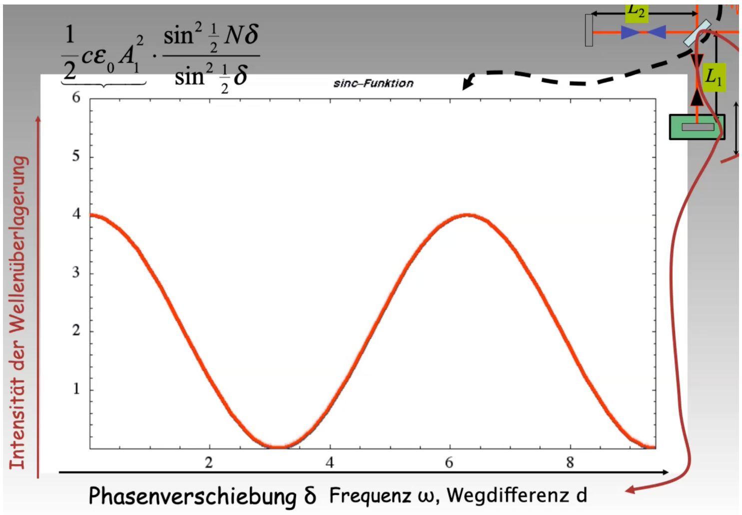
134.154 Lasers in Physics, Chemistry Biology and Medicine

Lecture on 23.11.2021

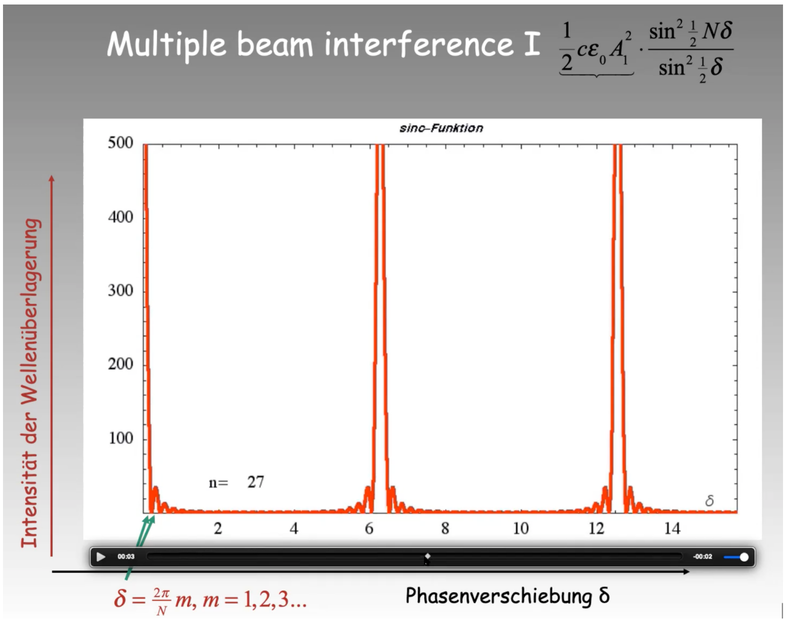
<u>Two and multiple beam interference</u>

To get this type of graph of sinc function **for two beams** have to be of the **same intensity**. The **Phasenverschiebung (phase shift)** stays the **same over time**, this is what we call coherent. In the case of the two beams the possible frequencies are broad (broad peaks) -> Intensity is distributed among frequencies.

**for one beam we get just the flat line (nothing to overlap with)



High contrast of the multiple beams can be only achieved if all **intensities** of the beams are the **same. If they don't have the same intensity, they wouldn't be able to cancel each other out to zero.**

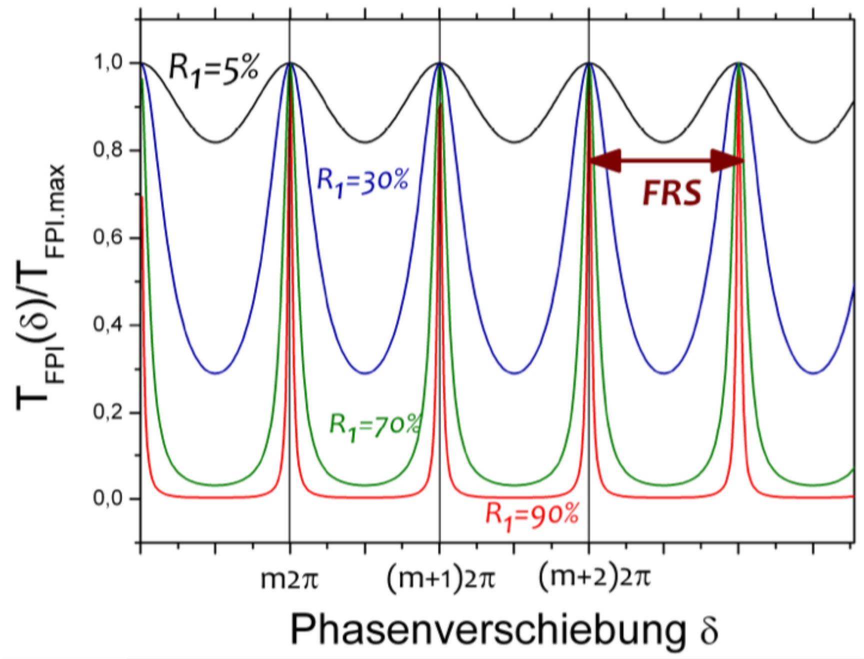


F (Finesse) referred also as **contrast** determines the **sharpness of the maxima**. Depends on the **reflection R** of the transition layer. With increasing reflection the sharpness increases. See next graph.

Equation for passive resonator:

$$F = \frac{2R_1}{(1-R_1)^2}$$

<u>Longitudinal modes, Etalon:</u>



- R1 = 5%: low reflection, case for “two beams”, low intensity
- R1 = 30%: increasing number of beams -> more contrast
- R1 = 70% analogous with 30%
- R1 = 90%: high reflection. Less frequencies allowed to enter the modes. Theoretically there is only one frequency allowed by the reflection of 100%, however it is not possible in practice.

These are so-called **longitudinal modes**. They are defined between I=0 and Imax.

Difference (**frequency spacing**) between adjacent longitudinal modes (easier said between two peaks) is given by (in active resonator):

$$\Delta \nu = \frac{c}{2L}$$

Where L is the length of the resonator.

Active resonators are called so, because there is an amplifier in it.

- The distance d between the reflective layers is generally large

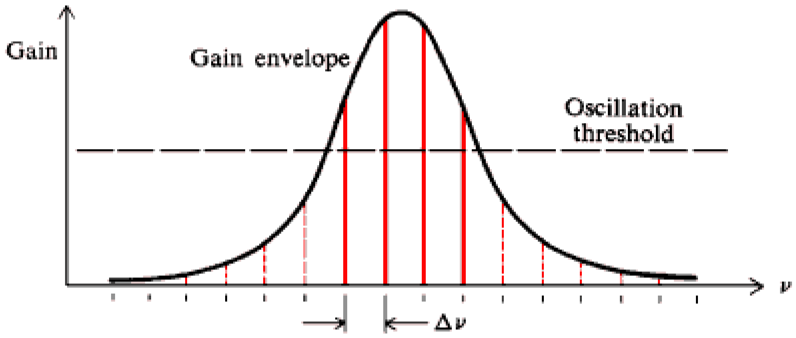
- The light is not introduced from outside but arises inside the FPI
- The light waves are amplified in the medium after each reflection on the mirror. The finesse F is given by the following formula (only R is replaced by G)

$$F = \frac{4G(\nu)}{\left(1 - G(\nu)\right)^2}$$

- An active resonator compensates R by the gain G(v)

Gain Profile: Measure of the ability of a laser medium to increase optical power
Depends on

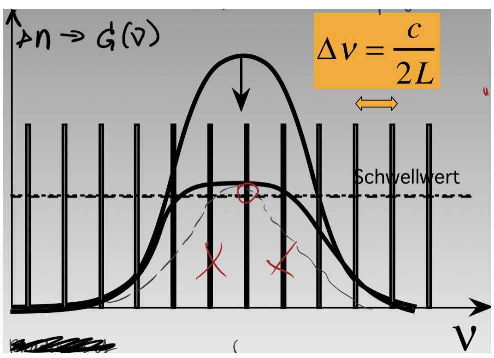
- Wave length (material and resonance curve dependent)
- Dynamical property (decreases with increasing light intensity)



Is it monochromatic (what exactly - light??)posible?
It is not possible if you have many modes presented

Possible scenarios:

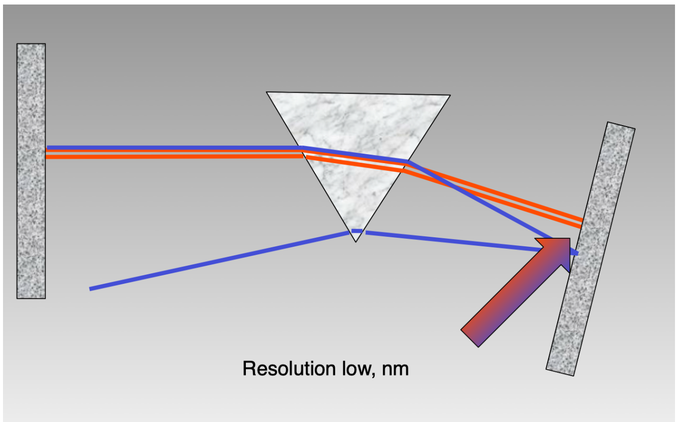
- Several modes - multi mode spectrum within the gain profile
- Single mode operation - narrow, but finite frequency spectrum corresponding to one mode of FPI. Meaning it is not possible to achieve only ONE possible frequency, because the R will never be 100%.
    - Single mode can be achieved by reducing gain -> mode competition. Only one mode is left performing as a single mode, because others fall below the threshold.



How can modes be selected? -> Introduction of frequency dependant losses

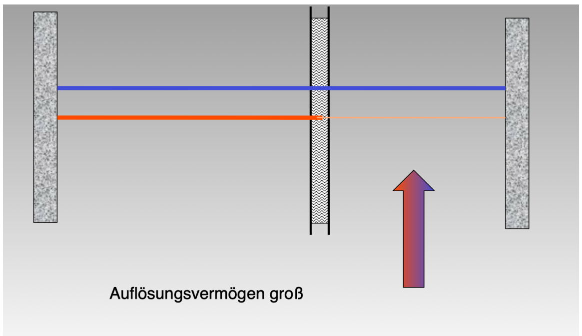
It can be done via optical elements with dispersive character

- Prism



Red: stable resonator -> low losses -> laser oscillation
Blue: unstable resonator. If you are willing to get the oscillation of the blue light you have to turn the prism. Therefore, the system is “tunable”.
Colors represent different wavelength, although it could be also the same color (when changing frequency within one color)

- Etalon (Polarisation elements)



Wavelength dependent -> by tuning (turning) elements the introduction to the losses for specific wavelengths are possible. Turning the polarisation element by 2Pi makes the same polarisation direction -> no losses.

134.154 Lasers in Physics, Chemistry Biology and Medicine

Lecture on 30.11.2021

Frequency Spectrum of the laser:

The frequency and frequency width of the laser are determined by the following factors:

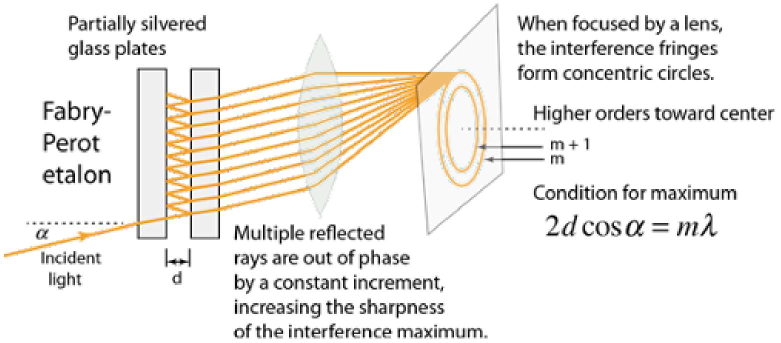
- Resonance and frequency range of the amplifying medium determine the frequency range of the laser.
- Only resonance frequencies can be developed in the amplifying range.

Optical Resonator

- Required for the proper use of the medium and intensification of light inside the LASER.
- Longitudinal Modes: How they are spaced (c/2n)
- Fabry Perot Resonator: Only specific frequencies are allowed.

Active Fabry-Perot resonator, longitudinal modes

- The resonator modes (the so-called longitudinal modes) that will develop in an active laser resonator correspond to those of the passive FPI (Fabri-Perot interferometer) resonator. However, the following changes must be taken into account



Longitudinal mode (classical geometrical optics)

- **Fabry Perot interferometer (active element):** extremely high-resolution spectrometer. In laser spectroscopy it is often used as an analyzer and a wavelength metre.
- If the circles that compose Q are cut perpendicularly, the intensity waves can be seen.
- Wiki: In optics, a Fabry–Pérot interferometer (FPI) or etalon is an optical cavity made from two parallel reflecting surfaces (i.e.: thin mirrors). Optical waves can pass through the optical cavity only when they are in resonance with it.
- The refractive index of the medium must be taken into account for the effective resonator length.
- The light waves are amplified in the medium after each reflection on the mirror. This shows that in the corresponding formula for the quality for the passive resonator only R (reflection coefficient of the mirror) has to be replaced by the gain G.
- By introducing frequency-selective (dispersive) elements (e.g. Fabry-Perot interferometer, etalons), a few modes - in extreme cases a single mode - can be selected.

Mode Competition

The phenomenon that different resonator modes experience laser amplification in the same gain medium, leading to cross-saturation effects.

- Highly dependant on the frequency (wavelength dependent losses)
- Possible to end up with a single mode.
- When certain modes do not reach a specific threshold.
- Modes with low losses use up all the potential for amplification and thus cause modes with higher losses to fall below the threshold for lasing.

Origin of Mode Competition: Some modes find better conditions than others (closely related to the net losses, in principle “losing less” is better)

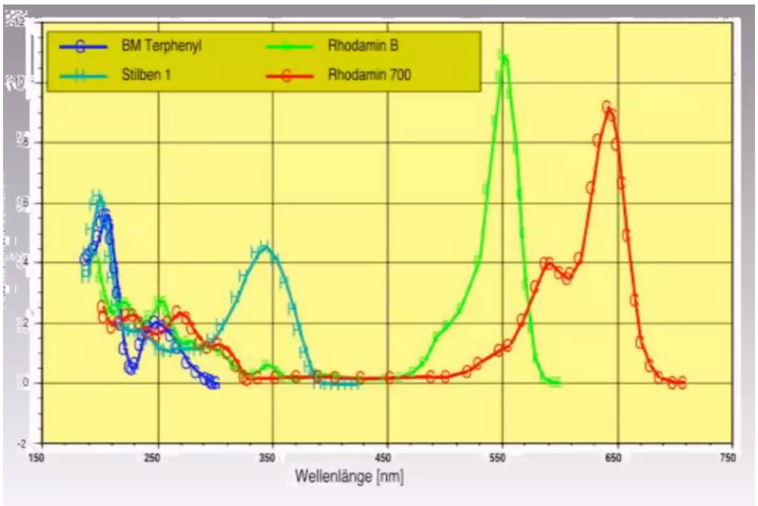
Broadening	**Trend Origin**	**Elements**	**Effect**
Homogeneous	Laser medium	Every mode uses the same pool of the amplification medium	Overall reduction of the gain profile
Inhomogeneous Reduces mode competition (some modes are eliminated)	Doppler effect.	Different types of molecules/atoms.	Reduces gain profile only around natural line width (mode). Does not influence other molecules/atoms

Laser Dyes

Coumarins: Green

Rhodamines: Yellow-Red

- The pumping possibility is restricted, since the dyes are in liquid state.
- They amplify the natural line with → specific wavelengths.



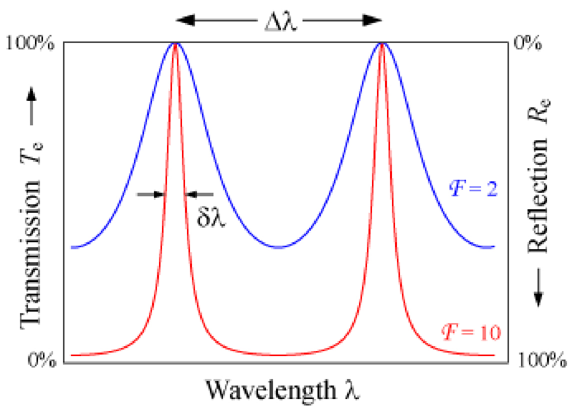
Ti-Sapphire Laser

- Large gain profile
- Ideal for Ultra-short lasers

Free spectral range

FSR - distance to the peak of the next order

Wiki: Free spectral range (FSR) is the spacing in optical frequency or wavelength between two successive reflected or transmitted optical intensity



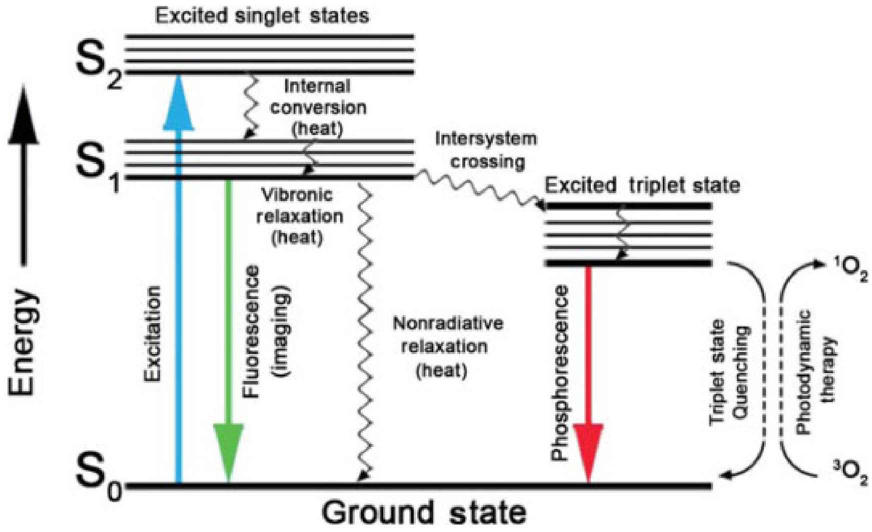
maxima or minima of an interferometer or diffractive optical element.

Wiki: The transmission of an etalon as a function of wavelength. A high-finesse **etalon or Fabry–Pérot interferometer** (red line) shows sharper peaks and lower transmission minima than a low-finesse etalon (blue). The free spectral range is Δλ (shown above the graph).

Emission types in dye lasers

1) Fluorescence: stimulated emission, when a photon hits the dye (singlet state: ↑↓ no unpaired electrons)
2) Phosphorescence: some time delay due to intersystem crossing (dye experience the transition into triplet state: ↑↑ two unpaired electrons)

Both phenomena occur due to the nature of different organic dyes



Tuning of Laser

Tunable lasers are usually operating in a continuous fashion with a small emission bandwidth, although some Q-switched and mode-locked lasers can also be wavelength-tuned.

$\Delta E \cdot \Delta t = 1$

* Requirements for the pumping for a single mode dye laser - continuous pumping source; we need to create a continuous population inversion, for example with an argon laser, which excites the dye

** Dye lasers have a broad emission spectrum. When this broad gain spectrum is combined with a diffraction grating or a prism as one of the cavity mirrors, the dye laser output can be a very narrow frequency beam. Frequency tuning over even larger ranges is accomplished by inserting different dyes into the laser cavity.

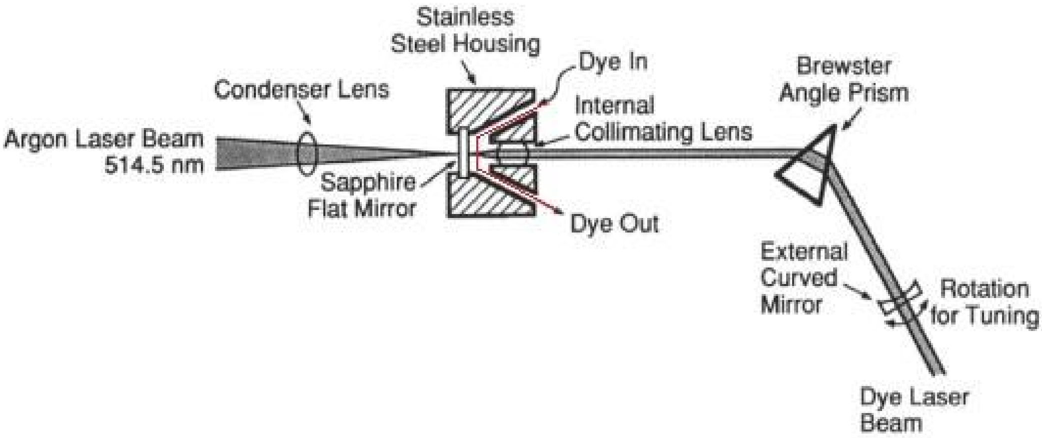
*** Linewidth narrowing and FSEs used in cw dye lasers are birefringent crystals, prisms, gratings, and Fabry–Perot etalons. Often two or more FSEs are necessary to achieve single-longitudinal-mode oscillation. The first stage: utilising prisms or birefringent filters to yield a bandwidth compatible with the free spectral range (FSR) of the first of two etalons. The second stage: the second etalon has a FSR and finesse necessary to restrict oscillation in the cavity to a single-longitudinal mode.

Dye jet

Fast flow of the dye solution at speeds of a few m/s is important to induce heat dissipation and hence reduce thermally induced optical inhomogeneities in the active medium

Wiki: Dye jet is a sheet-like stream in open air from a specially-shaped nozzle. With a dye jet, one avoids reflection losses from the glass surfaces and contamination of the walls of the cuvette. These advantages come at the cost of a more-complicated alignment.

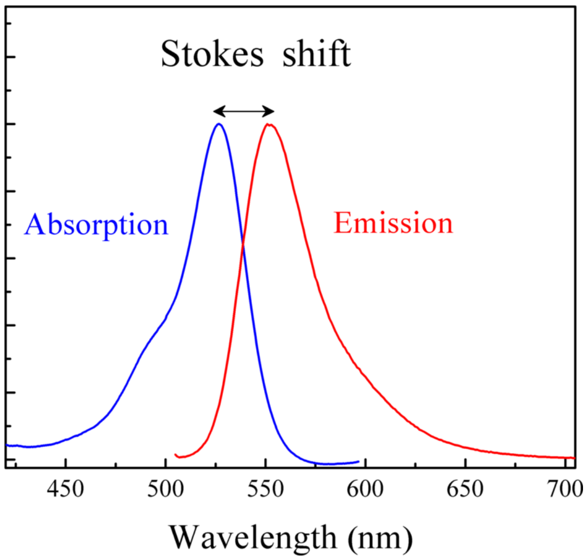
*Most dye lasers are arranged to have the dye and its solvent circulated by a pump into the gain region from a much larger reservoir, since the dye degrades slightly during the excitation process. Dyes typically last for 3 to 6 months in systems where they are circulated.



Stokes shift

The Stokes shift is due to the fact that some of the energy of the excited fluorophore is lost through molecular vibrations that occur during the brief lifetime of the molecule's excited state. This energy is dissipated as heat to surrounding solvent molecules as they collide with the excited fluorophore.

A larger Stokes shift eliminates spectral overlap between absorption and emission and allows detection of fluorescence while reducing interference. This also eliminates quenching of fluorescence and gives a stronger signal when used for biological imaging.



Lock-in Technique

It is a phase sensitive detection technique, the main goal is to detect small signals at a specific frequency and phase.

* Another large application of dye lasers is for producing ultrashort optical pulses by a technique known as mode locking. In this process, all of the longitudinal modes of a dye laser (as many as 10,000) are made to oscillate together (in phase), causing individual pulses as short as 50 fsec (5 × 1014 sec) to emerge from the laser, spaced at intervals of the order of 20 nsec. These short pulses are of interest in studying very fast processes in solids and liquids and may have applications for optical communications.

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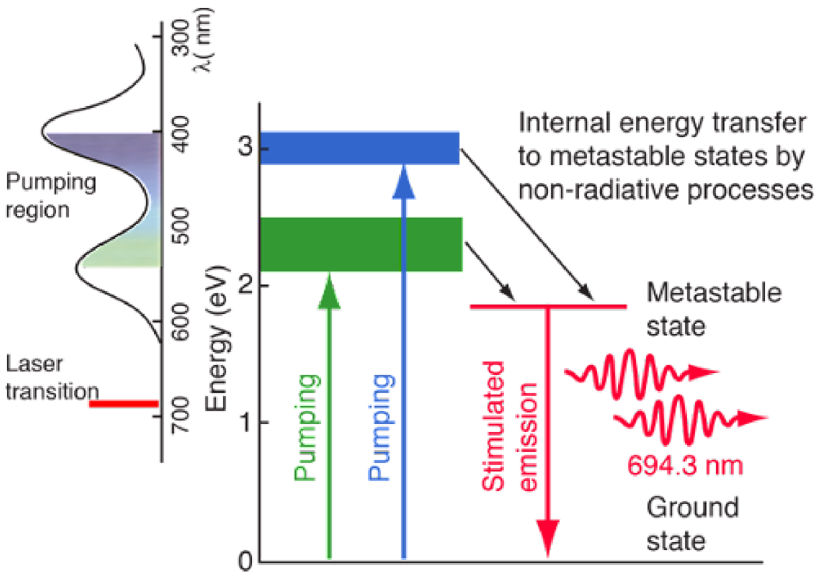
Types of LASERS

Type	**Features**	**Example**
Solid-state laser	Ideal for population inversion → creating extra levels Pumping possibilities reduced (plasma or electrical discharge not possible because solid) -> pumping with light (usually intense white light, often LEDs)	Nd:YAG (Neodym-dotierter Yttrium-Aluminium-Granat) infrared light --- Rubin (Ruby is a three level system) P.S. pumping is very inefficient (you have to hit it very hard)
Semiconductor (diode) laser	Current is the pump source	Laser printers and CD players: Diode Lasers (PN junctions)
Dye laser	Phosphorescence, FLuorescence	Rhodamine - orange light (Made from Complex Organic Dyes)
Gas laser	Electrons excite the atoms, then… **The quote of great people as our Prof: "Plasma physics and so on" hahahahh**	Helium-Neon laser (ideal 4 level system) --- Argonionen Laser (the laser light is in a better area than He-Ne) can operate in DC = continuous light source

Ruby laser diagram



Excimer laser

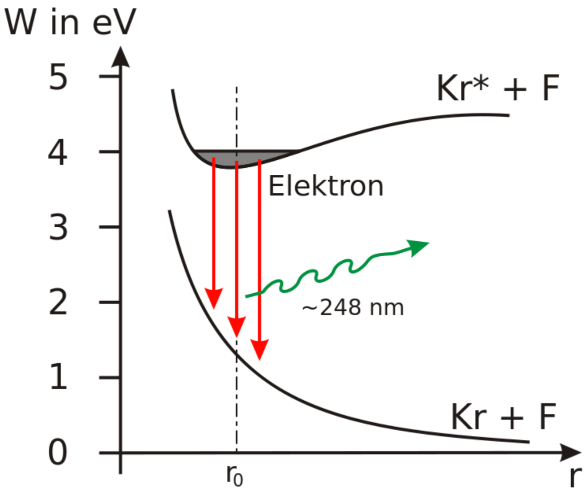
Form of ultraviolet laser which is commonly used in the production of microelectronic devices, semiconductor based integrated circuits or "chips", eye surgery, and micromachining.

Wiki: Laser action in an excimer molecule occurs because it has a bound **associative** excited state, but a **dissociative** ground state. Noble gases such as xenon and krypton are highly inert and do not usually form chemical compounds.

However, when in an excited state (induced by electrical discharge or high-energy electron beams), they can form **temporarily bound molecules with themselves (excimer)** or **with halogens (exciplex)** such as fluorine and chlorine. (Excimer = Excited Dimer)

The excited compound can release its excess energy by undergoing spontaneous or stimulated emission, resulting in a strongly repulsive ground state molecule which very quickly (on the order of a picosecond) dissociates back into two unbound atoms. This forms a population inversion.

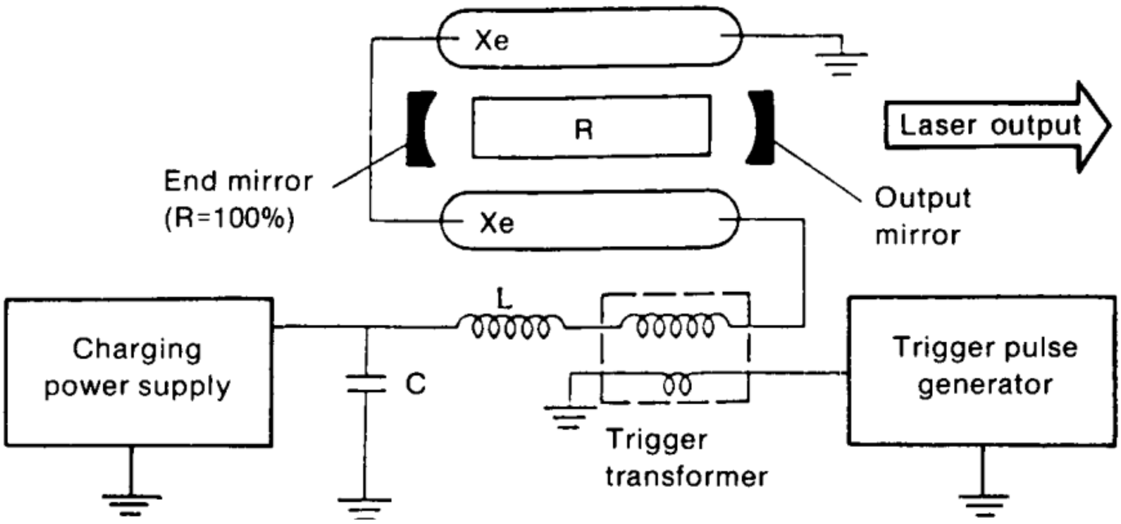
- Only 2-level laser that exists
- Very short wavelengths -> delivers very short pulses in the range of UV (~10-20ns)
- But very large and inhomogenous laser beam profile (1x2 cm cross sections, various transversal modes and inhomogenous intensity contribution)



Lecture on 07.12.2021

Solid State Laser

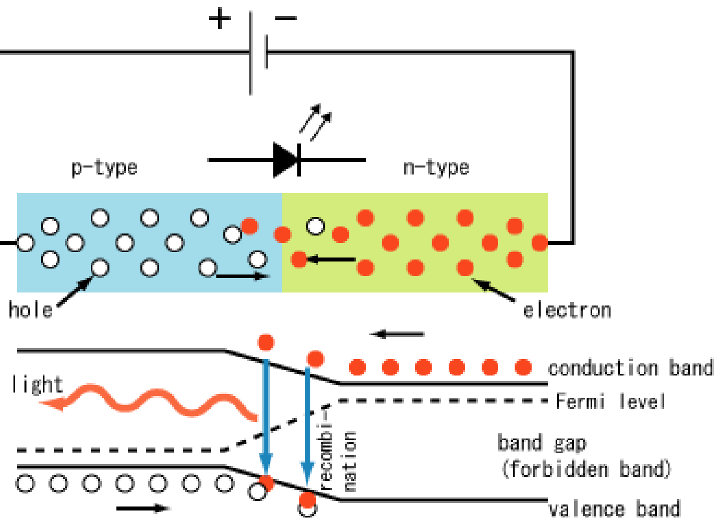
- Nd:YAG Laser (Nd, Ho = doping atoms; YAG, YLF = types of glass)
- Ti:Sapphire

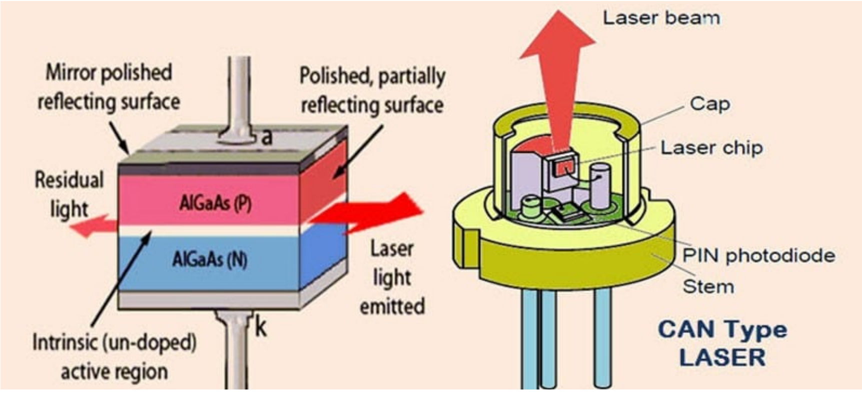


- The amplifying medium is a solid = doped (3-4+ Ions, typically metals, for example, Ti^{3+}) glass (transparent to avoid light absorption, for example, YAG)⟶ located at the centre of the cavity R.
  P.S. Using solid medium shrinks the possibility of being pumped differently. For instance, you cannot put glass into plasma (it will be destroyed). In other words, not all pumping sources are suitable for solid state laser. Usually, intensive white light is used for pumping.
- These lasers have an intense power lamp pumping the LASER and induce population inversion.
- Dopen atoms energy states are used for population inversion and amplified light production.
- They could be operated in pulses or continuous manner.
- Changing dopen atoms ⟶ Changing the wavelength of the laser light
- Typically solid state lasers operate in the infrared wavelengths (780 nm-1.4 µm). There is a trick (Frequency doubling effect) to change the output of the YAG laser to green visible light (higher energy and frequency).
- Erbium:YAG laser consultations can be found on the internet ⟶ Medical applications for dental application to remove plaque or fillings, cosmetic skin treatments to remove wrinkles, and superficial basal cell carcinoma (due to multi line systems). Process: laser light with special wavelength is absorbed by water in the top layers of skin

Laser Diode (Solid state)

- Light emission: 0.7 eV ⟶ Infrared-red spectrum
- Application in CD burners and laser printers.
- Driven by voltage (pump), the doped p–n-transition allows for recombination of an electron with a hole. Due to the drop of the electron from a higher energy level to a lower one, radiation, in the form of an emitted photon is generated. This is spontaneous emission.
- Stimulated emission can be produced when the process is continued and further generates light with the same phase, coherence and wavelength.
- Semiconductor material determines the wavelength of the emitted beam (from infra-red to UV)





Tunable Laser

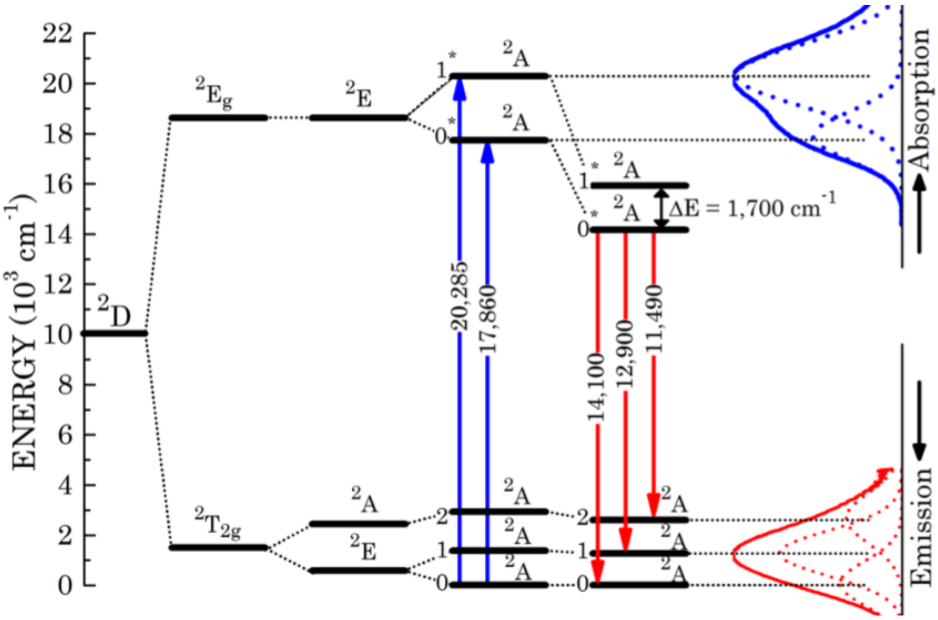
Characteristics:

- **Frequency of amplified light can be chosen**
- **Large gain profile with many many modes oscillating (in the gain profile)!**
- **Mode selection is used by adjusting the cavity of the laser and other elements** (piezoelectric or rotable quartz)
- Medium could also be substituted by Ti:Sapphire → has similar features to DYE- broad emission and absorption spectrum → left shifted
    - Dye lasers (Blue [courmarines], red [rhodamin 700], green [rhodamin B])
    - Ti: Sapphire (infrared or far red)

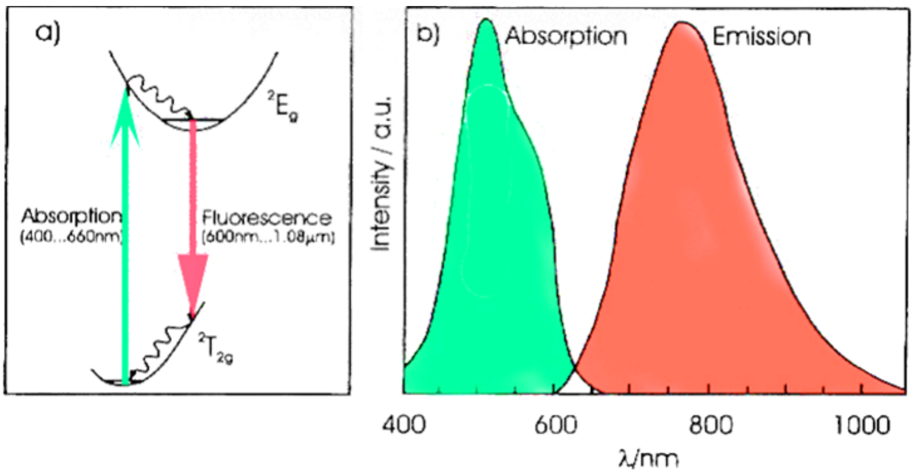
Broad reinforcement profile

- The best prerequisite for ultra-short-lasers
- The Schrödinger equation describes the electronic level occupation → important to achieve population inversion (800 nm → IR spectrum). It might shift with the type of glass that is used

Energy state diagram of the Ti^{3+} ions in the sapphire matrix



The ground multiplet levels are tagged 0, 1, 2. The upper multiplet levels are tagged 0* , 1* , replotted on the right side of the figure. The energy separation ΔE is Stokes shifting.



P.S. Absorption is in green spectrum then argon laser can be used for pumping (green light)

Pulsed Lasers

- Multimode Lasers

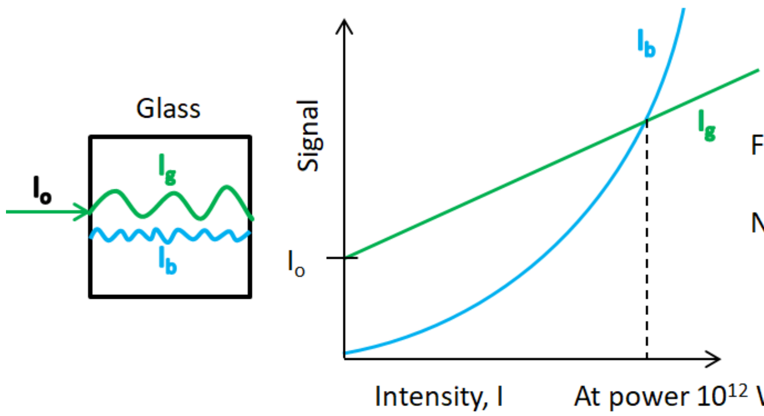
CW Laser

- Single Mode Laser

Frequency doubling effect

An optical effect that occurs in spatially asymmetrical materials that have a second-order nonlinear susceptibility. Two photons with the same frequency can interact with the material and combine to form a single photon with twice the frequency of the original photons. At high powers we can see the second-order frequency. P.S. it can happen in a frequency doubling unit within a resonator.

- Susceptibility is proportional to the electric field. This nonlinear susceptibility is VERY small.
- High intensities of light available ⟶ nonlinear processes become more probable



Fundamental harmonic:

$$I_g \propto I_o \cdot \chi_1$$

Next harmonic (non-linear susceptibility):

$$I_b \propto {I_o}^2 \cdot \chi_2$$

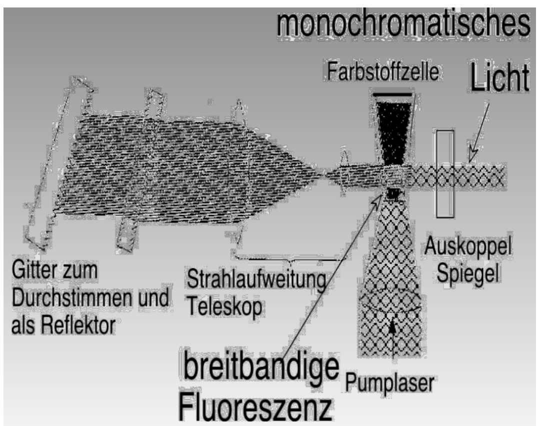
$$\boxed{\chi_2 \ll \chi_1}$$

At power 10^{12} Watt blue light is detectable

Simple Pulsed dye laser

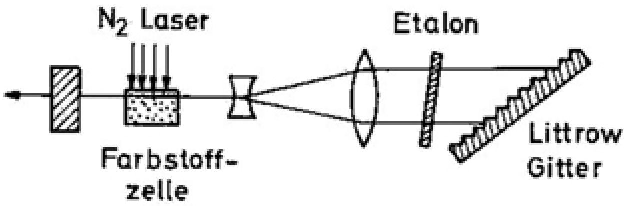
(not single mode, this is for multimode ⟶ tunable wavelength)

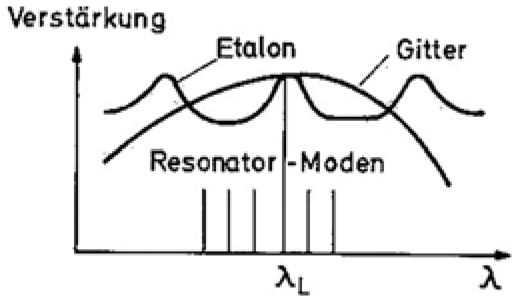
- Depends on the dye what laser is used for pumping ⟶ wavelength selective characteristics
- Wavelength selection is controlled by rotating grading mirror
- A lens is used to broaden the beam to not focus the whole intensity on a small area of the grading



mirror, otherwise it leads to thermal overload and grading mirror damage

- A lens broadens the beam, if this is missing → destructive thermal load would be formed

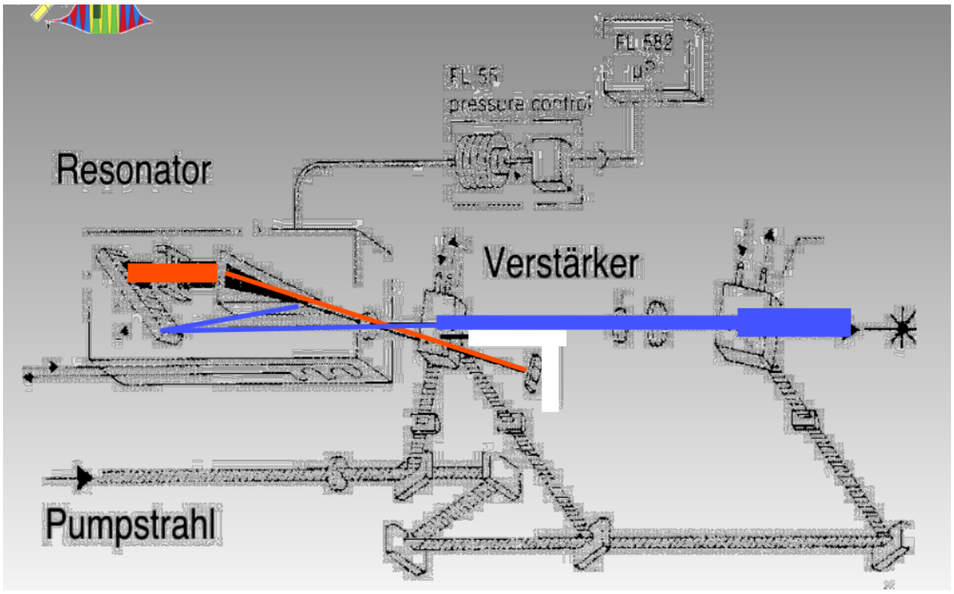




Pulsed Dye Laser

(more "sophisticated and convenient")

- Oscillating beam with a dye cell (flowing dye)
- In this device the output coupling (**oscillating BLUE beam,** it has the same frequency as the red beam) (4-5%) is not achieved by a semi-transparent mirror but differently, using a prism → instead of a semi-transparent mirror, a 100% reflective mirror is used.
- **Laser amplifier without cavity:** The prism reflects a small part of the beam (~5%) (the red beam splits into red and blue lines)
- The out coupled laser beam which already has all desired characteristics (wavelength, modes, etc. -> shown as blue beam in figure) is driven through dye-cell again to amplify it again → efficiency is amplified and improved (this can be repeated by sending the "final beam" through another dye cell another time)
- Pumped by an excimer laser "Pumpstrahl" → XeCl
- Fabry-Perot Interferometer can be implemented into the system → some modes available in the Doppler Broadening → sensitive to pressure and temperature changes → as a consequence the wavelengths would be shifted (not a desirable effect)



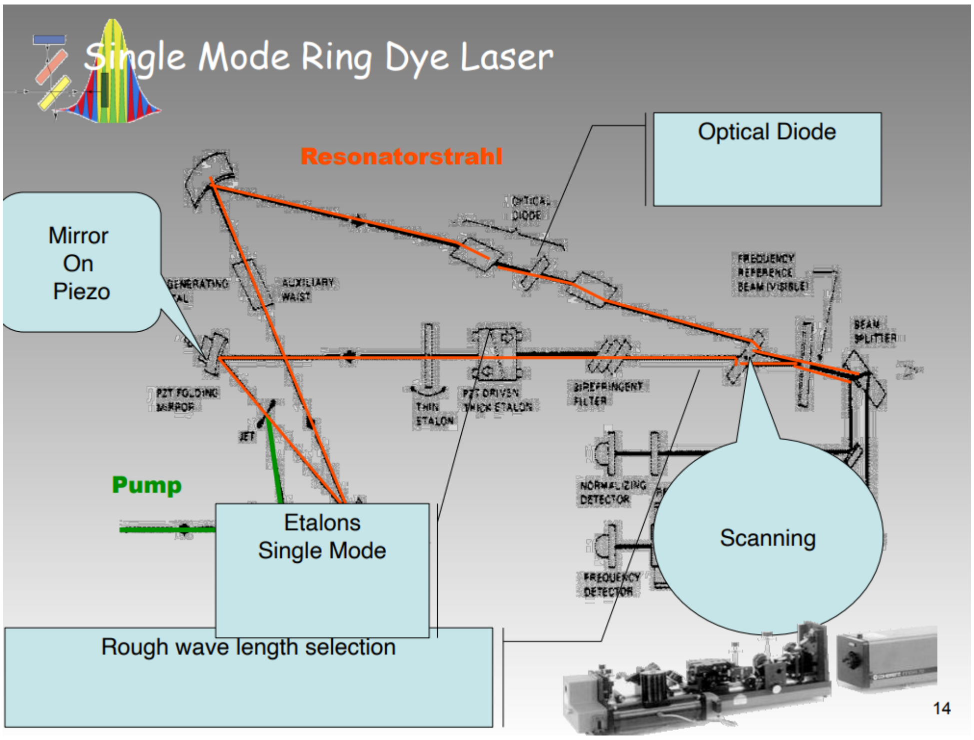
Single-mode Ring Dye Laser

Keep in mind: It has a very inhomogeneous beam profile

1. A dye must be pumped (CW-For single mode, Argon ion laser) → Initiation of the laser

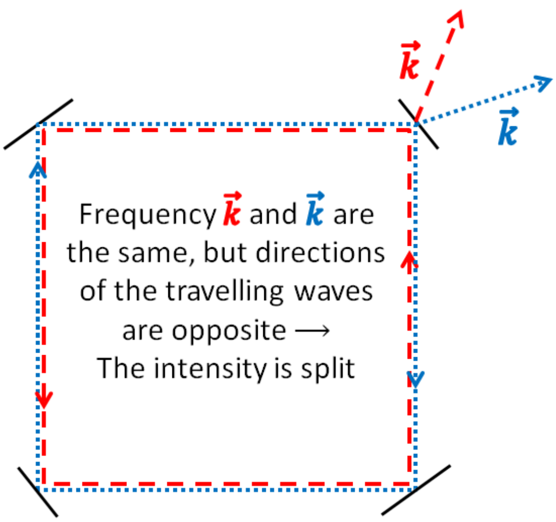
2. The mirrors create a "ring cavity"
   - In other (non-ring) configurations there is a standing wave in the medium. The beam always uses the same path through medium, that means that no spatial mode competition occuring (an undesired mode might just use another path through medium -> no competition).
   - In the ring laser, there is no standing wave but we have a travelling wave (position of the max/min travels in space ⟶ strong mode competition ⟵ "One mode eats up all the amplifying medium").
3. The scanning section allows the rotation selection and the introduction of losses for small frequency ranges
4. Mirror on Pieso - stabilizing the laser cavity
5. Changing the effective length of resonator - selecting a mode
6. Some etalons can be added to adjust the system to a "single mode" operation

Mode competion - introducing losses for the modes. Some modes experience more losses than the other and get suppressed.



Drawback: There is no possibility to include losses to the involved modes. Both signals are equally favoured because they have the same frequency (they just travel in different directions).

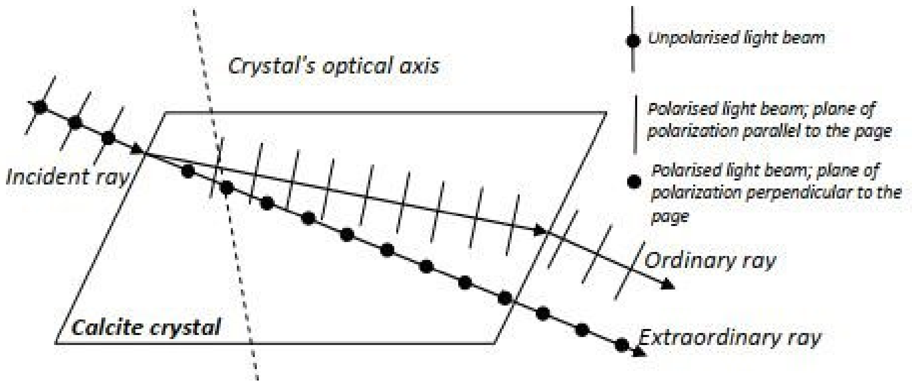
To compensate for the introduction of losses in the system a "optical diode" is introduced. It combines crystal double refraction and Faraday Effect - rotation of polarization by magnetic field.



It can control the direction of the polarization, and filter one of the traveling waves.

★ *Single mode tunable laser was demonstrated during a video.*

Double refraction = birefringence

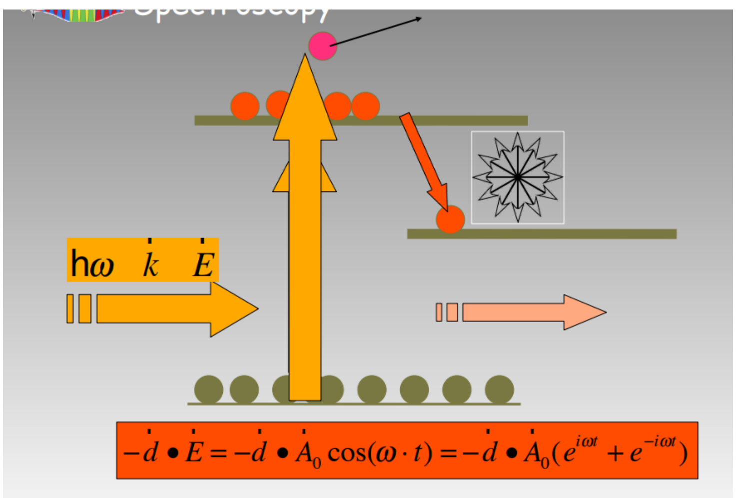


Principle Methods of of Laser Spectroscopy

For laser spectroscopy we need high precision of single mode laser
(extremely sensitive → 1 atom/particle)

- The system of interest is disturbed by our laser and changes the populations of its different levels.
- After we change the population of the system with the laser the system's <u>response</u> to the change of population has to be analysed if we want to investigate the material of the system (spectroscopy) or can be used e.g. for surgical operations (response can be complicated).
- Ways how the system's response to the population changes can be measured:
  - Excited electrons leave the atom -> the system is ionized (pink electron in figure below)
  - Spontaneous emission by excited electrons dropping back to lower level -> photons can be detected (fluorescence spectroscopy)
  - As the system absorbs light, the intensity of the laser after it travelled through the system can be measured and compared to the intensity entering the system -> low intensity of laser beam after system = high absorption

- → Was the system ionised? (spontaneous emission of a photon to the ground state or another level)
- <u>This excitation is measured counting the spontaneous emitted photons because the laser system has "populated" and excited level.</u>



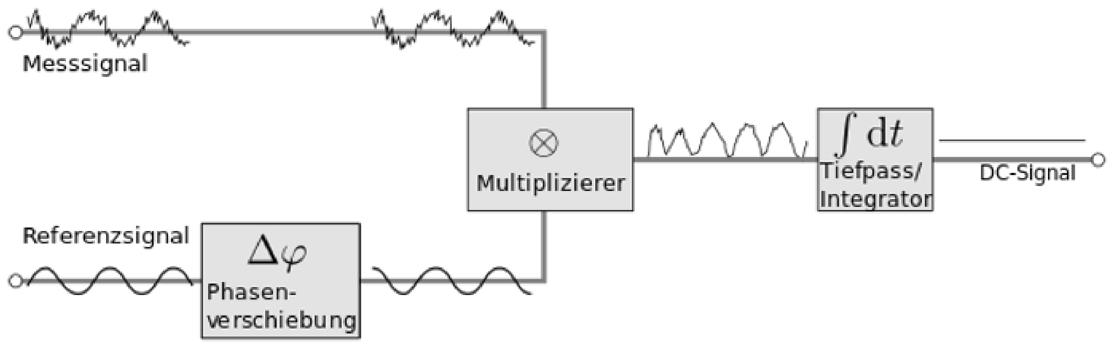
Excitation of the system can be detected by:

- Fluorescence spectroscopy (Tunable laser + detection of spontaneously emitted photon)
- Ionization spectroscopy (the most sensitive method)
- Absorption spectroscopy (resonate excitement lead to absorption, requires lock-in technique)

Hyperfine Structure:

- Doppler free spectroscopy on atomic beams
- Isotopic effect

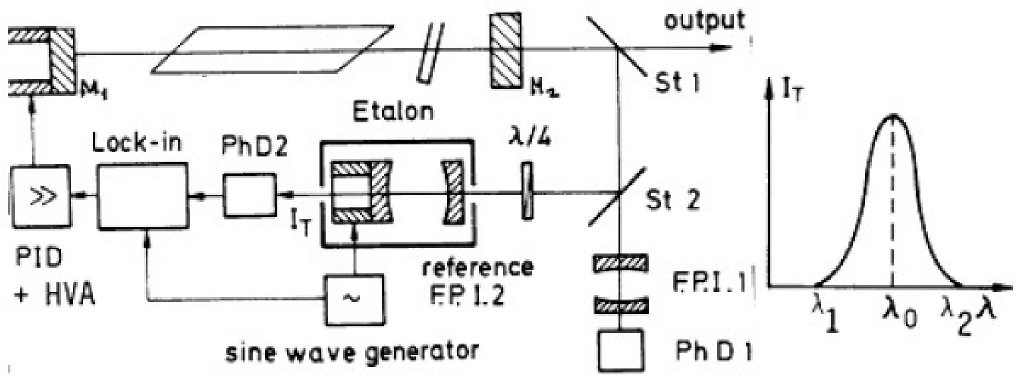
Lock-in amplifier 💛



If frequency of measurement and reference are different, after multiplication (equal to cross correlation) the output is 0.

Similarly this is done with lasers: a reference signal is used and compared to the laser light. If a difference is detected between the signals we know that tuning/change of resonator length is still necessary.

This is all in chapter 3.8 of the 2017 german lecture notes! (Doubt it will be relevant for the test, but it's a common thing in electronics)



Wikipedia: "A lock-in amplifier is a type of amplifier that can extract a signal with a known carrier wave from an extremely noisy environment. Depending on the dynamic reserve of the instrument, signals up to 1 million times smaller than noise components, potentially fairly close by in frequency, can still be reliably detected."

Lecture on 14.12.2021

Spectroscopy - Laser application

Function of Laser: narrow bandwidth → change population of electron states of the sample that we want to analyze, frequency dependent.
1st step : the laser changes the population of electron levels of our sample. The amount of excited electrons depends on the frequency of the (tuneable) laser -> at the frequency where the sample is in resonance with the laser, absorption takes place and electrons are excited to higher level. (With a ultra-short-pulse-laser instead of a narrow-bandwidth-laser, we can observe the time dependent behaviour of the sample instead of the frequency dependent behaviour).

frequency/time resolution.

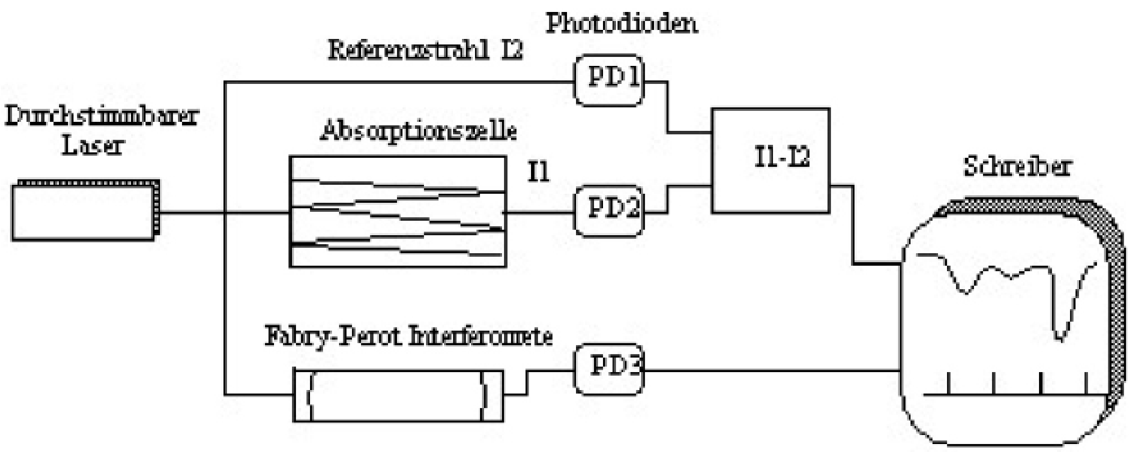
2nd step: detect answer of system: different possibilities, e.g. absorption spectroscopy, fluorescence spectroscopy, …

Classical spectroscopy: Broadband, less efficient because many frequencies present.(?)
If we consider this "At the frequency where the sample is in resonance with the laser, absorption takes place and electrons are excited to a higher level." then it makes sense to take a laser with a narrow bandwidth, so we have all the intensity at the right frequency. So the efficiency is higher.

Absorption spectroscopy

→ How much of initial intensity I_0 is absorbed by sample at specific frequency of the laser. Absorption curve: Dip in transmitted intensity at resonance frequencies.
I_0 is much bigger than the absorbed intensity. → high SNR

$$\alpha(\omega) \approx \frac{I_0 - I_{trans}}{I_0 \bullet x} \qquad (6.3)$$



Increase sensitivity by using lock-in technique: laser frequency or intensity are modulated periodically. → measure small signals hidden in noise.

Components:

Tunable Laser I_0

Absorption cell

Photodiodes or Photomultiplier as detectors before (PD1) and after the absorption cell (PD2), compare their outputs and record. This difference is really small, so light in the absorption cell is reflected back and forth to increase absorption length x.

FPI: When scanning the laser (changing wavelength), output of FPI moves. It's a control to see if mode/frequencies are set correctly.

Estimation of scale we talk about:

- no excitation: ~4 photons/s detected (noise)
- Excited sample: ~100 photons/s detected

Fluorescence spectroscopy

Not absorption is measured but spontaneous emission of analyzed sample.

Much more sensitive than absorption.

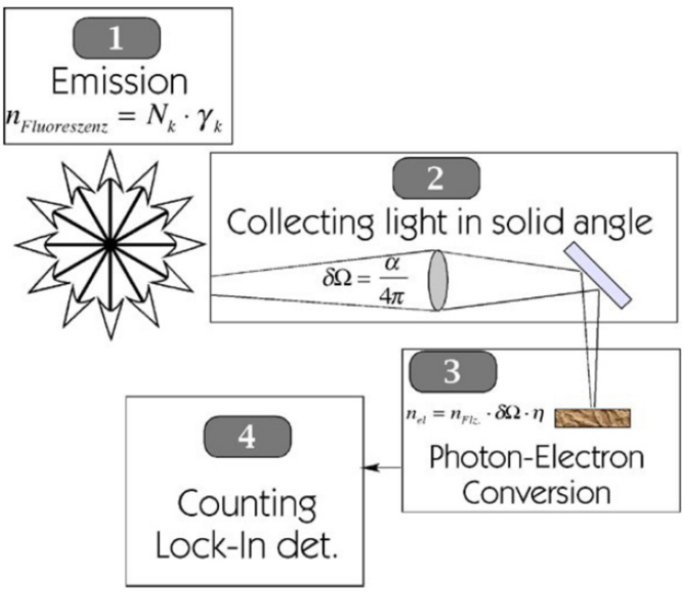
Emission is proportional to population of excited level (N_k). $n_{Fluor} = N_k \gamma_k$

Limitation: detection of emitted light: emitted photons are emitted isotropically (in all direction)

+: absorption/detection in any direction, so also where no laser photons are → low noise

-: can't just detect anywhere.

2. Emitted photons are collected with a lense. The size of the lense (and thus the amount of photons that we can collect) is limited. Ideal state: big lense close to the sample -> the bigger the lense, the higher curvature needed for correct focal point -> can't be that near anymore because of big curvature. -> solid angle $\delta\boldsymbol{\Omega}$ is limited



Detection with Photodiodes/ photo multiplier.

Single mode dye lasers are used: continuous wave.

“We won’t go into detail how to calculate this but let me talk about it for 15min...”, XD

ΔI/I ratio of ≤ 10^14

Doppler broadening (since T ≠ 0 Kelvin, thermal oscillation of atoms) -> the Doppler Broadening can be much more significant than the frequency of the laser -> we have a problem

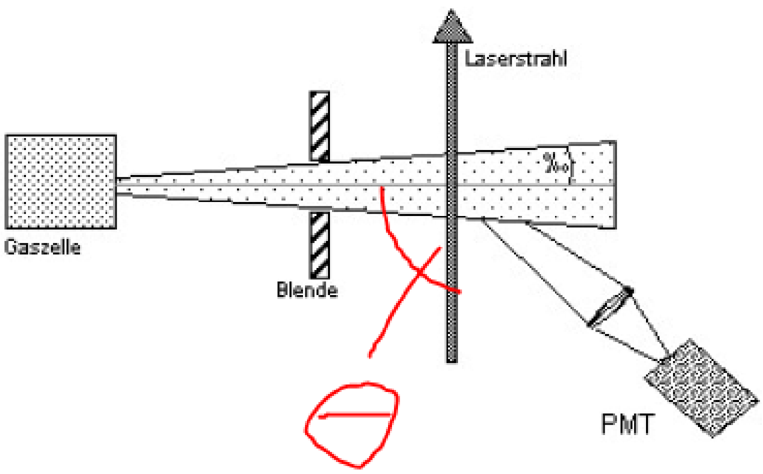
Method to avoid:

Doppler-free-spectroscopy

Instead of sending laser beam through a gas cell (where gas particles move in all directions due to thermal activity) we produce a gas beam (gas-cell with small hole, see figure below). We cross this beam with laser in perpendicular direction ⟶ Doppler-effect vanishes becauses movement of atoms dominant in the direction of the beam.

$$\delta v = v_0 \frac{v}{c} \cos(\vec{k}\vec{v}) = v_0 \frac{v}{c} \cos(\theta)$$

because theta = 90°; cos(90°)=0



Velocity of particles can be measured by using other angles of the laser (Θ)

END of content for Test 2.

OLD TEST PRACTICE

1. Excimer LASER.

1) Mark correct answers (multiple)

The excimer laser is a gas laser

The excimer laser is a pulsed laser

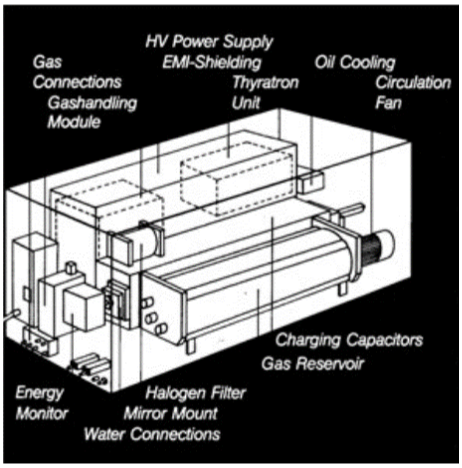
2) Explain the principle and the important parameters, types and specifications of an excimer laser. Discuss important applications (what and why)

Important parameters of the Excimer Laser:

- Operational in the UV spectrum wavelengths
- Because of its large beam cross-sections, the electric field distribution typically consists of many transversal modes and the intensity distribution is inhomogeneous.
- An excimer (Excited Dimer) is a molecule that can only exist in an excited state.
- The amplifier medium (the dimers) requires short, intense discharge pulses, which require sophisticated electronics and electrode arrangement
- The electronic ground state (also both molecular partners in the ground state) is anti-bonding.
- **When the molecule partners are excited, they can form an excited dimer-molecule which, in the case of suitable molecules, can disintegrate into the ground state through dipole light emission, where it dissociates immediately. This scheme represents an ideal four level laser, because the basic state is initially not occupied and is immediately "emptied" again.**
- Could be used as a pump laser for dye lasers due to its short wavelengths (157-353 nm).

Principle of the Excimer Laser:

1. The gas molecules are used as a laser pump
2. Electron discharge and fall from the negative electrode and they will interact with the medium and pump molecules → "putting molecules in their excited state" (ex: KrF is unstable and can randomly produce a photon)
3. The amplifier medium (dimers in a large volume) needs short intense discharge pulses that require sophisticated electronics and electrode arrangements.
4. Produced (secondary) and initial photons travel in the same direction inside the LASER cavity.
5. These photons pass through a series of mirrors and eventually pass through a convex lens to sharpen the beam into a point
6. This point source hits the target and creates plasma (which can get hotter than the surface of the sun T= 10,000 °C)



134.154 Lasers in Physics, Chemistry Biology and Medicine

Types and Specifications:

Possible laser media:

- ★ ArF (193 nm)
- ★ KrCl (248 nm)
- ★ XeCl (308 nm)
- ★ F2 (193 nm)
- ★ XeF (351 nm)

- The corresponding laser gases (Ar, F, Xe, Cl , etc.) are in a buffer gas. He or Ne are among the commonly used ones.
- Gases are susceptible to strong chemical changes because of the intense UV radiation.
- Required in a large volume → The outputs are "large" beam cross-sections. Typically around 1 cmx2cm

Most Important Applications:

Medical Appliances: Refractive corneal surgery: (e.g. ArF) with pulse durations of 10 – 100ns) → Photoablation.

Fun fact: Kansas State University pioneered study of Excimer Laser as basis of LASIK

- Power Density: 10^7-10^10 W/cm2
- Exposure time: < 1 µs
- Pulse duration: 10-100ns
- Physical effect: Excitation + dissociation

Semiconductor appliances: Micromachines (MEMS). Today, thanks to semiconductor device fabrication these small arrangements of machines are able to build small devices.

Also used as a pump laser for dye lasers.

Why:

- It delivers pulses in the UV with MW per pulse (typically around 10-20 ns), which is suitable for semiconductors and medical applications.
- Incredibly precise → "the ability to focus a beam as small as 0.25µm micrometres and capable of removing 0.5% of a human hair's width at a time" (From: Patent Drs. Blum, Srinivasan, and Wynne "Far ultraviolet surgical and dental procedures" 1988)

2. Click below the correct answers concerning Absorption Spectroscopy (AS) as compared to Laser Induced Fluorescence Spectroscopy (LIF)

LIF is more sensitive than AS

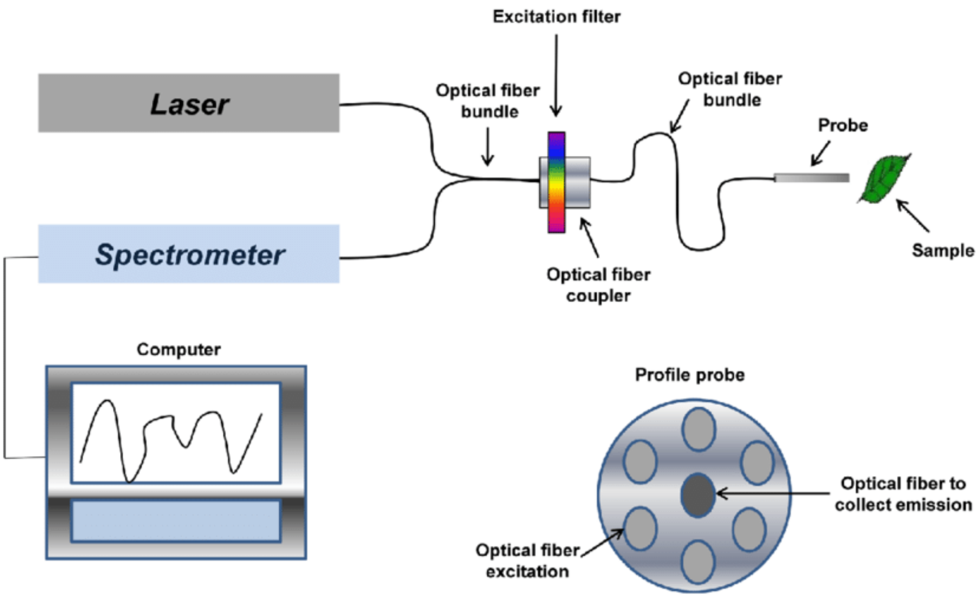
In LIF, in general the detected light is much broader (frequency spectrum) than the laser light

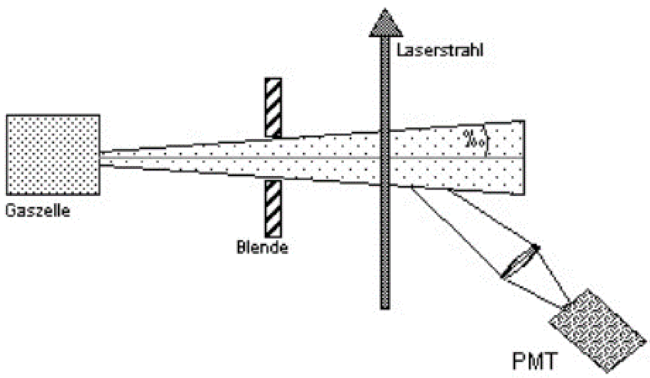
AS and LIF can be performed with pulsed and CW lasers as well

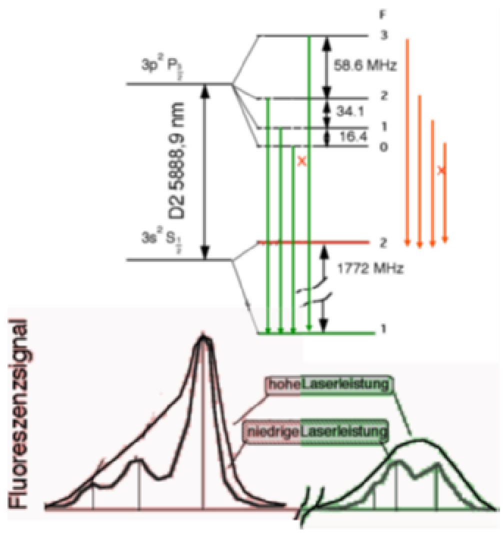
Sketch a possible LIF experiment explaining all components of the sketch and explain the resulting measured data (also in a figure)

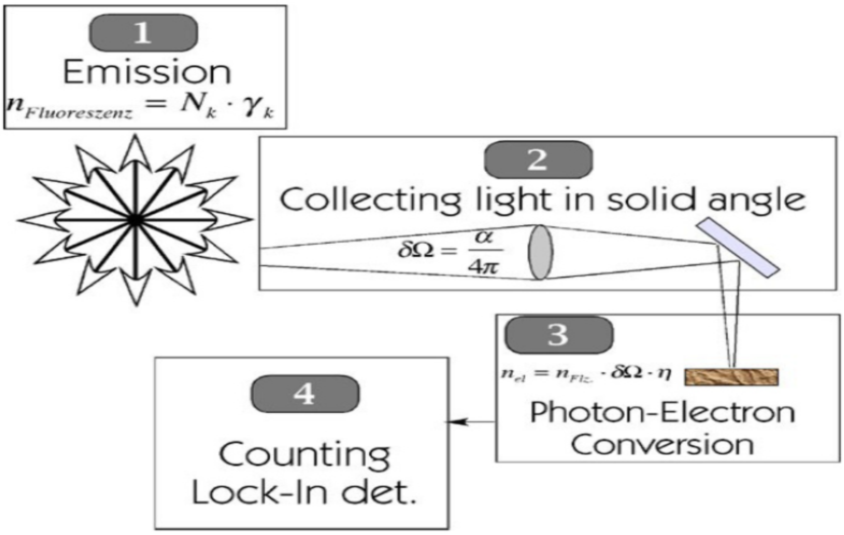
- Definition: WIKI: *"Laser Induced Fluorescence is a spectroscopic method in which an atom or molecules is excited to higher energy level by the absorption of laser light followed by spontaneous emission of light"*

- Consequence of the Doppler effect on the excitation geometry. Which is observed on the frequency shift, the particle velocity and the angle between the direction of the particle velocity and the direction of the momentum of the photons.
- <u>Applications:</u> Detection of purity, optical tumour diagnosis, imaging of paleontological specimens, detection and quantification of DNA sequencing, trace protein, measurement of ion functions and velocity space diffusion and convection of plasma.
- <u>How?</u> Selection of wavelength at which the selected intel of observation has its largest cross-section
- <u>Why select this technique?</u> 3 orders of magnitude better than the UV absorbance spectroscopy.









3. Suppose that you have a laser dye that allows amplification of light between 520 and 580 nm. How many laser modes can oscillate (in principle), if no mode competition takes place and the resonator has a length of 0.5 m (Velocity of light c=3x10^8 m/s)

$$Number\ of\ Modes\ Oscillating\ [n] = Nc/2L$$

$$N = 2L(1/\lambda_1 - 1/\lambda_2)$$

n =198347

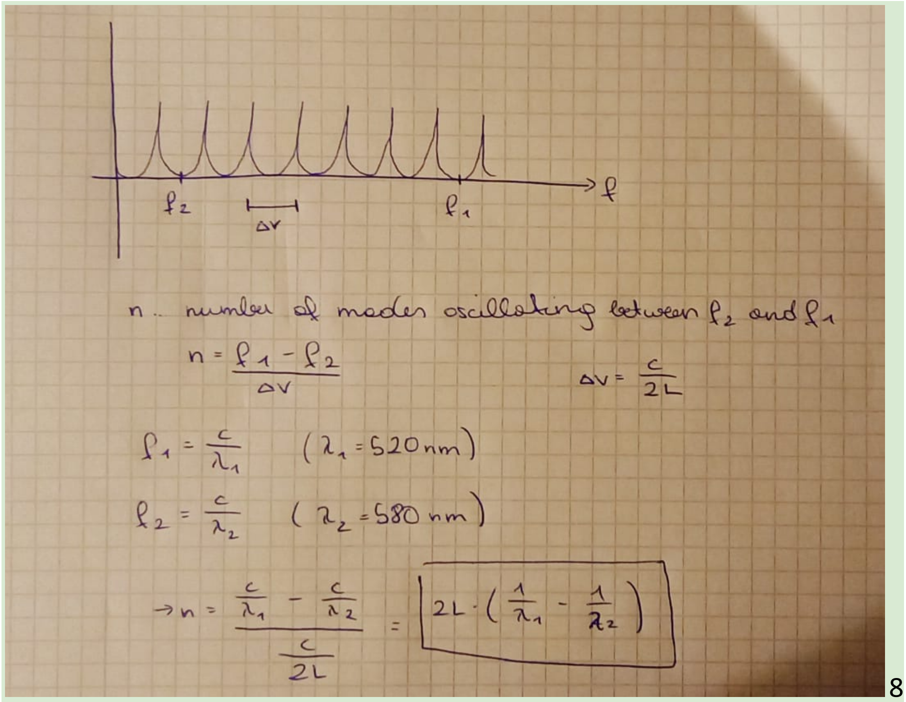
From WhatsApp group

$N = 2L(1/\lambda_1 - 1/\lambda_2)$ = 198939, close enough?

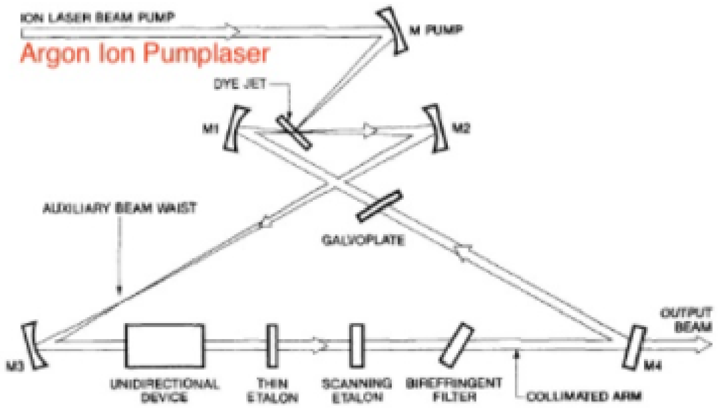
→ difference of number of modes of upper and lower limit (why?)

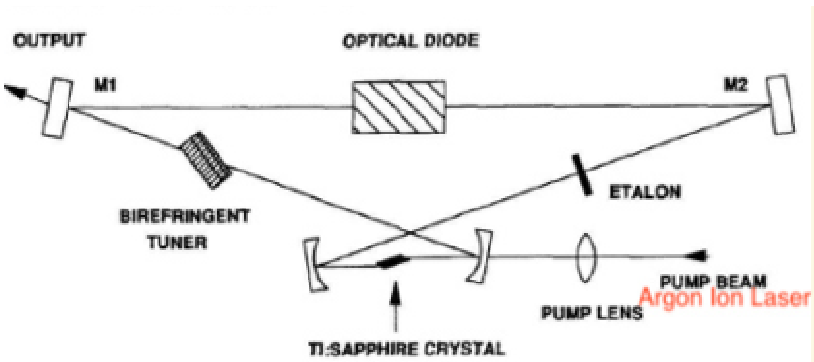
In general $N = L/(\lambda/2) = 2L/\lambda$

Rosas explanation:



4. In the following different tunable LASER schemes are shown. Which ones can operate in single mode operation?





Explain what is needed to scan a basically "monochromatic" single mode operating laser. What defines the maximal scan width? Explain the basic physics of the elements needed.

A laser can be "tuned" to operate in single-mode and yield a monochromatic output. Monochromaticity refers to the "colour purity" in the case of a laser, the spectral bandwidth of the laser < 1 MHz (sometimes referred to as the laser linewidth). Any number of longitudinal modes can

lase provided they lie within the window where the gain exceeds the loss. The number of these lasing modes (*N*) is given by the gain bandwidth divided by the resonator frequency spacing: $N=B/\Delta\nu$
This is done by “shifting” the active, oscillating laser mode on the frequency axis (changing the length of the resonator).

Remark: shifting the laser mode alone is not enough, since it would move out of the maximum of the transmission curve of the frequency-determining etalon and thereby promote a mode jump. This is why it is necessary to readjust these elements with single-mode lasers.

The etalon mode is made to overlap with one of the laser cavity modes and only a single longitudinal mode lases. The spectral width of this mode is controlled by the reflectivity and stability of the cavity which is quantified in the cavity’s quality factor *Q*

How can this be achieved?

- Mounting one of the resonator mirrors on a piezo element
  Physics of the element required (piezo element) → voltage leads change in resonator length
  OR
- Inserting a small rotatable glass (quartz) plate approximately at the Brewster angle in the resonator. Here the effective resonator length is changed by changing the path of the light in the material.
  Physics of the element required (rotable quartz) → It must be installed at the Brewster's angle to minimise reflection losses.

Note from Andreas:
Single Mode can be achieved by using a ring resonator, leading to high mode competition. Ring resonator leads to two moving waves, using an optical diode one of them is inhibited.
Scan width is defined by the emission spectrum of the dye (laser medium).
To have single mode and change wavelength of the laser first coarse (prisma, birefringent filter) and then fine (change of resonator length via piezo element, rotable quartz) tuning is necessary.
Afterwards etalons in the resonator may have to be adjusted also.

5. How would you define Mode Competition? (one correct!)

Modes with low losses use up all the potential from amplification and thus cause modes with higher losses to fall below the threshold for lasing.

6. Contrary to radiation sources with broad emission continua used in conventional spectroscopy, tunable lasers offer radiation sources in the spectral range from the UV to the IR. With extremely narrow bandwidths and with spectral power densities that may exceed those incoherent light sources by many orders of magnitude. Therefore: (only one is correct!)

- No monochromator is needed, since the absorption coefficient and its frequency dependence can be directly measured from the difference between the intensities of the reference (incoming) beam with and the transmitted beam. The spectral resolution is higher than in conventional spectroscopy. With tunable lasers it is only limited by the linewidths of the absorbing molecular transitions. Using doppler-free techniques, even sub-Doppler resolution can be achieved.

- Because of the high spectral power density of many lasers, the detector noise is generally negligible. Intensity fluctuations of the laser, which limit the detection sensitivity, may essentially be suppressed by intensity stabilisation. This furthermore increases the signal-to-noise ratio and therefore enhances sensitivity.

7. Ring Lasers are often used instead of linear LASER resonators. Select the correct statements below. (More than one correct answer, a wrong answer reduces the number of points)

The mode spacing in a linear laser, as well as in a ring laser is c/(2L)

In most cases ring lasers are used to realise single mode lasers. The mode competition in a ring laser is more efficient than in a linear cavity.

8. Describe the principle of an ultra-short laser system and what you need for realising an ultra-short laser system. Sketch!

The first step in generating ultra-short pulses is to take advantage of the laser's mode structure. Due to the molecular nature of the active medium, the gain profile of most lasers will be inhomogeneously broadened. Accordingly, a large number of modes will generally oscillate.

9. In the following figure the absorption dependencies on wavelength for some human "materials" are shown. Fill into the figure below a useful laser at the appropriate wavelengths. (Type of lasers and its wavelength must be given), which can be used for treatment of at least one of the three issue types shown. You must also indicate, for which tissue the laser can be used.

The different absorption maxima of different types of tissue (e.g. skin, blood, etc.) are important for practical application, which enables different tissues to be influenced selectively by selecting the wavelength.

Laser radiation that strikes tissue is partly reflected and another part is absorbed in the tissue. A good statement about the radiation to be expected in the tissue can be obtained from measurements of the reflection of the laser radiation on the tissue surface.

To increase the effectiveness of the laser radiation through increased absorption (or lower reflection losses), for example, the corresponding part of the skin can be colored with a dye.

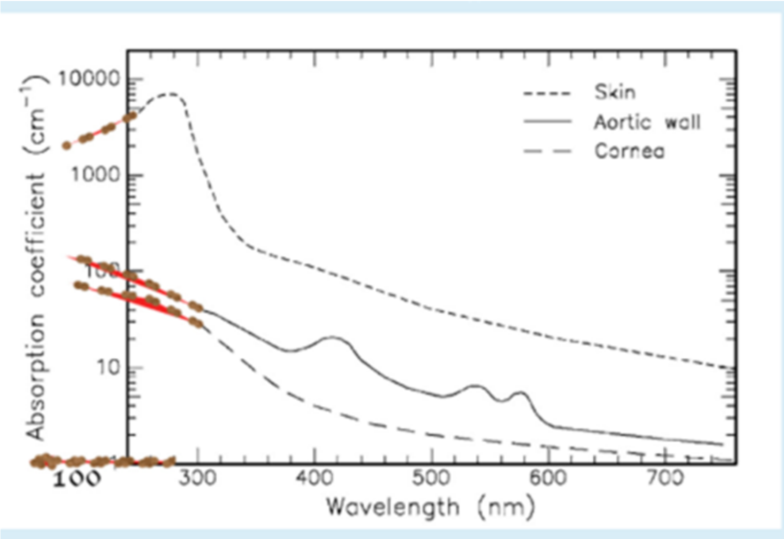
When increasing the laser power or with extremely high absorption of the laser radiation, in many Cases tissue ablated by the energy supply.

From this it follows that an ablation of the tissue then causes the least damage occurs when the process of "photoablation" is the main cause of the ablation. This will be generally a short wavelength (high photon energy) is required as this is used to break up of the molecular bonds is required. An important candidate for laser surgery is therefore the Excimer laser, which delivers intense, short-wave radiation.

- Der Argonionenlaser wird hauptsächlich vom Blut absorbiert. Er eignet sich daher besonders zum Koagulieren. Der Argonlaser zeichnet sich auch durch eine geringe Reflexion an der Haut aus.
- Der CO_2 Laser zeichnet sich durch eine hohe Absorption seiner Strahlung im Wasser des Gewebes (90% Wasser) aus. Deshalb eignet er sich zum Schneiden und Vaporisieren, vorausgesetzt dass die damit verbundene hohe thermische Belastung des Gewebes nicht stört.
- Der Excimerlaser (193, 248, 308 nm) für die schädigungsfreie Abtragung von Gewebe.
- Verschiedene Infrarotlaser wie der Er-YAG (etwa 4μ), die besonders gut von Wasser absorbiert werden und mittels „explosiver Desorption" eine relativ schädigungsfreie Abtragung ermöglichen.
- Die Strahlung des Nd-YAG Lasers dringt wegen der relativ geringen Absorption besonders tief in das Gewebe ein. Durch die gleichmäßige Verteilung der Energie auf einen großen Gewebebereich eignet er sich besonders für die Koagulation ohne unerwünschte Abtragung des Gewebes.
- Der Farbstofflaser zeichnet sich dadurch aus, dass er einen großen Wellenlängenbereich überstreicht und selektiv abstimmbar ist. Dadurch kann er prinzipiell für verschiedenartigste Aufgaben eingesetzt werden, vornehmlich aber für Photoaktivierung, wo relativ kleine Intensitäten benötigt werden.
- Femtosekundenlaser verschiedener Wellenlängen für effektive, störungsarme Ablation.

Translation:

- Argionlaser: mainly absorbed by blood, therefore useful for coagulation. Skin hardly reflects Argionlaser
- CO2 Laser: highle absorbed by water in tissue: can be used for cutting and vaporizing, if the high thermal load produced doesn't affect the tissue
- Excimerlaser: used for damage-free removal of superficial tissue layers
- Infrared lasers like Er-YAG absorbed very well by water -> used for relatively damage-free erosion of tissue by "explosive desorption"
- Nd-YAG: penetrates deeply into tissue due to small absorption. Even distribution of energy on big tissue areas -> useful for coagulation without erosion of tissue
- Dye-laser: tuneable for a broad spectrum of wavelengths. Can be used for different applications, principally for photo-activation, where relatively small intensities are required
- Femtosecond-laser: different wavelengths for effective ablation with little disruptions



Absorption coefficient (cm⁻¹)
10000
1000
10
100
300
400
500
600
700
Wavelength (nm)
Skin
Aortic wall
Cornea