Advanced Optics (PHYS690)

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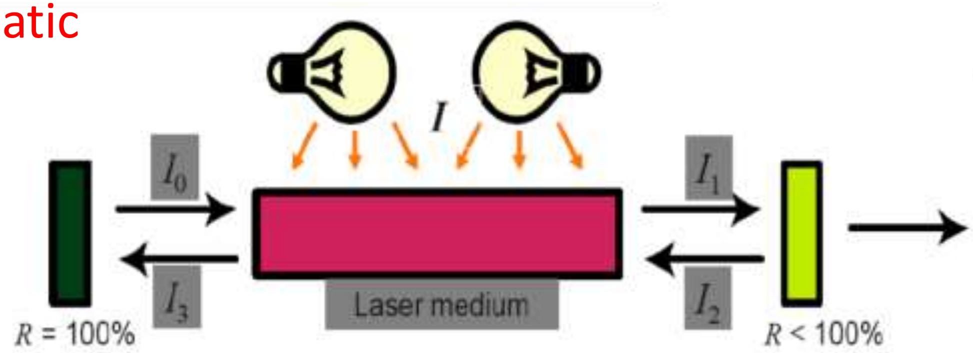
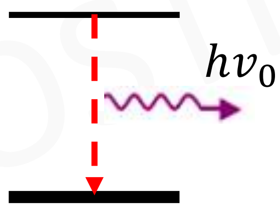
Summary

- Laser: a devices that produce intense beams of light.

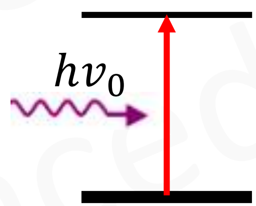
- Monochromatic
- Coherent
- Collimated
- Brightness



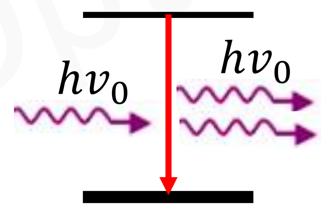
Light
Amplification by
Stimulated
Emission of
Radiation



– Spontaneous emission



– Absorption



– Stimulated emission

$$B_{21} = B_{12},$$

$$A_{21} = \frac{8\pi\nu^2}{c^3} h\nu B_{21}$$

population inversion (N2 > N1)

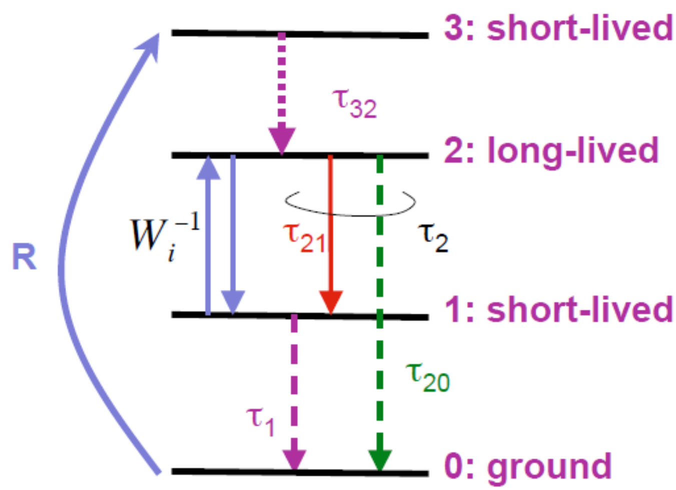
- **Upper level should be pumped strongly and decay slowly.**

Laser

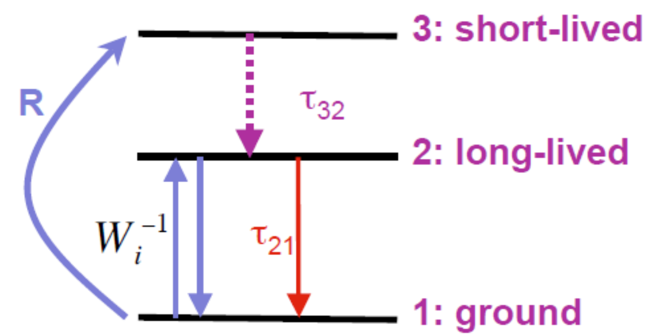
Light
Amplification by
Stimulated
Emission of
Radiation

Pumping schemes

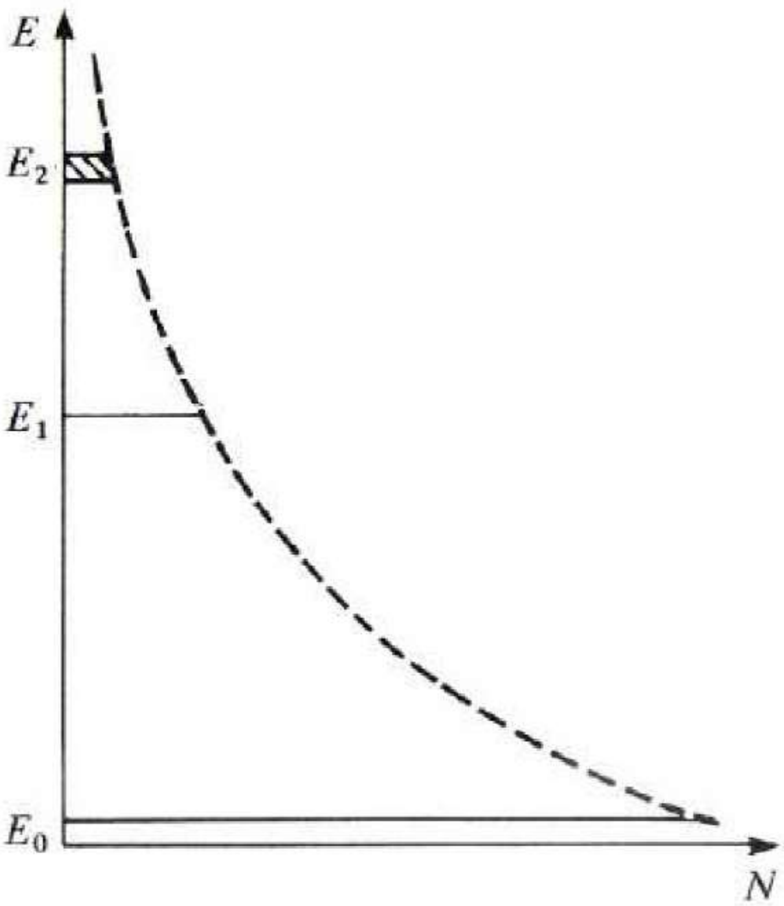
Four level pumping



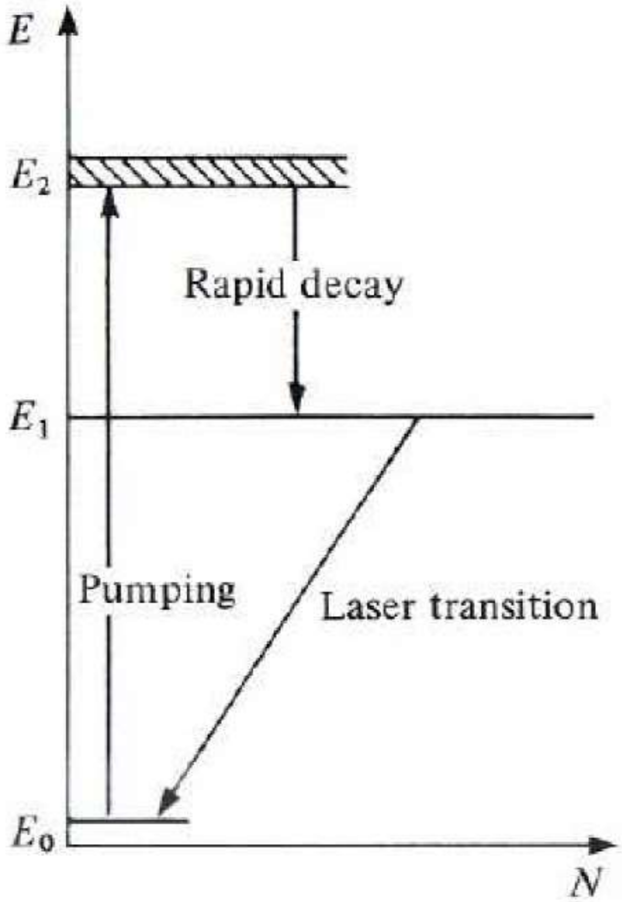
Three level pumping



Three level system w/ or w/o pumping

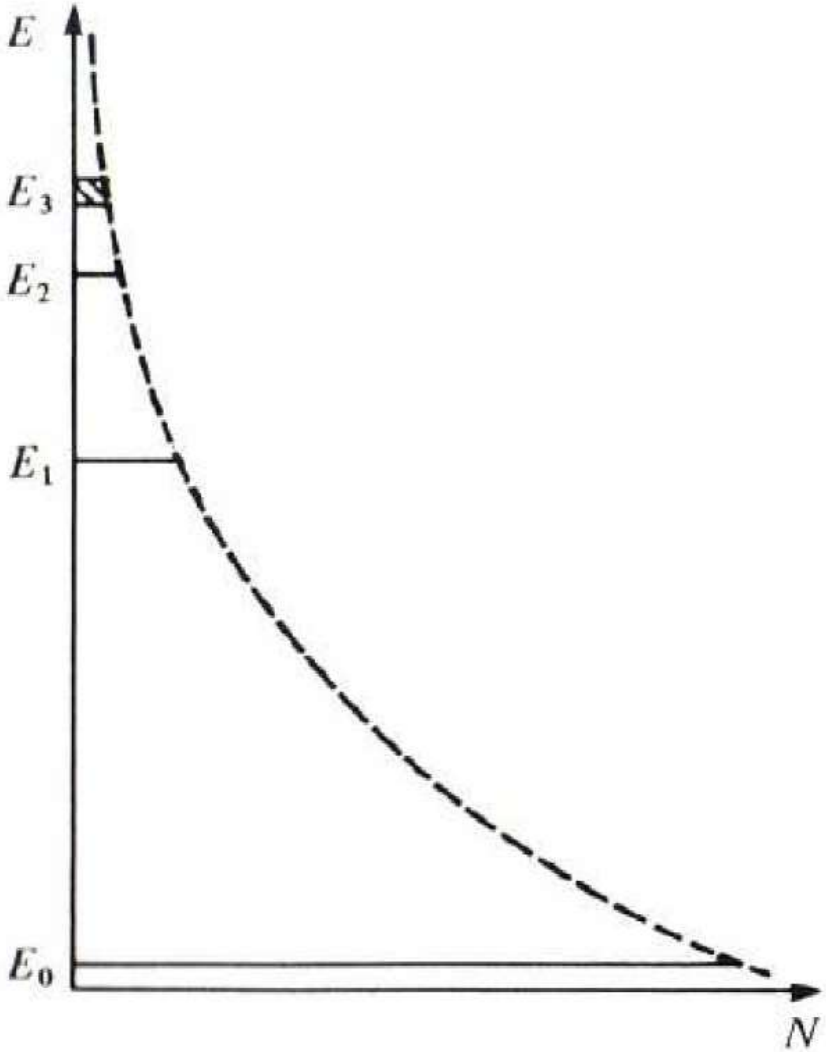


The distribution at thermal equilibrium (Boltzman)

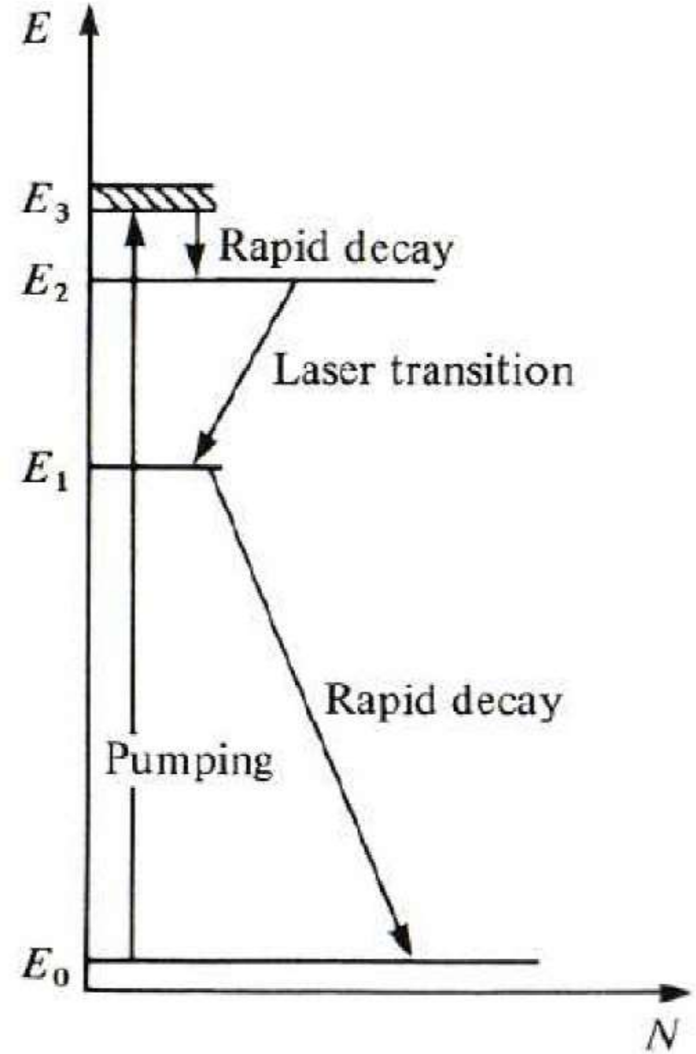


The distribution with pumping

Four level system

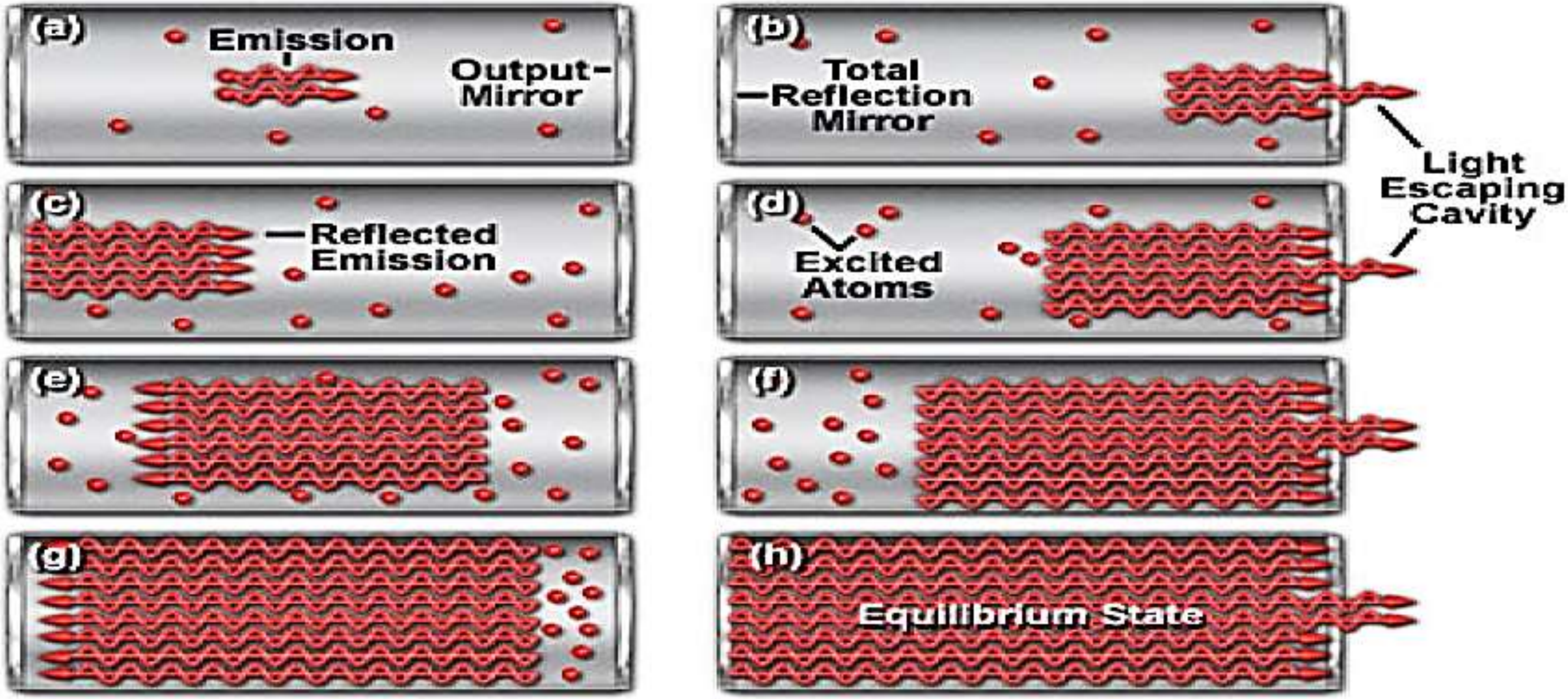


The distribution at thermal equilibrium (Boltzman)



The distribution with pumping

Stimulated Emission in a Mirrored Laser Cavity

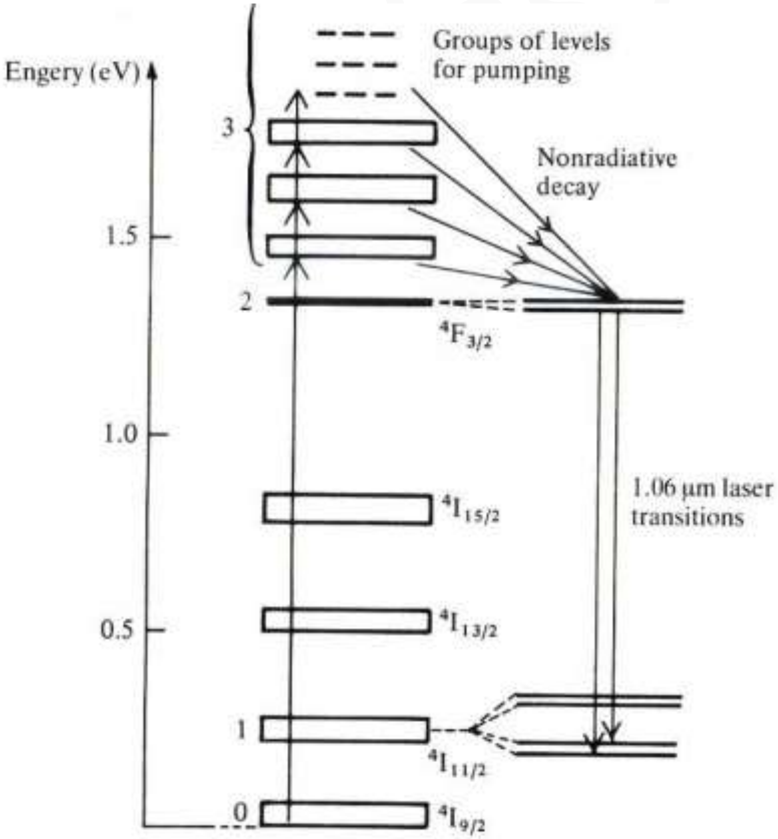


Types and classes of laser

Doped insulator lasers

- The active medium is solid containing impurities often introduced by doping.

- The first class of laser, using ruby crystals.
- A more modern example is Nd:YAG which consists of ythrium aluminium garnet ($Y_3Al_5O_{12}$) with neodymium Nd^{3+} impurity in ythrium sites.
- Pumping is by optical flash or diode laser.

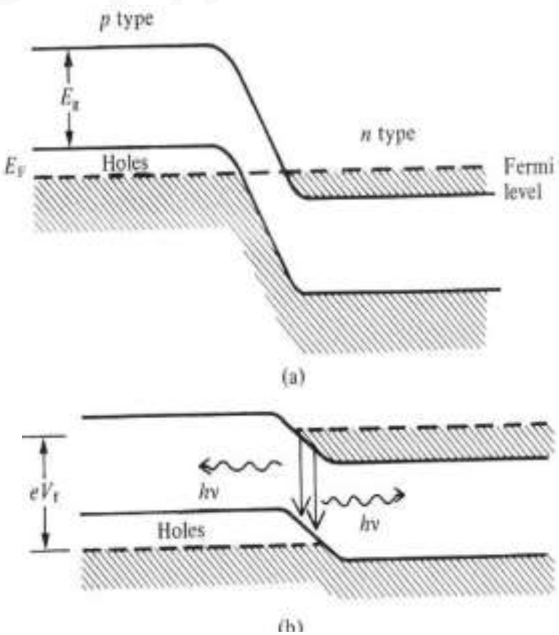


The Nd:YAG energy level diagram

Types and classes of laser

Semiconductor lasers

- Basically a diode junction.
- Region where BOTH excited electron states and holes are present.
- This is achieved using heavily doped ***n*** and ***p*** material and applying a forward bias to the junction.
- Under forward bias the active region is only thin, for exam ple in GaAs at room temperature 1 to 3 μm.
- No external mirrors are used. The faces are cleaved or gro und perpendicular to the junction.
- The pumping energy comes from the diode current. LASER action is induced above a certain threshold current density.
- Because the active region is thin the exit beam spreads due to diffraction.



Energy levels in a semiconductor laser (a) in equilibrium and (b) with forward bias

Types and classes of laser

Atomic gas lasers

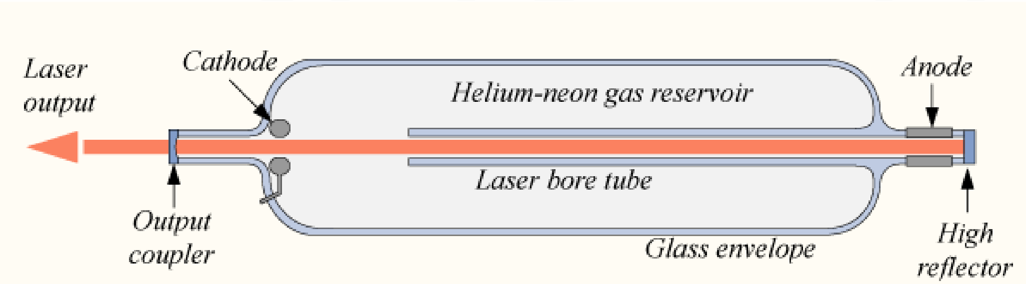
- Inelastic collision

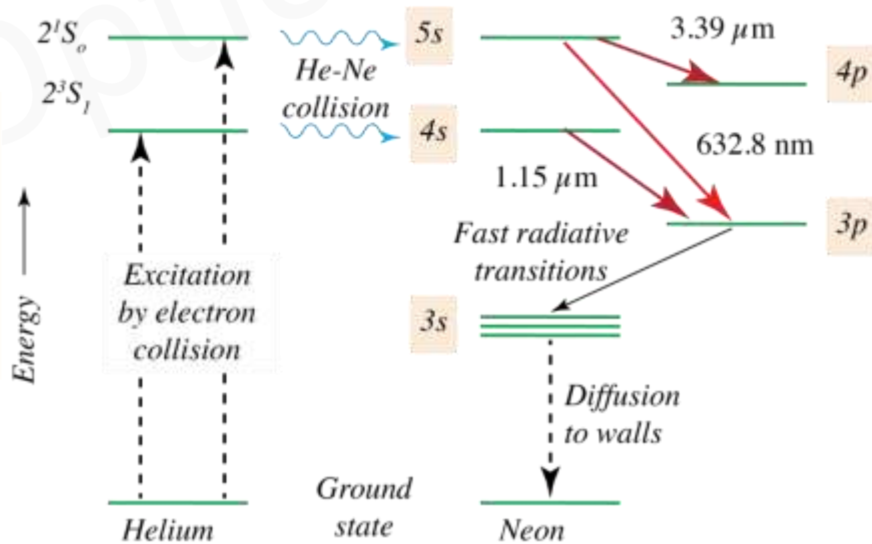
- The common He-Ne laser.
- Ne provides the energy levels and He provides pumping by electron and atomic collisions. Pumping is by a two stage process:

$$e_1 + He = He^{\star} + e_2$$

$$He^{\star} + Ne = Ne^{\star} + He$$

- Low power but high collimation
- Polarization selected by Brewster window
- and Δλ extremely small.

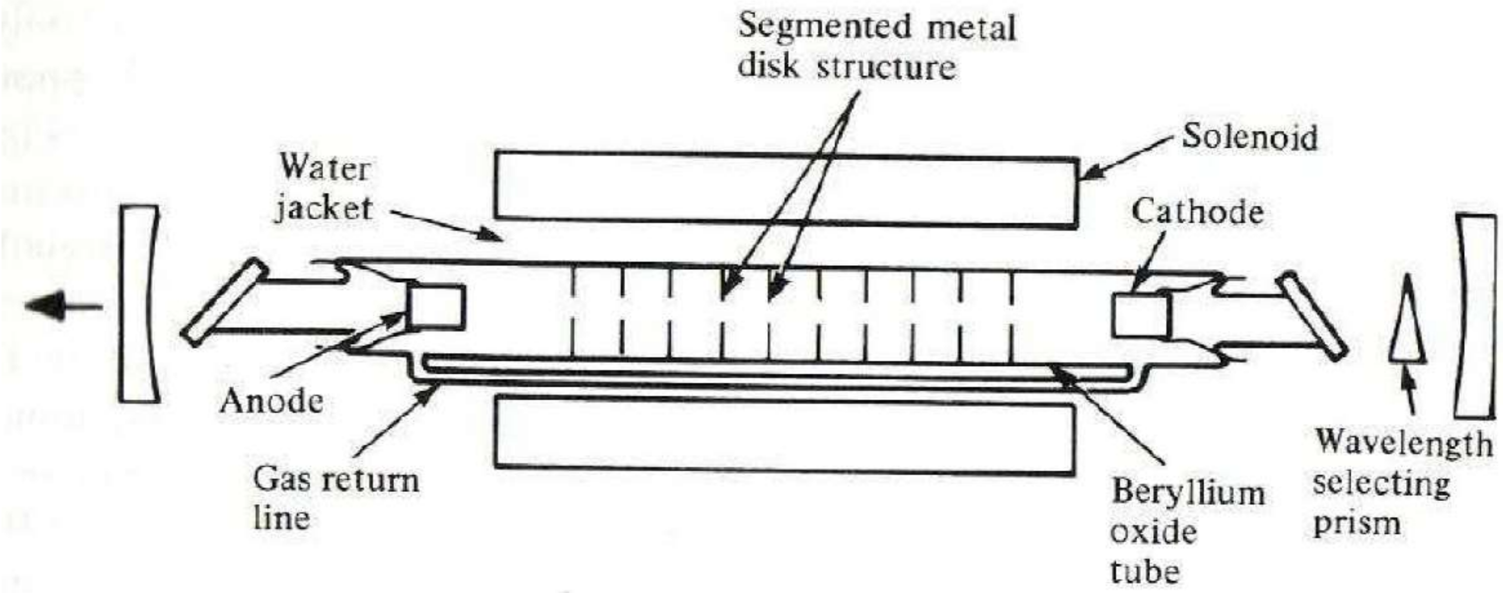




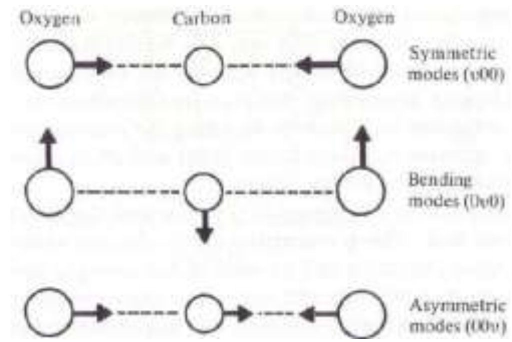
Types and classes of laser

Ion lasers

- High discharge currents are used to strip the atoms of electrons to form ions.
- An example is the Ar ion laser. High discharge current 15-50 A.
- Used to pump dye lasers.
- Transitions correspond to 4P-4S, 514.5nm and 488nm.



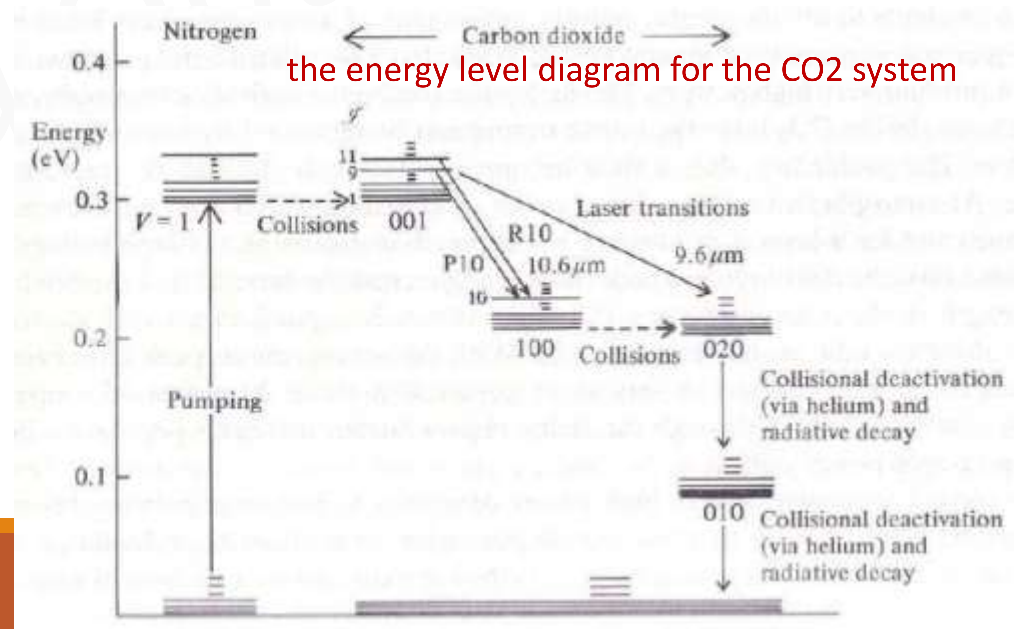
Types and classes of laser



Molecular lasers- the carbon dioxide laser

- Very important in industrial applications.
- Use the vibrational modes of the molecule. For CO2 laser the main transition is at a wavelength of 10.6μm.
- They use d.c. discharge to pump.
- Can easily obtain 100 watts CW from a laser 1 meter long.
- Using gas dynamic pumping can get an incredible 100kW of CW power.

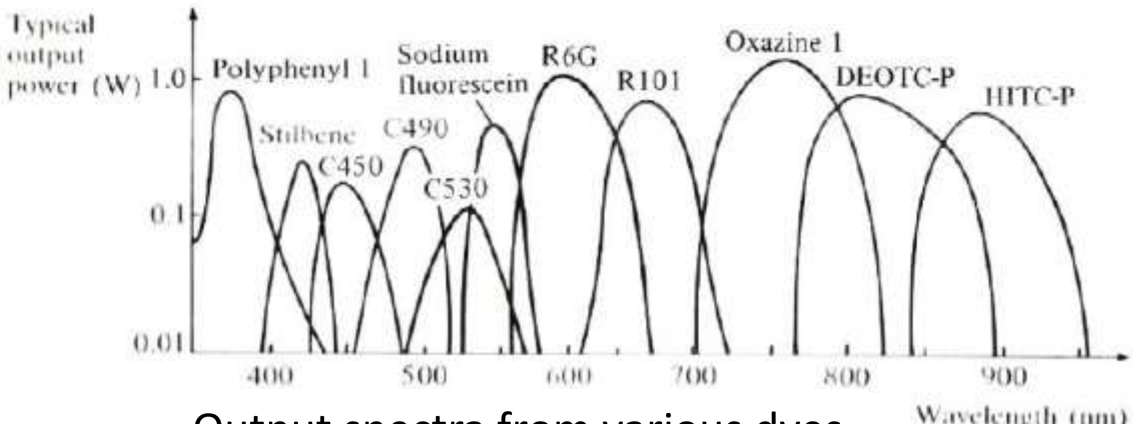
the energy level diagram for the CO2 system



Types and classes of laser

Liquid dye lasers

- These contain an organic dye in a solvent.
- Such dyes can be excited by absorption of short wavelengths and fluoresce by emitting at longer wavelengths. Pumping is done optically using radiation from another laser, for example a Ar ion laser.
- There are a large number of electronic energy levels in bands. Therefore get a large number of possible LASER transitions and such lasers are tunable.
- Use laminar flow in a thin layer to prevent build up of absorption losses (absorption T1 to T2).



Output spectra from various dyes

Types and classes of laser

Raman lasers

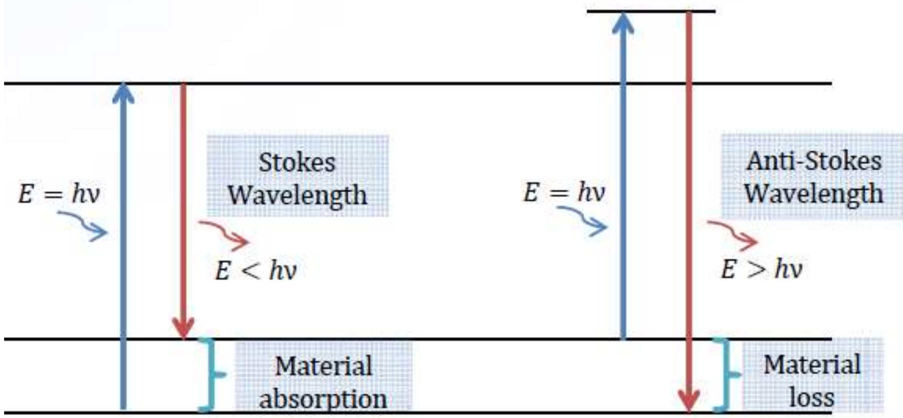
- A **Raman laser** is a specific type of laser in which the fundamental light-amplific ation mechanism is stimulated Raman scattering.
- Raman lasers are optically pumped. However, this pumping does not produce a population inversion as in conventional lasers.
- Rather, pump photons are absorbed and "immediately" re-emitted as lower-fre quency laser-light photons ("Stokes" photons) by stimulated Raman scattering.
- The difference between the two photon energies is fixed and corresponds to a vibrational frequency of the gain medium.
- This makes it possible, in principle, to produce arbitrary laser-output wavelengt hs by choosing the pump-laser wavelength appropriately.
- In optical fibers made of silica, a wavelength separation between pump light an d laser-output light is about 100 nm.

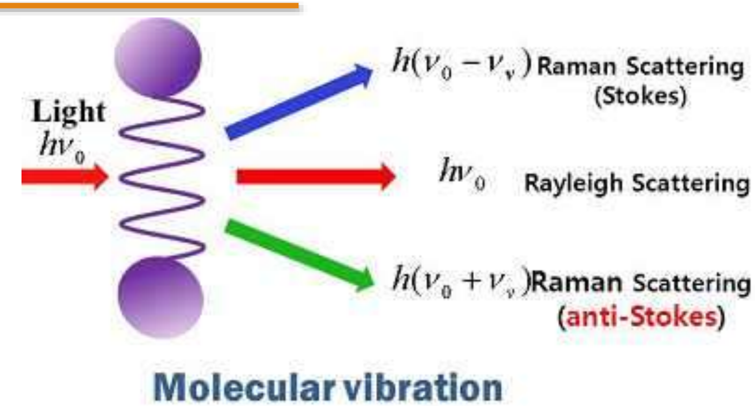
Stimulated Raman Scattering

g

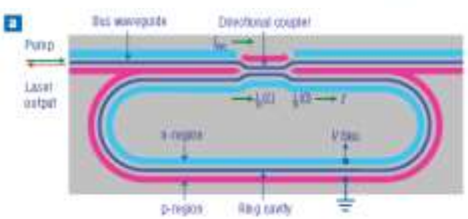
❖ Raman scattering

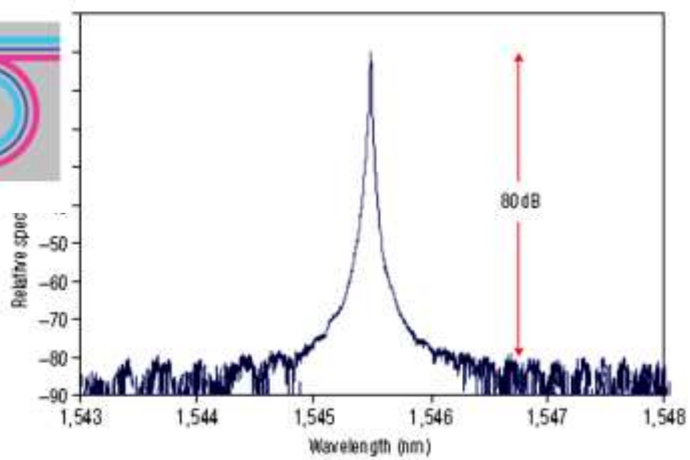
- Inelastic scattering

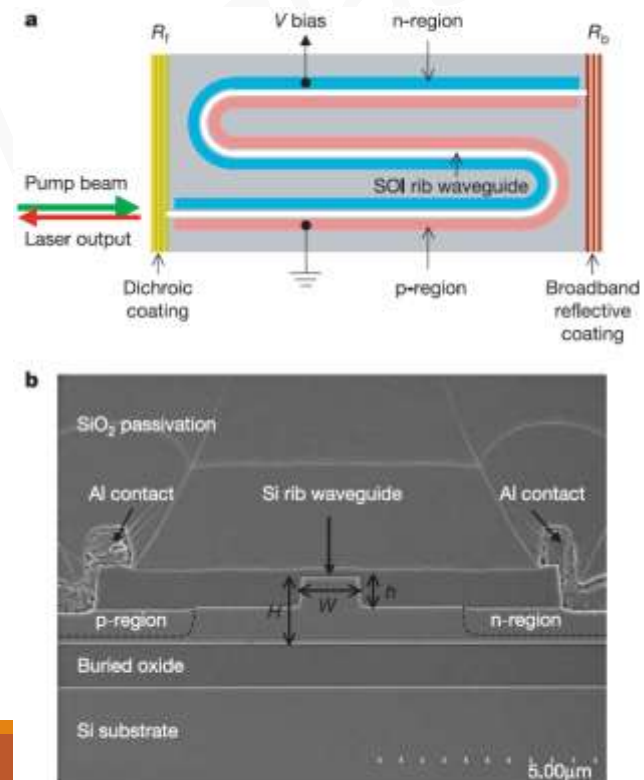




❖ Raman Si laser spectrum







- ✓ Pump laser at 1430.5nm, lasing at 1545.5nm
- ✓ Side-mode suppression ratio > 80dB
- ✓ Laser spectral linewidth < 100kHz

Nature Photonics 1, 232 - 237 (2007)

Nature 433, 725 (2005)

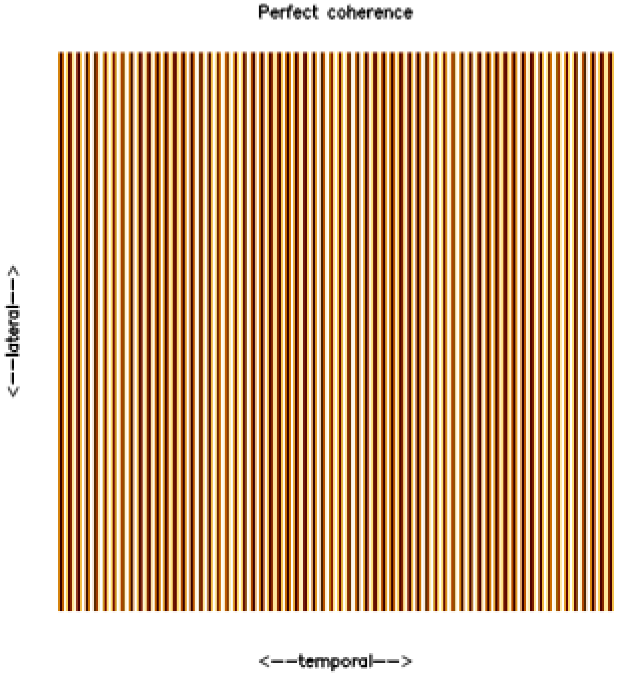


Figure 1: Perfect coherence

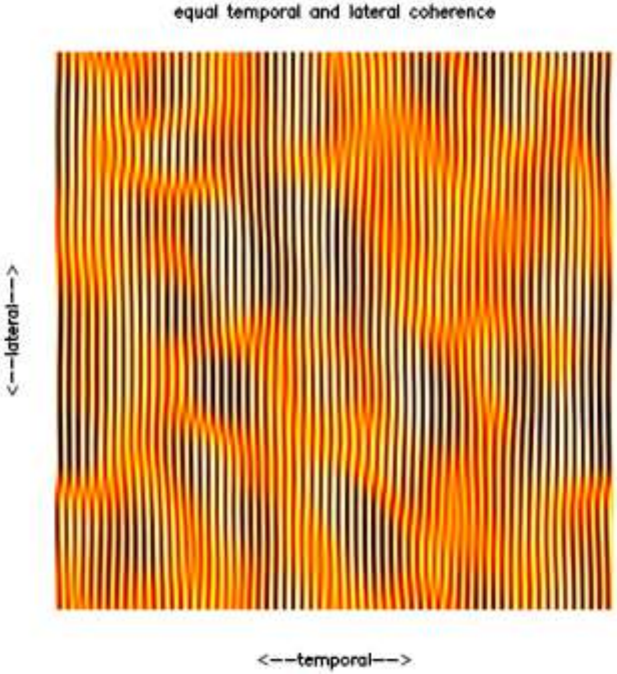


Figure 2: Equal temporal and lateral coherence

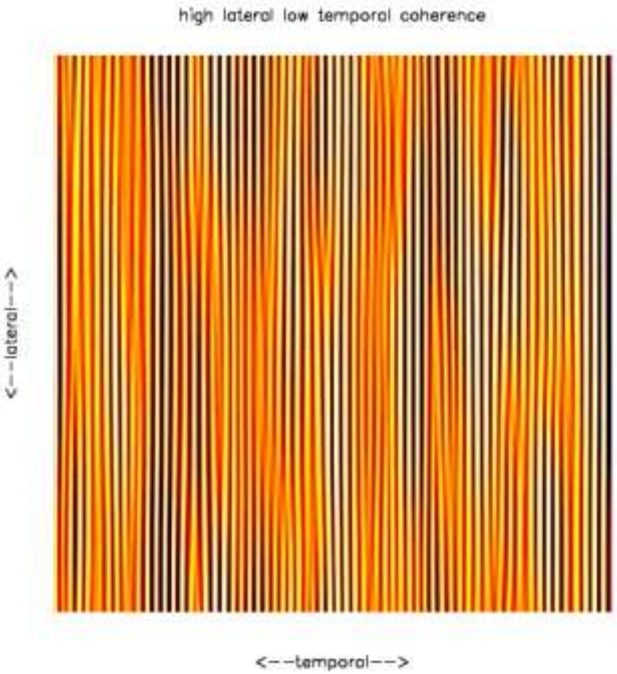


Figure 3: High lateral and low temporal coherence

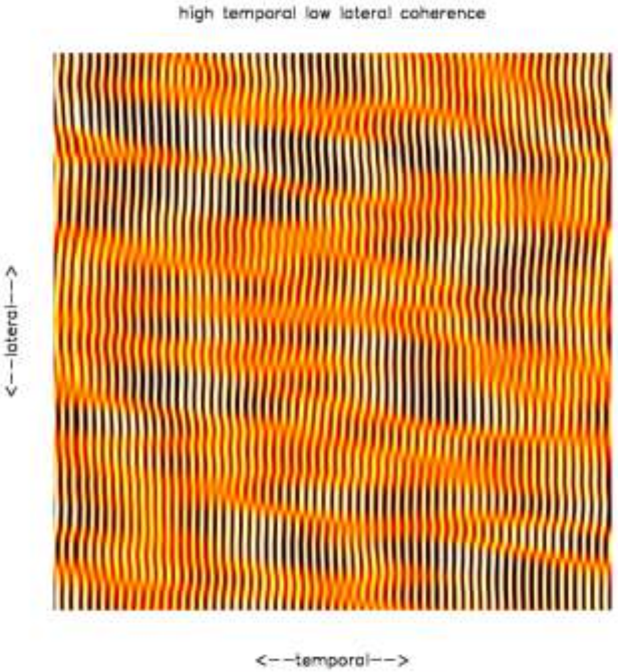


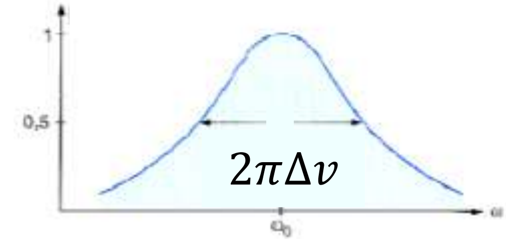
Figure 4: High temporal and low lateral coherence

Coherence length (time)

- The coherence length

$$L = \frac{c}{n\Delta v}$$

Δv : the bandwidth of the source



- The coherence time

$$\tau = \frac{1}{\Delta v} \approx \frac{\lambda^2}{c\Delta\lambda}$$

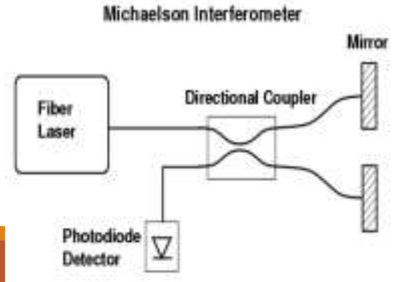
- Examples, 200 kHz linewidth at 1550 nm gives a 10 km coherence length.
- How to measure it?

Direct spectrum measurement for low coherence length laser (grating or FPI)

Interferometer (Michaelson interferometer)

Self-heterodyne measurement

Two identical lasers

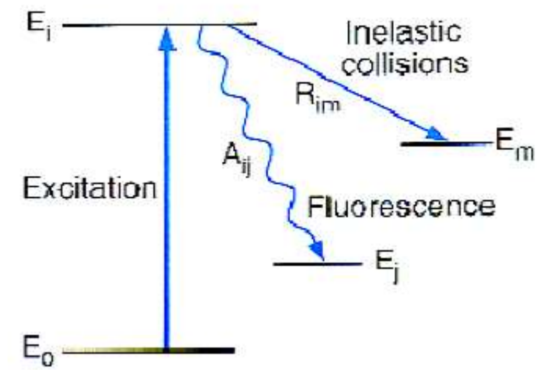


Typical examples of laser coherence lengths

Laser Type	Typical coherence length
Lamp pumped Nd:YAG	1 cm
HeNe (non-stabilized)	20 cm
HeNe (stabilized)	1 km
Argon/Krypton	1 cm
Argon/Krypton + Etalon	1 m
Dye Laser	5 .. 250 m
Fiber Laser (non-stabilized)	50 μm
Fiber Laser (stabilized)	100 km

Broadening

Homogeneous – Natural line width



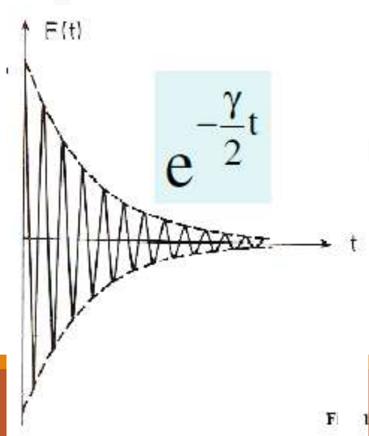
- The number of atoms in an excited state decays as a consequence of radiative and non-radiative transitions.
- The time for decaying a fraction 1/e of the atoms is the lifetime of the state.

$$N_i(t) = N_i(0)\exp[-(A_i + R_i)t]$$

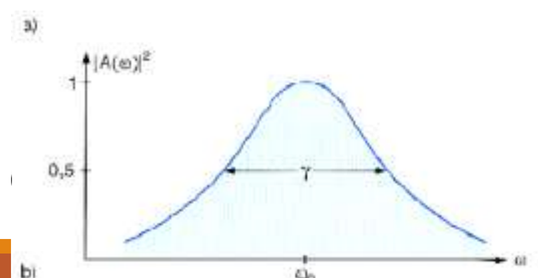
- Amplitude of radiation decay with time, with a damping constant.
- Because of the damping, the frequency of the radiation change.
- The spectral lineshape has a Lorentzian profile.

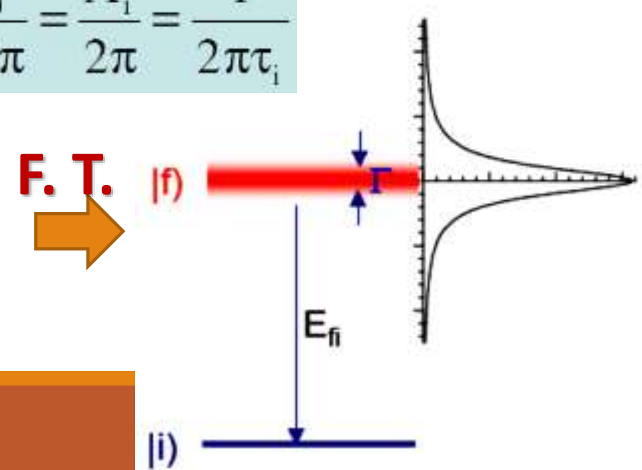
$$\delta\omega = \gamma \qquad \textit{Natural Linewidth}$$

$$\delta\nu = \frac{\gamma}{2\pi} = \frac{A_i}{2\pi} = \frac{1}{2\pi\tau_i}$$



$$e^{-\frac{\gamma}{2}t}$$





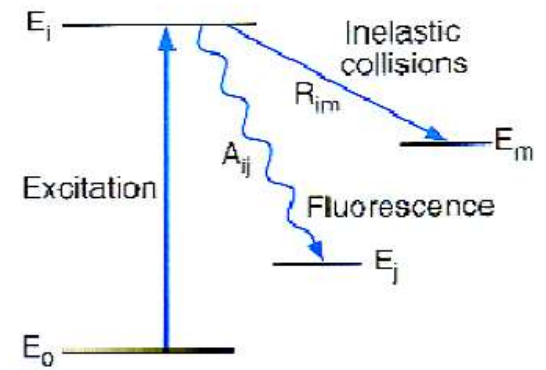
Broadening

Homogeneous – Collisions

- **Inelastic collisions**: Energy is transferred, causing a quenching of the atom, without radiative process. Pressure quenches the fluorescence.

- There is a decay of the intensity of emitted radiation. Then pressure decreases the lifetime of the excited state. This induces a *pressure broadening.*

- Inelastic collisions broadens the Lorentzian shape of spectral lines.



$$\delta\omega = \gamma$$

Natural Linewidth

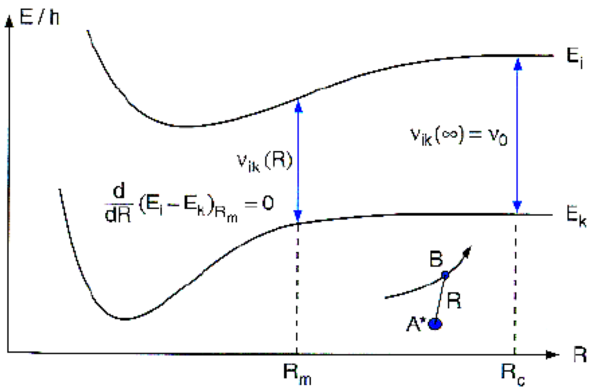
$$\delta\nu = \frac{\gamma}{2\pi} = \frac{A_i}{2\pi} = \frac{1}{2\pi\tau_i}$$

$$A_i = \frac{1}{\tau_{eff}} = \frac{1}{\tau_i^{spont}} + 2\sigma_i^{inel}\sqrt{\frac{2}{2\mu kT}} \cdot p = \gamma_{rad} + \gamma_{in.coll}$$

Broadening

Homogeneous – Collisions

Elastic collisions: Atoms interact with each other when they are close. Each atomic energy level reacts different to the interaction potential Epot. Then radiation emitte d during collisions shows a shift in the frequency.



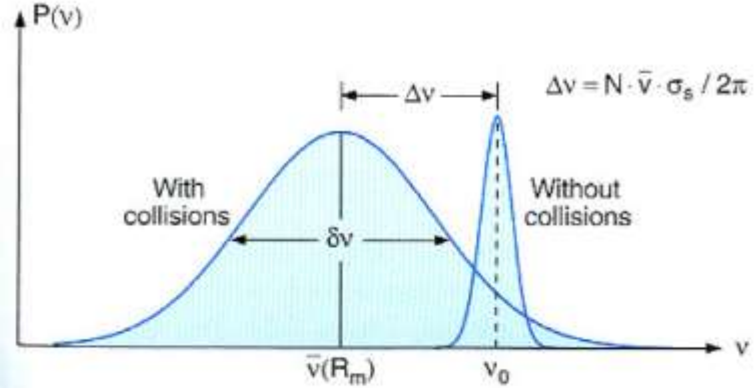
- Elastic collisions shift the peak frequency to lower or higher values depending on the nature of the interaction potential.
- Inelastic collisions broadens the Lorentzian shape of spectral lines.

$$A_i = \frac{1}{\tau_{eff}} = \frac{1}{\tau_i^{spont}} + 2\sigma_i^{inel}\sqrt{\frac{2}{2\mu kT}} \cdot p = \gamma_{rad} + \gamma_{in.coll}$$

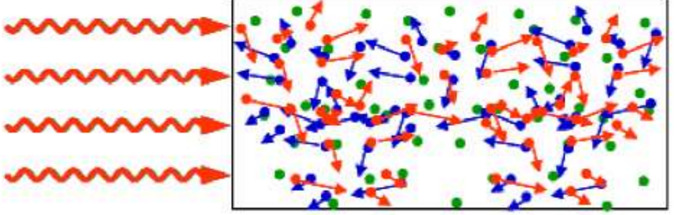
$$\delta\omega = \gamma$$

Natural Linewidth

$$\delta\nu = \frac{\gamma}{2\pi} = \frac{A_i}{2\pi} = \frac{1}{2\pi\tau_i}$$

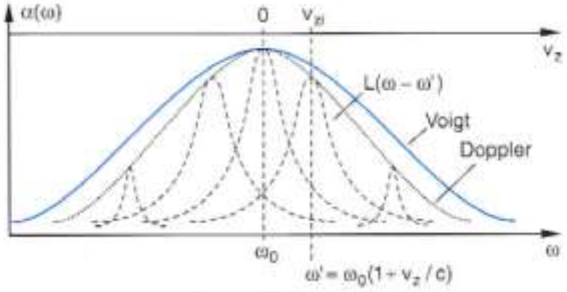


Broadening



Inhomogeneous – Doppler Broadening

Elastic collisions: The light emitted or adsorbed by an a tom is detected with larger/smaller frequency if the ato m approach/leaves the observer.



- The distribution of velocities of the atom gas produces a distribution of frequencies.

- The spectral line shape is proportional to the velocity distribution. It has a Gau ssian line-shape.

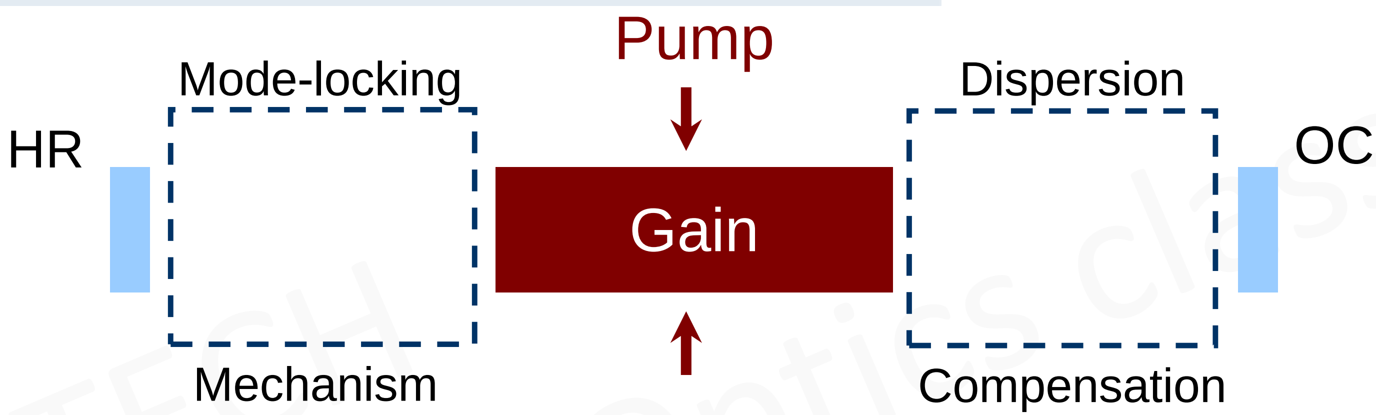
- Since every spectral line has a Lorentzian natural line-shape, the resulting line -shape is a convolution of both.

- Line shapes provide information not only on lifetimes, but also on temperatur e and pressure.

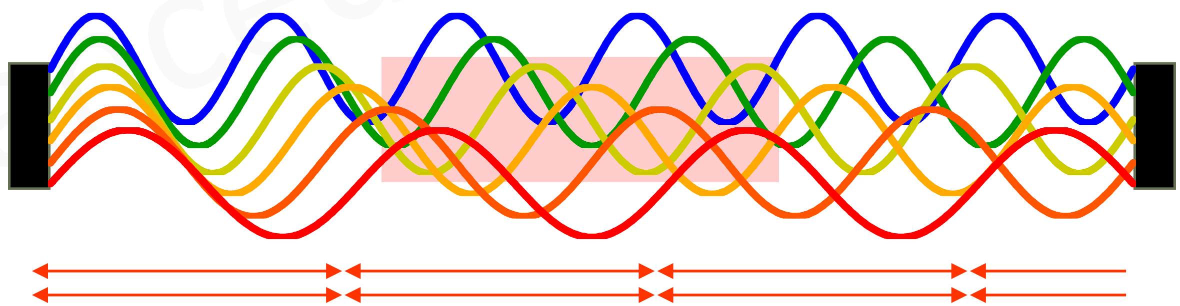
Ions in crystals or glasses

Basic principles of ultrafast lasers

Components of ultrafast laser system



Cavity modes



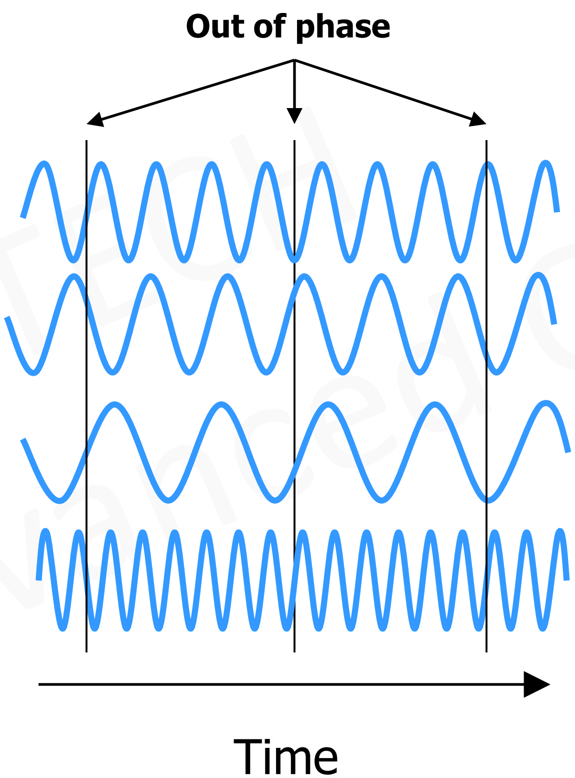
$\lambda_n = 2\,L/n$ $\Delta f = c/2\,L$



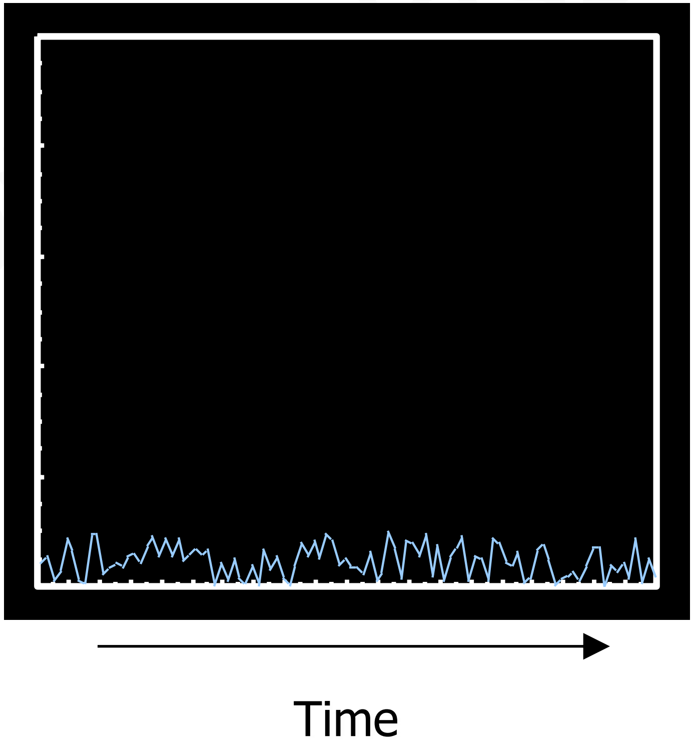
Concepts of Mode Locking

Mode locking is a method to obtain ultrafast pulses from lasers, which are then called mode-locked lasers mode

RANDOM phase for all the laser modes



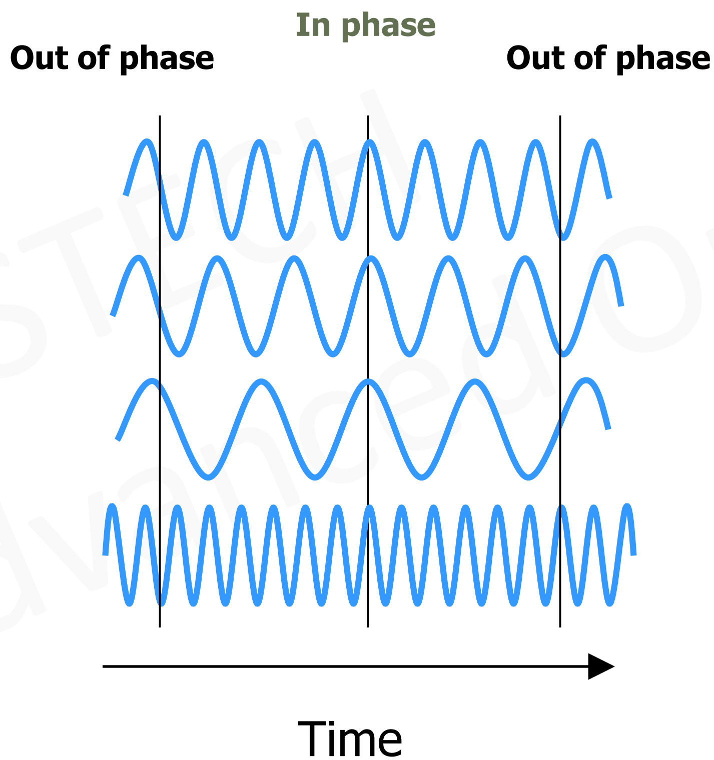
Irradiance vs. Time

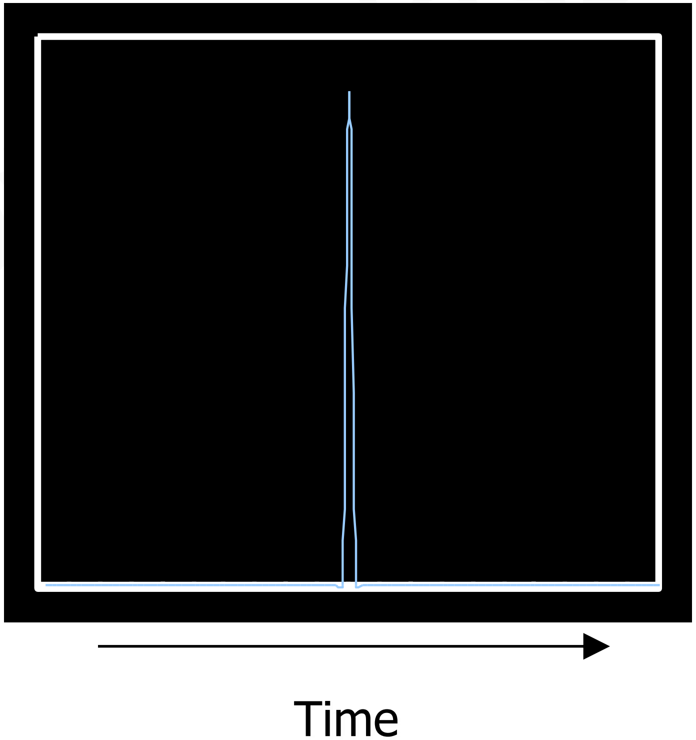


Concepts of Mode Locking

Mode locking is a method to obtain ultrafast pulses from lasers, which are then called mode-locked lasers mode

LOCKED phases for all the laser modes

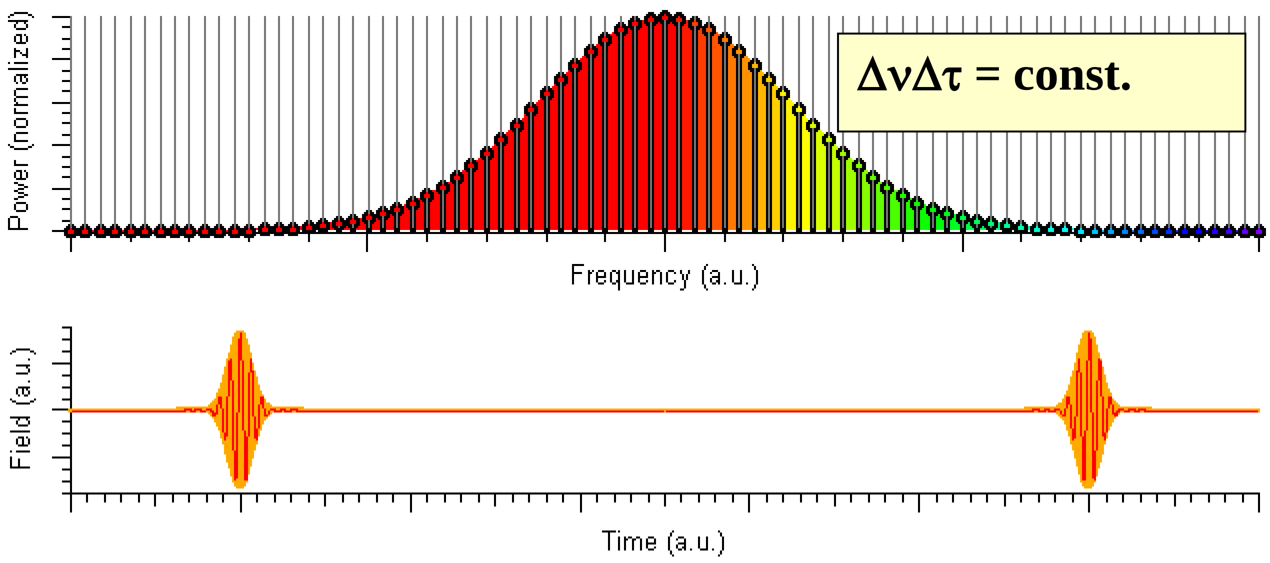




Del Mar Photonics

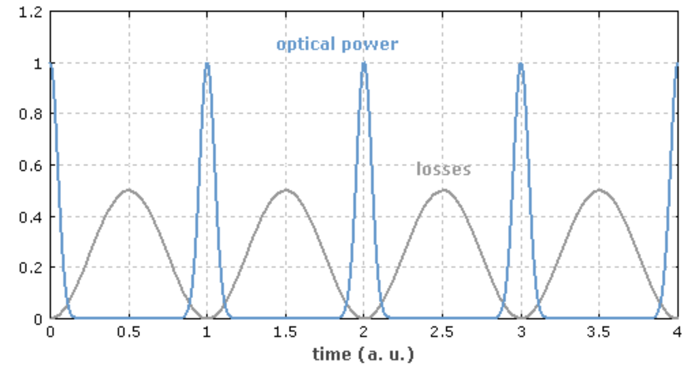
Basic principles of ultrafast lasers

Bandwidth vs Pulsewidth



Del Mar Photonics

Mode-locking Mechanisms

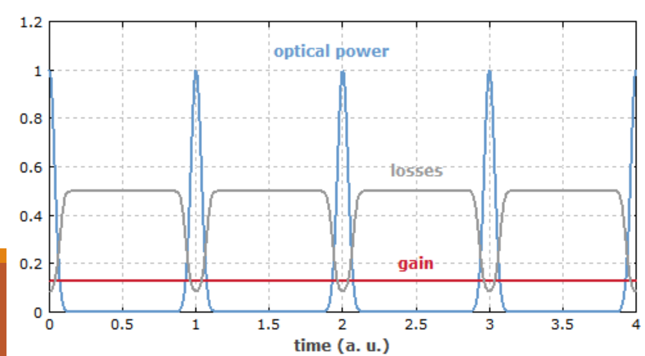


Active mode-locking

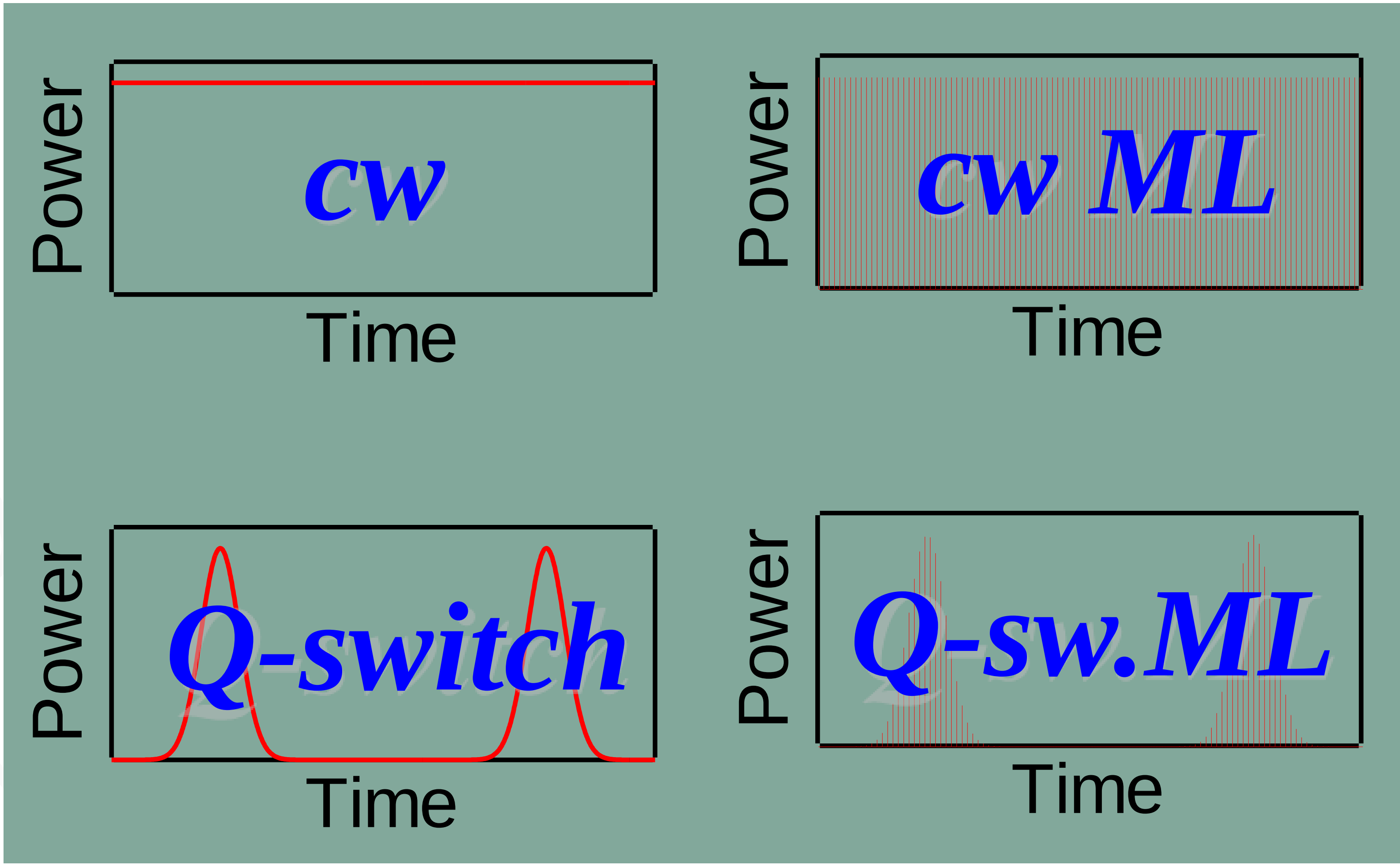
- Acousto-optic modulator
- Synchronous pump mode-locking

Passive mode-locking

- Saturable absorber (dye, solid state)
- Optical Kerr effect



Types of Laser Output



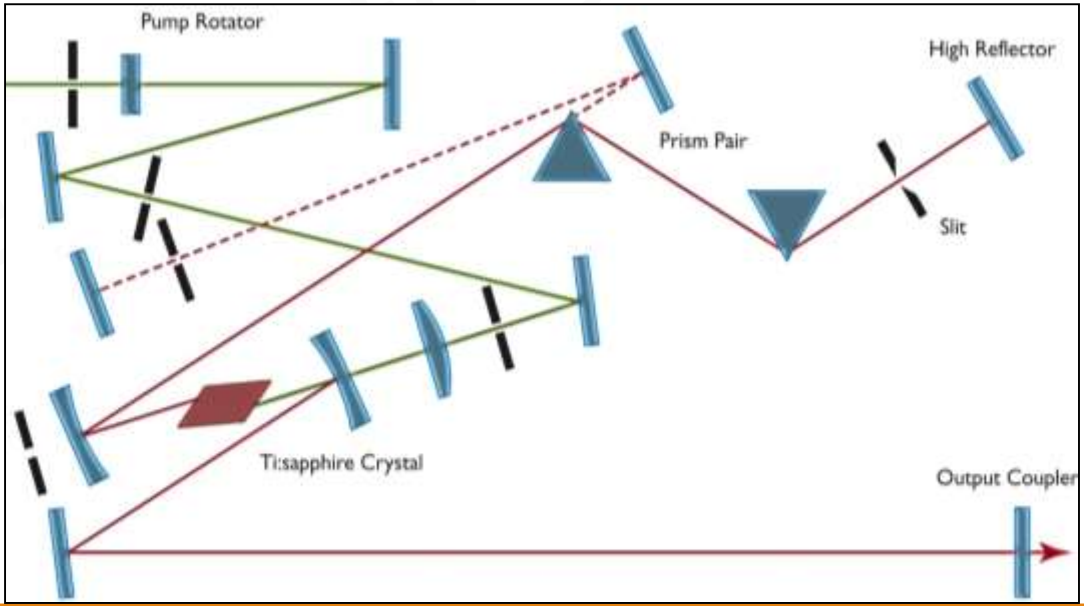
Del Mar Photonics

Cavity configuration of Ti:Sapphire laser

Tuning range 700-1000 nm
Pulse duration < 20 fs
Pulse energy < 10 nJ
Repetition rate 80 – 1000 MHz
Pump power: 2-15 W

Typical applications:

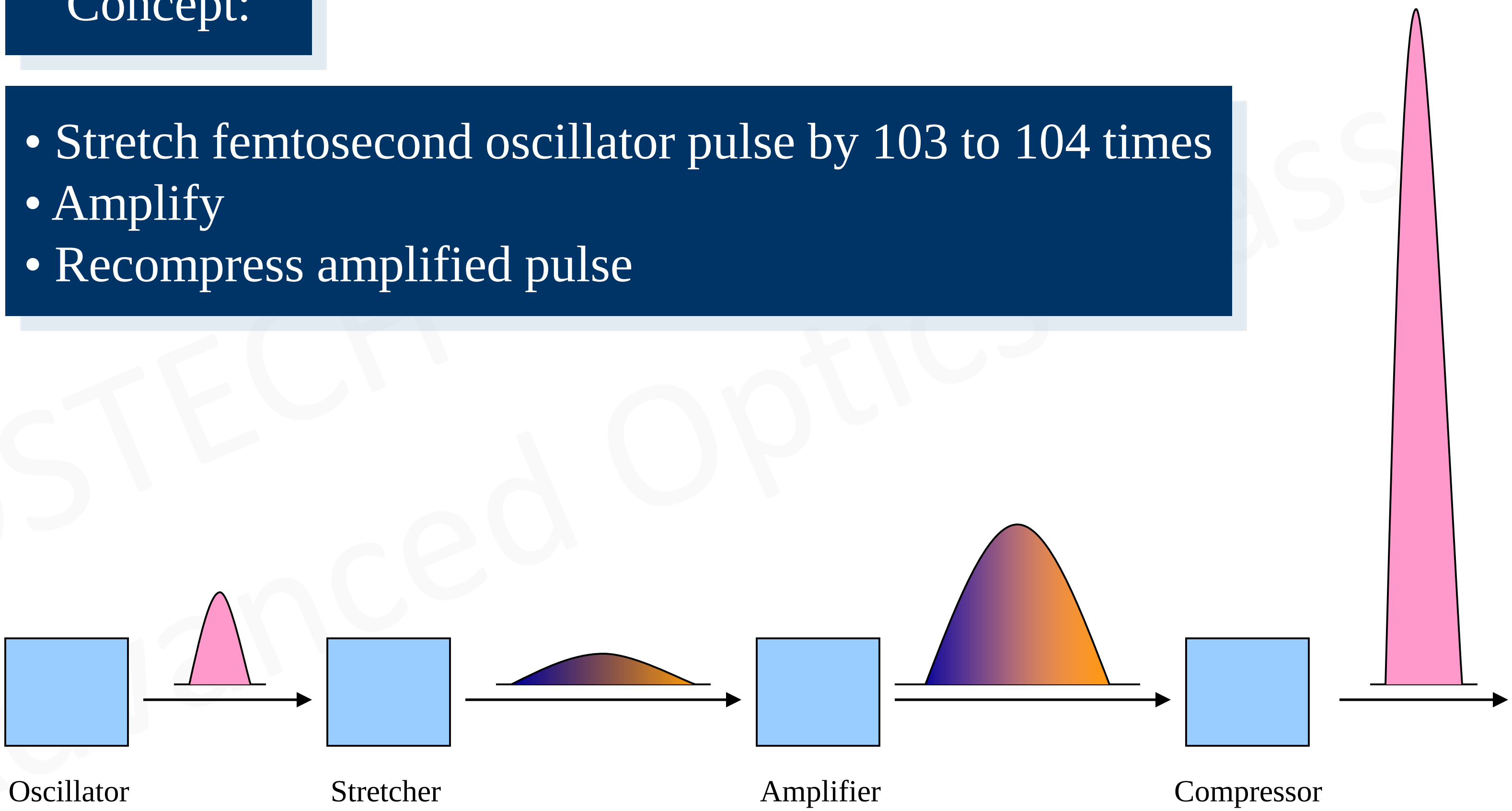
- time-resolved emission studies
- multi-photon absorption spectroscopy
- imaging



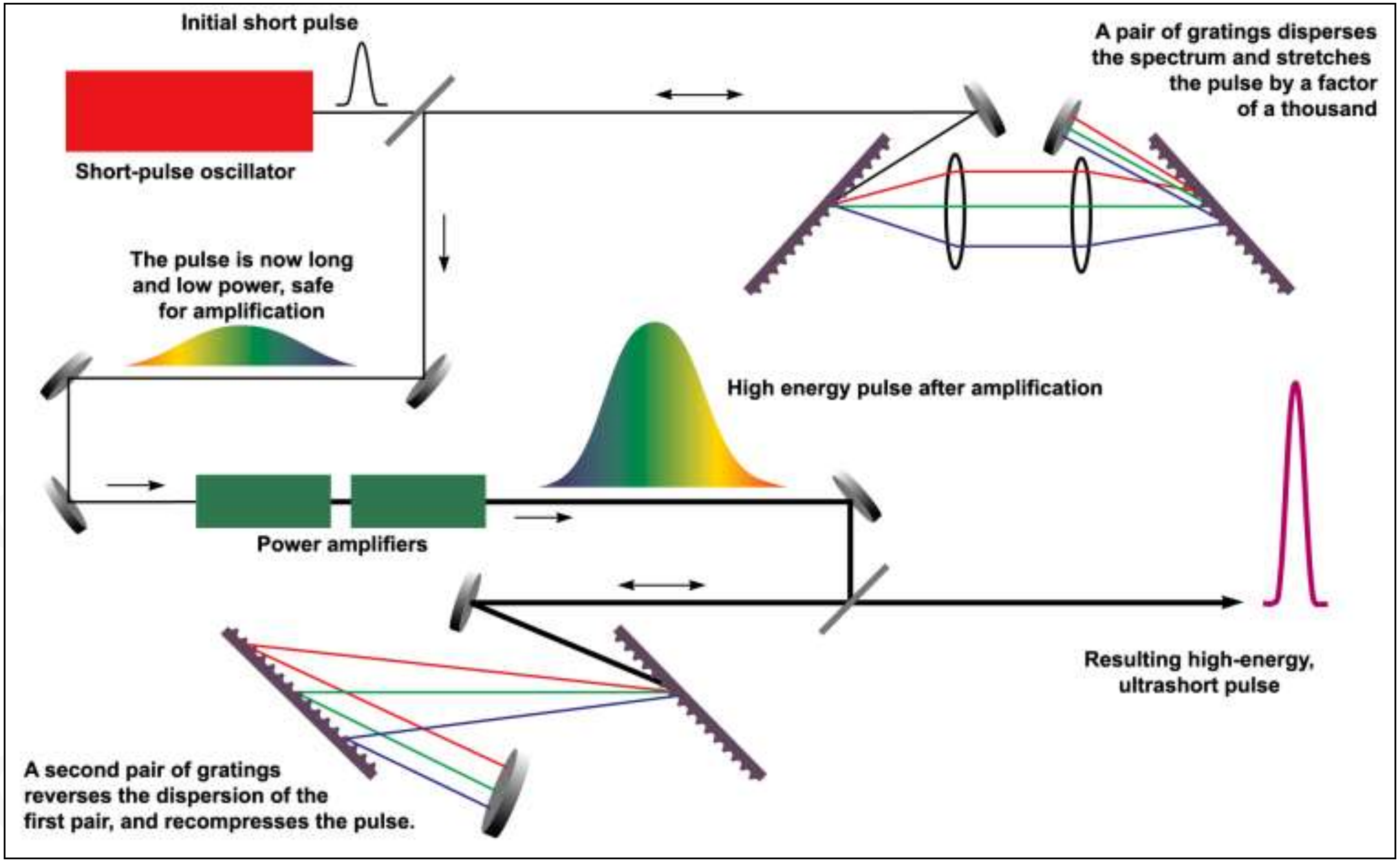
Amplification of fs Pulses

Concept:

- Stretch femtosecond oscillator pulse by 103 to 104 times
- Amplify
- Recompress amplified pulse



Chirped pulse amplification



- Femtosecond pulses can be amplified to petawatt powers
- Pulses so intense that electrons stripped rapidly from atoms

$$I = \frac{I_0}{|1-h|^2} = \frac{I_0}{1+|r|^2 - 2|r|\cos\phi}$$

$$I = \frac{I_{max}}{1+(2\mathcal{F}/\pi)^2\sin^2(\phi/2)}$$

$$\mathcal{F} \equiv \frac{\pi\sqrt{|r|}}{1-|r|}.$$

$$I_{max} \equiv \frac{I_0}{(1-|r|)^2}.$$

$$Q \stackrel{\text{def}}{=} \frac{f_r}{\Delta f} = \frac{\omega_r}{\Delta\omega},$$

$$\mathcal{F} \equiv \frac{v_{FSR}}{\Delta v} = \frac{\lambda_{FSR}}{\Delta\lambda}$$

$$Q = v_0 T_{rt}\frac{2\pi}{\eta}$$