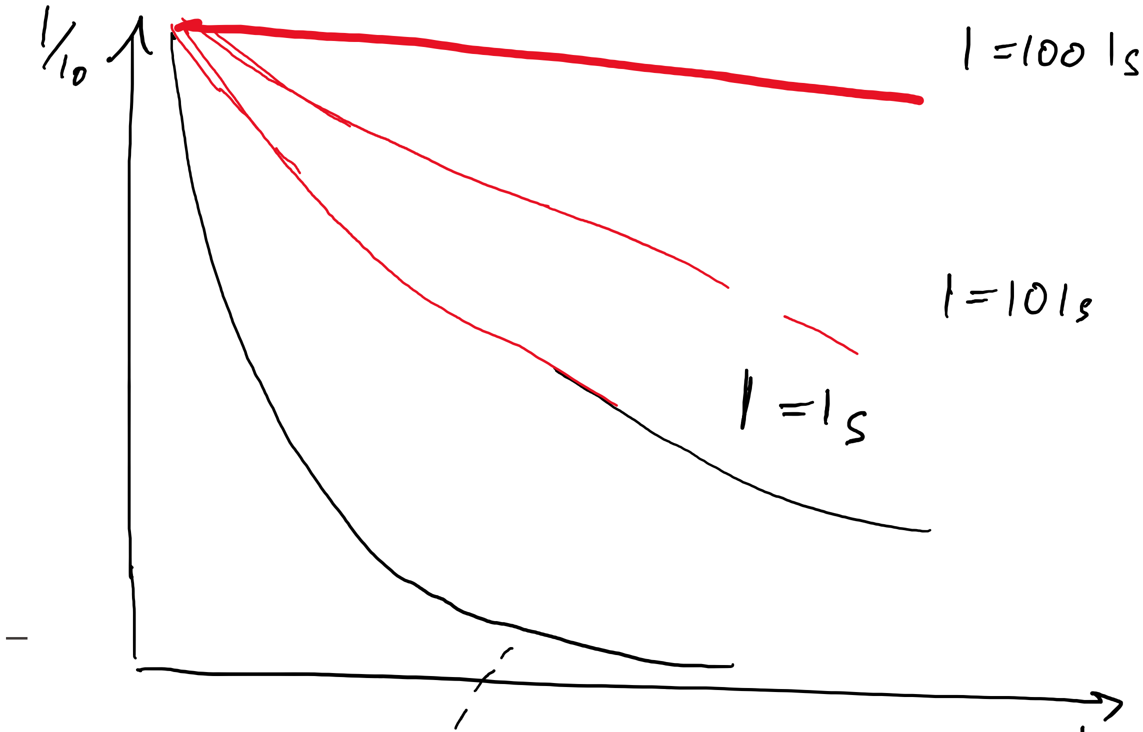
$$\frac{dI}{dz} = \alpha I \longrightarrow \frac{dI}{dz} = \alpha \frac{I}{1 + 2\, I/I_s}$$

SOLUTION:

$$\ln\left(I/I_0\right) + \frac{2}{I_s}\left(I - I_0\right) = -\alpha z$$

ONLY CONTRIBUTION WHEN $I \ll I_s$

when $I \sim I_s$ CANNOT BE NEGLECTED



$L\alpha = L / L_{abs}$

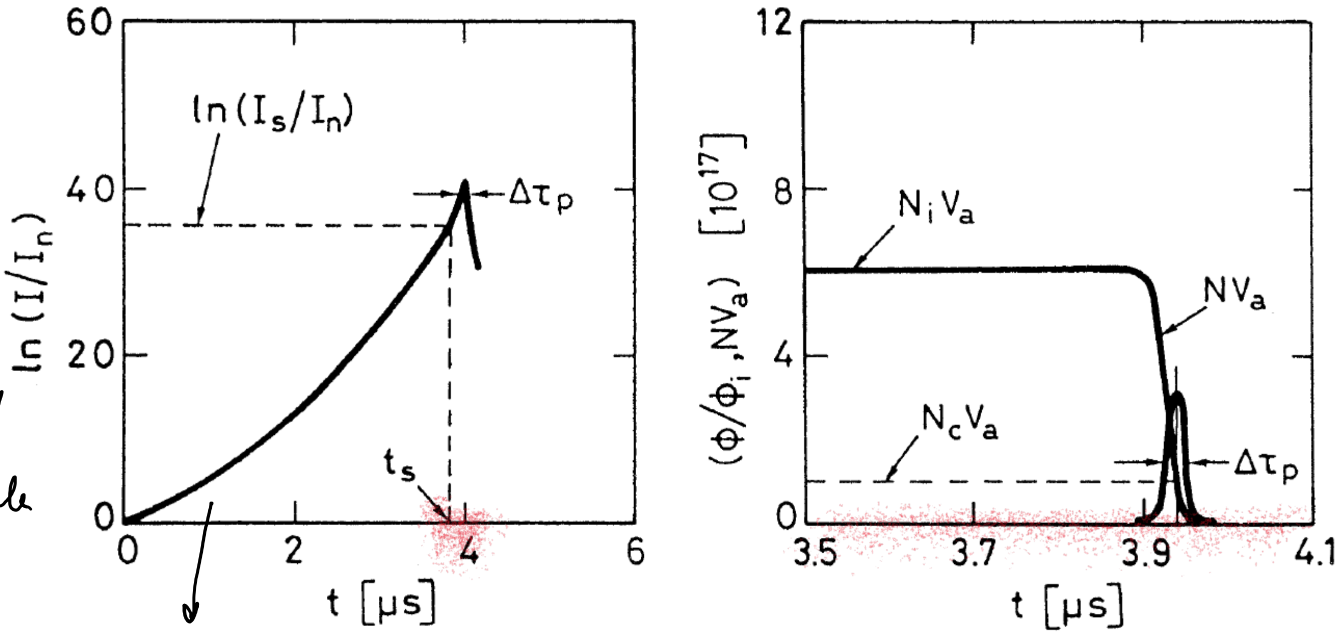
BLEACHING ↓ THE SYSTEM IS TRANSPARENT

ABSORPTION IS SATURATED

$I \ll I_s$ exp decay

$$\ln\left(\frac{I}{I_0}\right) + \frac{2}{I_s}(I - I_0) = -\alpha z$$

What happens when we place a similar 2-level saturable absorber, resonant with the laser, wavelength in a cavity?



log. scale

INITIALLY : HIGH LOSSES! ($N_2 \sim 0$ sat) ⇒

→ INTENSITY GROWS WHEN ΔN_{medium} IS LARGER THAN HIGH THRESHOLD

→ SLOW GROW UNTIL $I \sim I_s$ → LOSSES BECOMES SUDDENLY LOW WITH A LARGE INVERSION

Passive Q-Switching of Nd:YAG laser

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Cr:YAG

Absorption range 0.8-1.2 um

High damage threshold

→
- INSERT THE ABSORBER IN THE CAVITY
- CHECK THE PULSE REP. RATE AS A FUNCTION OF I_{PUMP}

ν_{REP} DEPENDS ON THE POP. DYNAMICS

NOT CHOSEN EXTERNALLY LIKE IN ACTIVE Q-SWITCH SYSTEM

→ CHEAPER, SIMPLE / CAN BE INTEGRATED IN COMPACT LASERS (microchip..)

PART 2 – Kerr lens mode locked Ti:Sapphire oscillator.

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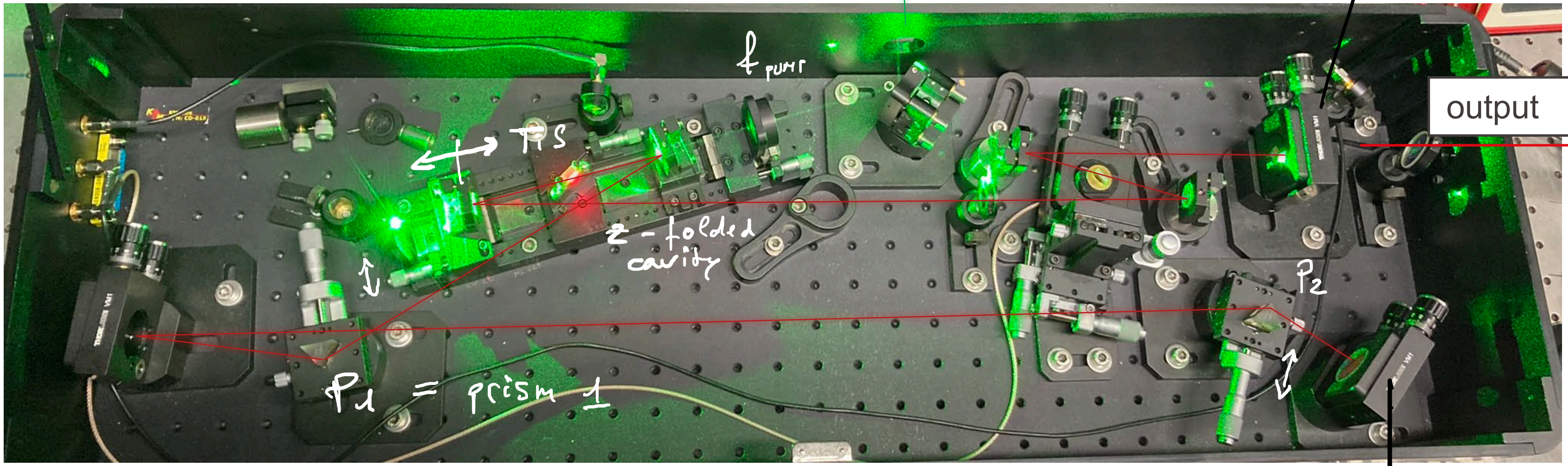
- Mode locking can be achieved by a modulator operating at the cavity roundtrip time

END MIRROR 1
PARTIAL
TRANSMISSION

PUMP LASER: CW 532 nm



END MIRROR 2
HIGH REFL.

- What is Kerr lens mode locking?
- What is the function of the prism?

$\chi^{(3)}$ effects: the nonlinear index of refraction

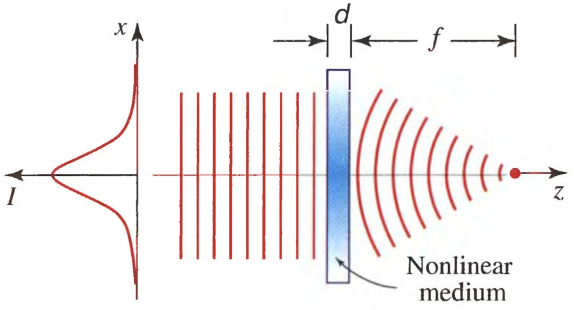
$$\tilde{P}^{(3)}(t) = \chi^{(3)}\tilde{E}(t)^3$$

$$n(\omega, I) = n_0(\omega) + n_2(\omega) I.$$

Note: this is one of the many terms of four-wave mixing, where three photon at frequency ω mix to generate the same frequency (ω+ω-ω->ω)

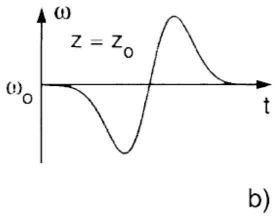
In space: Self-focusing

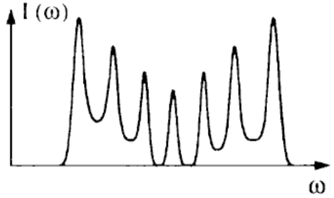
The radial variation of intensity translate into a radially varying optical path: this acts as a lens!



In time: Self-phase modulation and spectral broadening

$$\omega = \frac{d\phi}{dt} = \omega_0 - A\frac{dI}{dt}$$





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Solution to problem 2: Kerr-Lens mode locking

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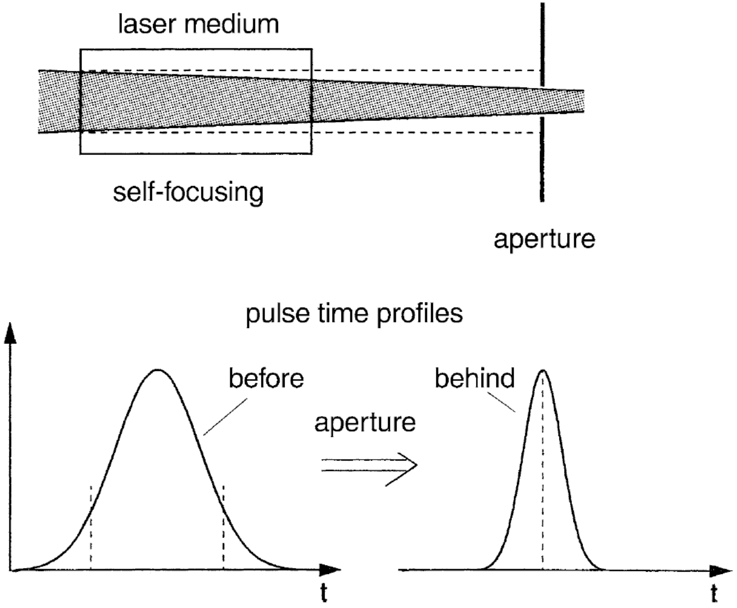
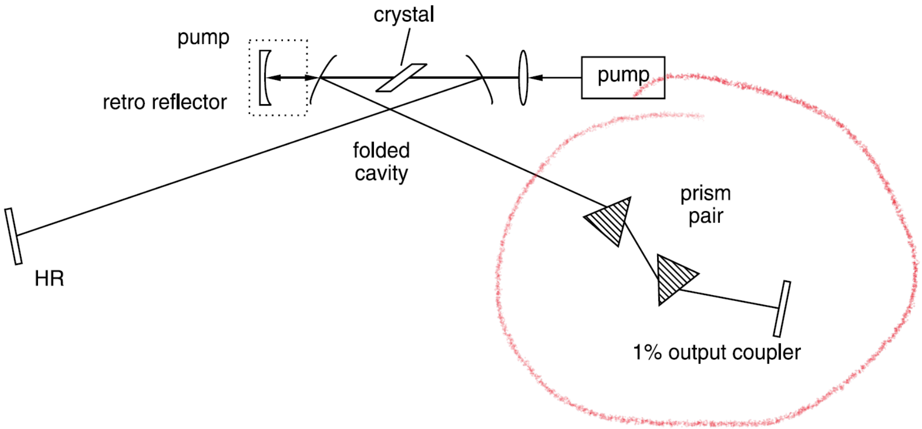
- Kerr-lens in combination with an aperture selects only the highest intensity part of the beam.
- This is an example of «artificial saturable absorber»: breakthrough for realizing reliable solid-state femtosecond lasers



- The artificial saturable absorber is nearly instantaneous (is a non-resonant electronic nonlinear effects) : very short pulses can be realized < 10 fs



Linear propagation of ultrashort pulses: chirp

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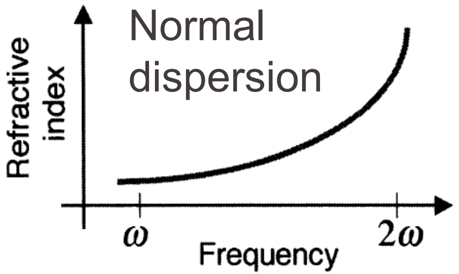
- Pulse formation competing effect : dispersion
- The effect of propagation in the frequency domain

ABS. PHASE DELAY

$$\tilde{E}_{\text{out}}(\omega) = \tilde{E}_{\text{in}}(\omega)\exp[-\alpha(\omega)L/2]\exp[in(\omega)kL]$$



- For rough estimates and for spectrally «narrow», well-behaved pulses (< 50 nm works still rather well) it is common to approximate the phase (either spectral or temporal) in a power expansion:

$$\varphi(\omega) = \varphi_0 + (\omega-\omega_0)\,\varphi_1 + (\omega-\omega_0)^2\,\varphi_2/2 + \cdots$$

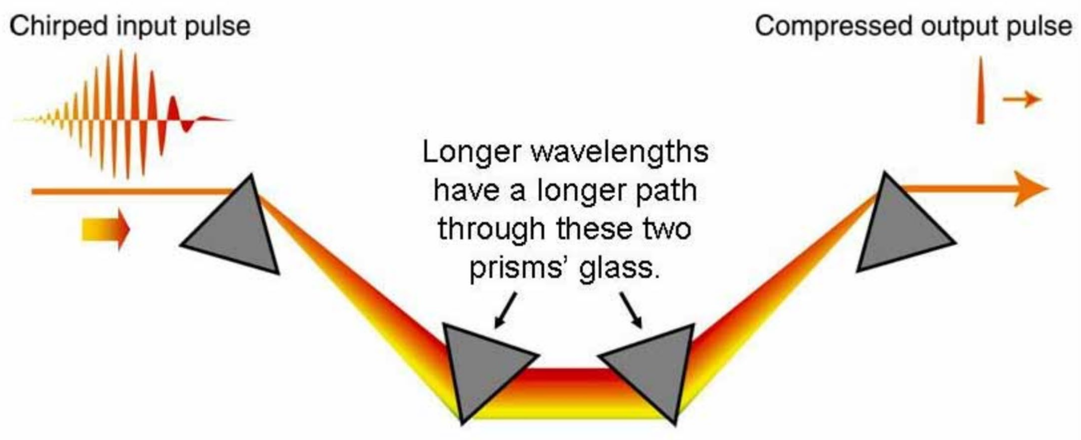
ABSOLUTE PHASE — SHIFT IN TIME — LINEAR CHIRP

ORDER: 0th; 1st, fs; 2nd, fs^2; 3rd, fs^3

Dispersion control

The different path of optical frequency through the glass can be used to achieve a net negative effective dispersion

The wavelenght-dependend angular dispersion is an example of **spatio-temporal coupling**: this effect can be used to control the spectral phase.

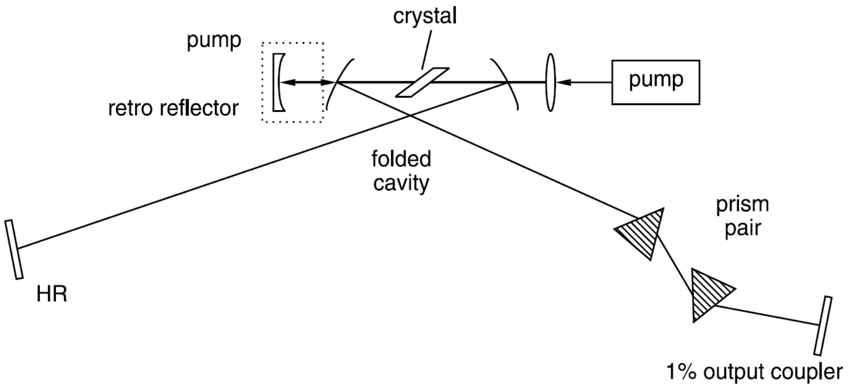


Intracavity dispersion control

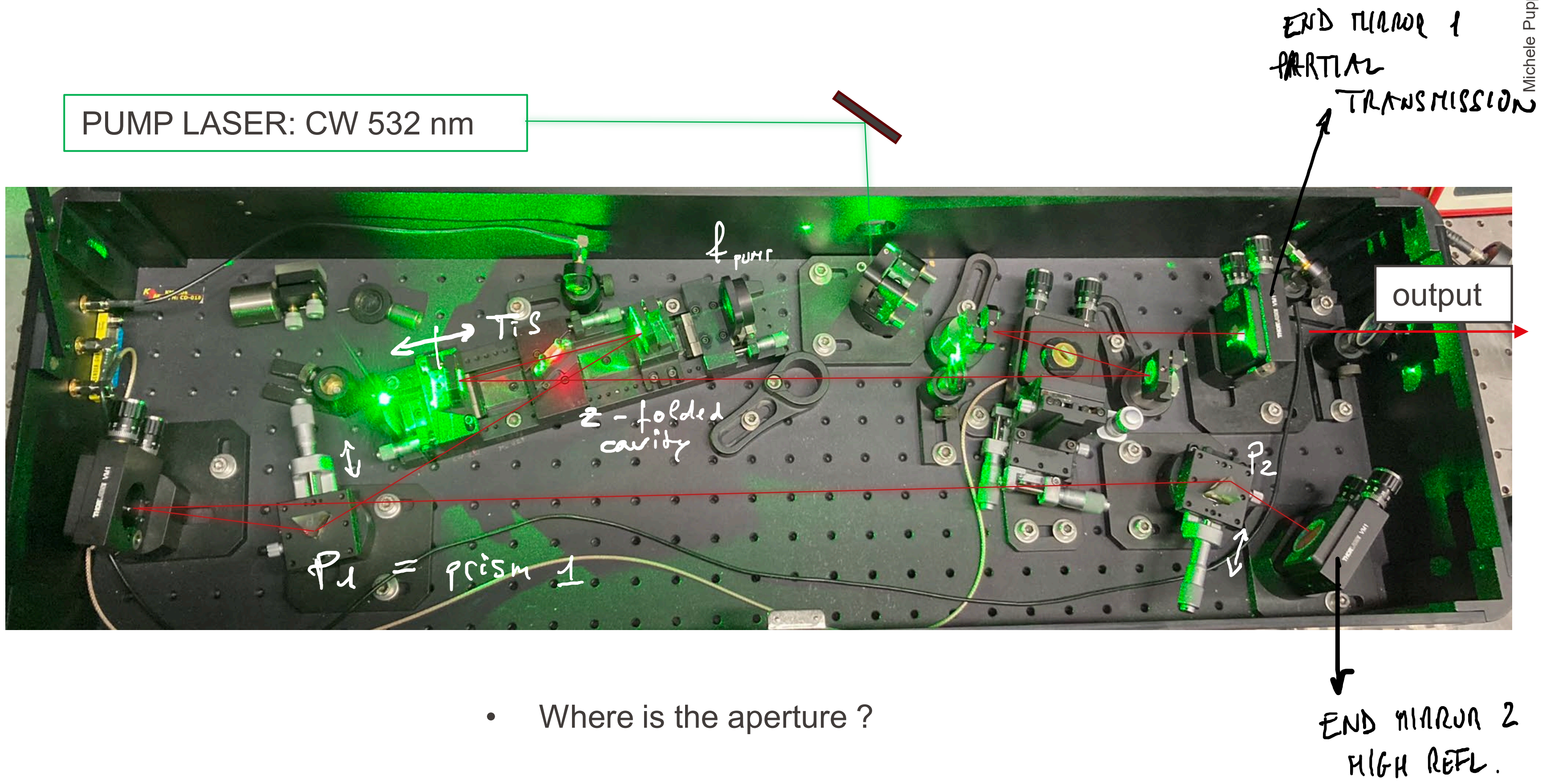
Intracavity prism pair:

Using prism cut to work at the Brewster angle, the losses can be kept low

This can solve the pulse reshaping problems in achieving a fs oscillator



KERR-LENS MODE LOCKED OSCILLATOR



- Where is the aperture ?

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Mathematical description: basic concepts

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Temporal description:

$\Phi(t)$ is the TEMPORAL PHASE

REAL E-FIELD

TIME DEP. PHASE

$$\mathcal{E}(t) = \frac{1}{2}\sqrt{I(t)}\,\exp\{i\,[\omega t - \phi(t)]\} + c.c.$$

FAST OSCILLATING CARRIER

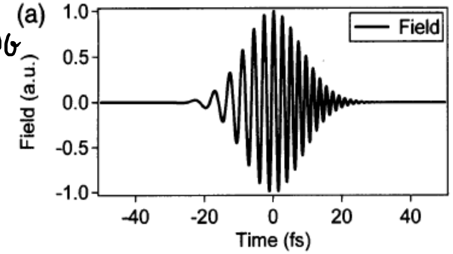
COMPLEX AMPLITUDE (NO CARRIER)

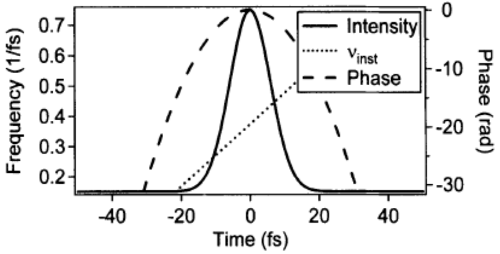
$$E(t) \equiv \sqrt{I(t)}\exp[-i\phi(t)]$$

$$\omega_{inst}(t) \equiv \omega_0 - d\phi/dt$$

$$\tilde{\mathcal{E}}(\omega) = \int_{-\infty}^{\infty} \mathcal{E}(t)\exp(-i\omega t)\,dt$$

FOURIER TRANSFORM





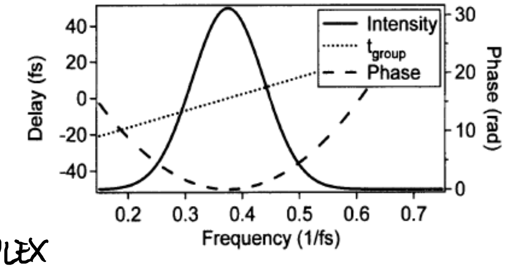
Spectral description:

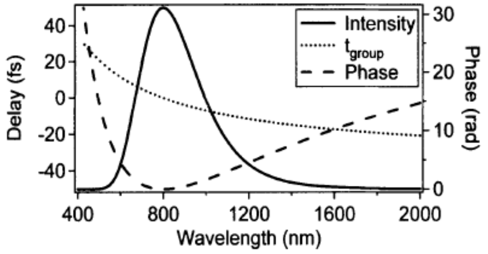
$$\tilde{\mathcal{E}}(\omega) = \sqrt{S(\omega)}\exp[-i\varphi(\omega)]$$

COMPLEX AMPLITUDE

Note: FT of a real field

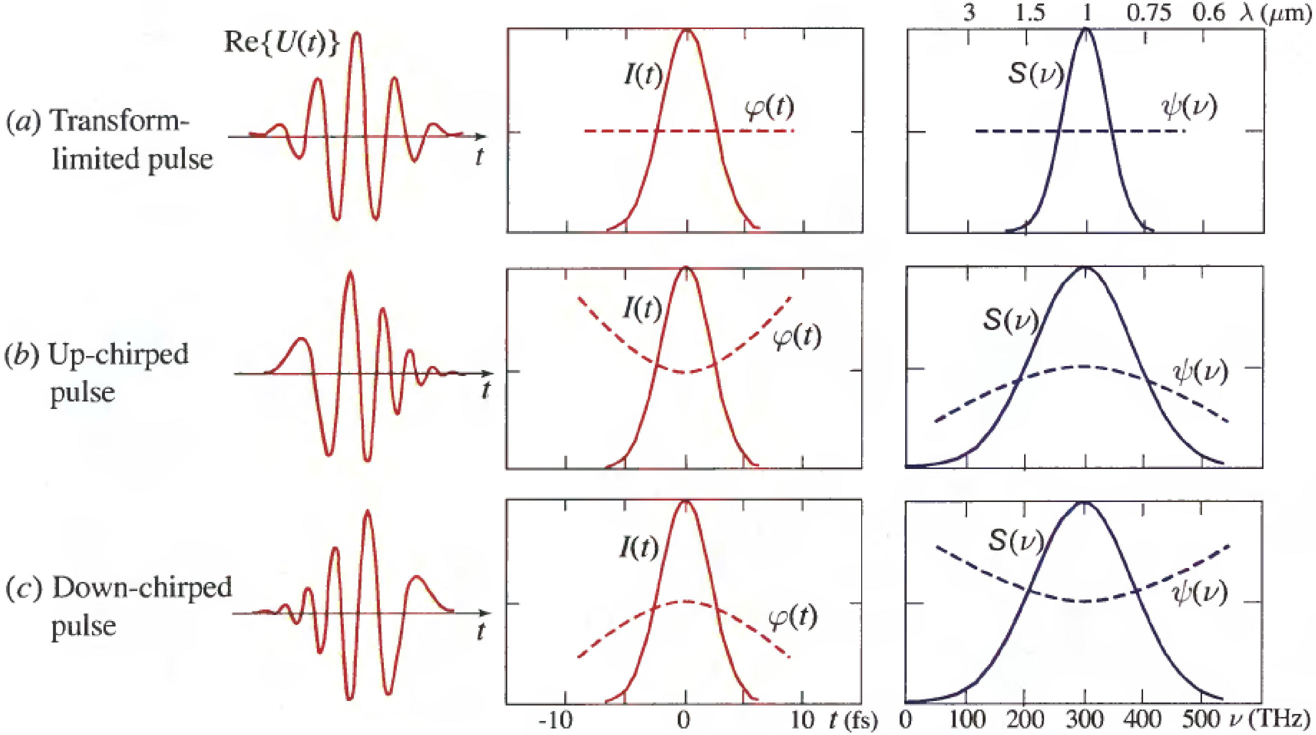
$\tilde{\varepsilon}(\omega) = \tilde{\varepsilon}(-\omega)^*$





$\varphi(\omega)$ is the SPECTRAL PHASE

Chirped pulses



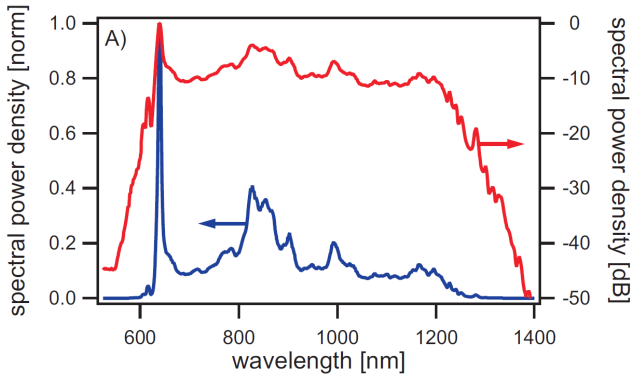
- A non-flat phase is the result of a non-transform limited pulse: by compensating the phase a shorted pulse could be produced.
- By controlling the phase one can stretch/compress the pulse.
- In matter the pulse achieve its minimum duration only in a location! Then it broadens again.

EPFL

State-of-the art: Octave-spanning Ti:Sapphire femtosecond oscillator

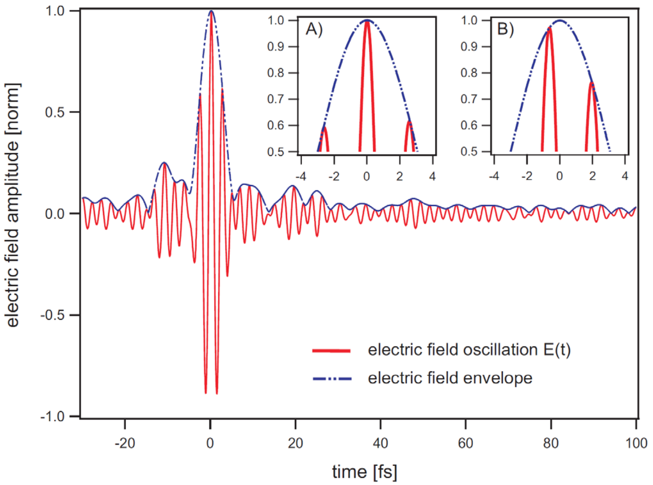
The whole amplification bandwidth (and beyond) of Ti:Sapphire is amplified

Based on specially designed «chirped mirrors» for dispersion control



Few cycle pulse: the carrier to envelope phase is very important.

Direct CEP detection is possible using an octave-spanning oscillator and an f-2f interferometer



Technique	Mode locker	Laser	Typical pulse duration	Typical pulse energy
Active mode locking	Acousto-optic modulator Pockels cell	Argon, cw HeNe, cw Nd:YAG, pulsed	300 ps 500 ps 100 ps	10 nJ 0.1 nJ 10 μJ
Passive mode locking	Saturable absorber	Dye, cw Nd:YAG	1 ps 1–10 ps	1 nJ 1 nJ
Synchronous pumping	Mode-locked pump laser and matching of resonator length	Dye, cw Color center	1 ps 1 ps	10 nJ 10 nJ
Colliding pulse mode locking CPM	Passive mode locking and eventual synchronous pumping	Ring dye laser	<100 fs	≈ 1 nJ
Kerr lens mode locking	Optical Kerr effect	Ti:sapphire	<10 fs	≈ 10–100 nJ

Mode-locked lasers very short pulses!

How is the pulse duration measured?