Part 1: Light and the Source of Light

- Bioluminescence (Difference between Fluorescence and Phosphorescence):
  - **Fluorescence:** emits light *immediately after photon absorption* *(immediate flash)*; light emission stops when excitation stops.
  - **Phosphorescence:** emission *delayed with excitation and stays for a while* once the excitation source is removed; lower 'glow in the dark' appearance.

- Phase velocity $c = \lambda \cdot f$, change of velocity of light in the medium $c' = c/n$ (c...speed of light in vacuum), material constant $n = \sqrt{\varepsilon\mu}$

- The law of refraction: $n_1 \sin(a_1) = n_2 \sin(a_2)$

- Visible light: White light = broad spectrum of light (total reflection) vs. Black light narrow spectrum of light (total absorption).

- Fourier Principle: $\Delta E \cdot \Delta t = 1$
  $If\ \Delta t \to 0,\ then\ \Delta E \to \infty$, in other words, there will never be monochromatic Supershort frequency lasers

Spectroscopy: Determination of a physical quantity as a function of energy (wavelength), for example, transmittance of light by some material (usually unknown) → Tool for analysis to distinguish and characterize spectra

- "Study of the absorption and emission of light and other radiation by matter"
- High Resolution Spectroscopy provides a better understanding of nature
- Measured depending on photon's energy (how the amount (intensity) of photons changes depending on their energy (frequency), after interaction with some matter)
- The result is a spectrum plotted as the function F(x) = I(E), I - intensity, E - energy
- Time resolved ultra-short (pico and femto) laser spectroscopy (huge intensity in short Δt)

What is the basic quantity of light?

Electric field vector $\overline{E}(r, t)$, time and space dependent. Whatever you do with the laser, the main process is that the electric field exerts a force on a charge in irradiated matter.

What is the source of all light?

Light is produced by an oscillating dipole: positively charged positively charged nucleus + electron, which jumps within states/energy levels.

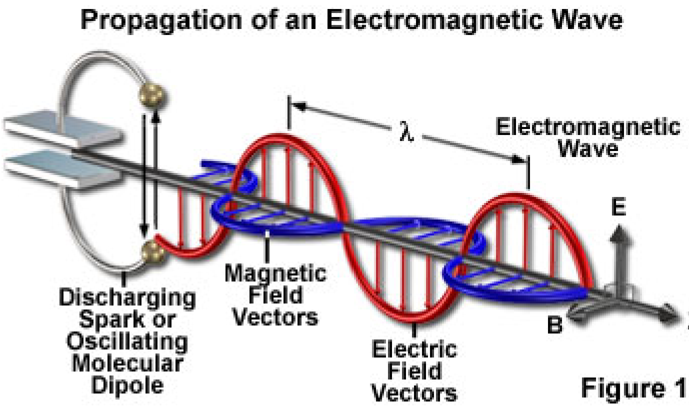
Electron drops during some short time $\Delta t \to \Delta E\ or\ \Delta f$ of emitted light ⇒ The light is never monochromatic.

Energy difference between energy states of an electron is released as an electromagnetic wave (local dipole radiation $\Delta E = h\nu = hc/\lambda$).

What is light?

An electro-magnetic wave: plain $E(x,t) = B\cos(\omega t \pm kx) + C\sin(\omega t \pm kx)$ or spherical wave $E(r,t) = \frac{C}{r}\cos(\omega t \pm kr)$ ⇒the intensity decays as the area ($A = \pi r^2$) of a sphere for a spherical wave $I \sim 1/r^2$, $E \sim 1/r$ ($I \sim E^2$) (emission in all direction generates a spherical wave)

ged nucleus + electron, which jumps within states/energy levels. Electron drops during some short time $\Delta t \rightarrow \Delta E$ or Δf of emitted light ⇒ The light is never monochromatic. Energy difference between energy states of an electron is released as an electromagnetic wave (local dipole radiation $\Delta E = h\nu = hc/\lambda$).



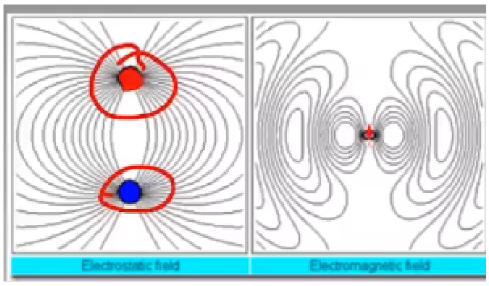
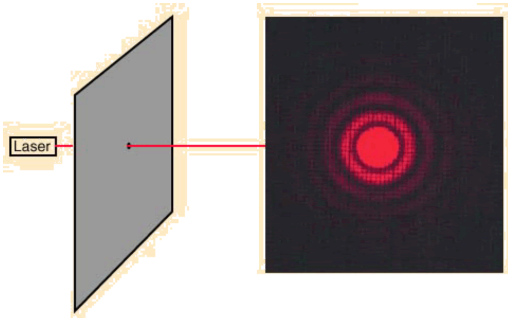


Figure 1

Can a sharp beam of light be produced?

It is not possible. Because when a sharp beam is produced with a pinhole the diffraction (beam gets wider after the pinhole). As a consequence the <u>wave-particle model</u> is then required to describe the propagation of light and interference.



Explained by the wave model of light.

Why does an electron stay in its orbit and doesn't fall on the nucleus?

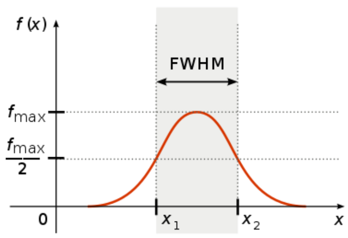
Due to Newton's second law: F centrifugal = F attraction, (F centrifugal $\sim v_e^2$)

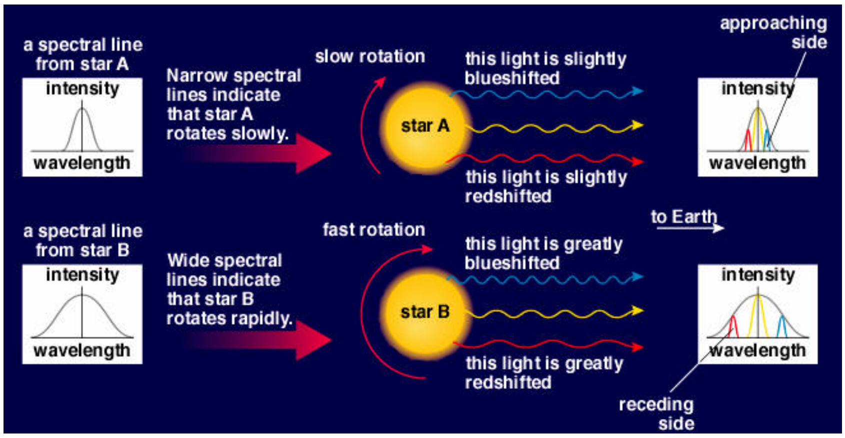
F attraction: positively charged nucleus attracts a negatively charged electron (Coulomb force)

Why does light experience Doppler broadening?

At rest, a Hydrogen atom would have an emission at λ_H = 656 nm (natural line) or equivalently at a frequency of λ_H = 4.5 × 10 (17) Hz. If the molecules are moving towards the observer, the frequency will go up due to the Doppler effect, and if they are moving away, it will go down. Finally, all the atoms move with some speed (Boltzman distribution), which leads to Doppler effect, so the half-width (Full width at half maximum = FWHM) of the spectra is larger than the natural line.

https://youtu.be/h4OnBYrbCjY a cool video for the Doppler Effect :)





Part 1: Summary

- ★ The source of all light is an oscillating dipole
- ★ Impulse of light is connected to Δt from Fourier principle - lifetime of the dipole radiation due to transition of an electron between two states
- ★ Atoms are in constant movement, so the light emitted experiences an inherent doppler effect
- ★ Absorption and emission of light are described with the <u>particle</u> model
- ★ Propagation of light and interference are described by the <u>wave</u> model

Part 2: Nature of Light

Atoms and Matter:

Bohr's atomic model is only intuitive, in reality this is approximated via quantum mechanics: the state of an electron is not characterized by a certain orbit, but by a wave function Ψ

$||\Psi|| = \Psi^2 \Rightarrow$ probability to find an electron in a certain region

Quantum theory:

Light can be described using: geometrical optics + waves + photons (particle and wave dualism)

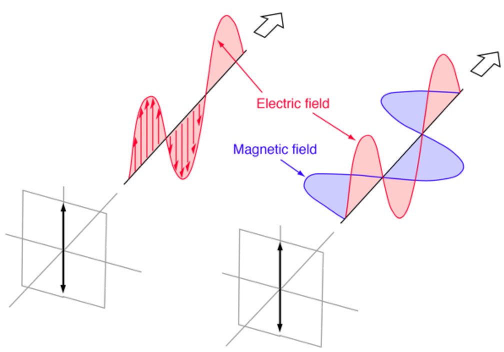
Energy (E) of quanta or photons moving at the speed of light:

$$E = hf = \frac{hc}{\lambda}$$

1eV = 1.602 x 10 (-19) J, h = 6,626 x 10 (-34) Js - Planck's constant

Energy Density (ρ): $\rho = hf * \phi$, photon density $[\phi]$= photons/<u>volume</u>

Power density (I): $I = hf * \varphi$, current density of the photons $[\varphi]$= photons/<u>time area</u>



Wave Optics:

Light is a transverse electromagnetic wave: an oscillating electric field (E) + magnetic field (H), which vibrates periodically and at the same frequency.

The direction of propagation is perpendicular to E and H, also $E \perp H$. The example in the picture is a linearly polarized light.

The light of most light sources (sun, incandescent lamp, gas discharge lamp) is unpolarised and can be interpreted as a statistical mixture of waves with all possible directions of polarization.

Energy Levels:

1. Can be found from $H_o\Psi_i = E_i\Psi_i$ - the Schrödinger equation, E_i - eigenvalue of Ψ_i

2. Energy of an electron on the level n: $En = -Ei/n^2 \Rightarrow$ Bohr formula for Hydrogen or hydrogen-like atoms: nucleus + 1 electron
   - Ei = 13,6 eV - Ionization Energy, En = Energy values, n = quantum number
   - Negative sign indicates that the inner orbits have less energy than the outer ones
   - E1 = − Ei = − 13,6 eV   Hydrogen Ground State

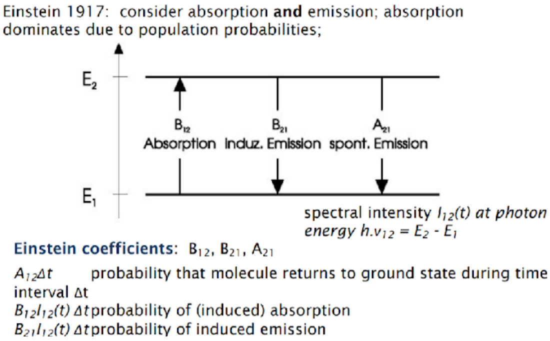
Part 3: Interaction of Light with Matter

Emission and Absorption of Light:

At the beginning all electrons are at the ground state ⇐ Boltzman's statistics, normal temperature.

Then we can add an outer field = e/m wave, which may cause induced absorption, if its energy (frequency) is high enough: $h\nu = E_2 - E_1$. If so, an electron uses the energy of the outer field to jump upwards, from the ground level E_1 to excited level E_2.

Beer's law:
$dI = \alpha \cdot I \cdot dz$, α- absorption coefficient (proportional to Einstein coefficient), I - intensity



Einstein Coefficients:

- The Einstein coefficients describe the probability of induced absorption / induced emission / spontaneous emission transition per time (Einstein Coefficient = 1/(per unit time*[energy density])).
- The coefficients are material dependent.

Natural Frequency:
"When an oscillator is driven at a frequency corresponding to a particular natural frequency, the oscillation is said to be in resonance. Energy is most efficiently supplied to an oscillator when the external driver acts at the resonance frequency."

Natural Oscillations → absorb or release energy like: $W = q \cdot h\nu$, q - number of photons

1. Induced Absorption

When the radiation field induces $E_1 \rightarrow E_2$ = a photon is absorbed $h\nu$.

Rate of induced absorption:

1) **(electron/time):** $\frac{\partial N_2}{\partial t} = R_{12} = B_{12} \cdot \rho(\nu) \cdot N_1$, B_{12}- Einstein Coefficient; $\rho(\nu)$ - energy density of incident radiation, N_1- number of electrons in the ground state.
2) **(photon/time):** $P_{12} = B_{12} \cdot \rho(\nu)$, B_{12}- Einstein Coefficient; $\rho(\nu)$ - energy density of incident radiation

*Atoms are in the excited state for a short period of time (around 10 x (-8) seconds), then induced or spontaneous emission will happen

**During each act of absorption an atom takes 1 photon from their population in the radiation field, if photon frequency coincides with the atom's natural frequency

Probability à la Wolfgang Husinsky:
The probability P_{12} (AKA dipole operator between the two lines) that a atom absorbs (emits) one photon per second is proportional to the number of photons ($given\ by$: $h\nu$)

Dipole Operator:
The energy of interaction E, between a system of charged particles and an electric field is given by the scalar product of the electric field **ϵ** and the dipole moment **μ**. Both of these quantities are vectors.

$$E = -\mu \cdot \epsilon$$

2. Induced Emission

When the radiation field induces $E_2 \rightarrow E_1$ = photon is emitted $h\nu$.

Rate of induced emission:

1) **(electron/time):** $\frac{\partial N_1}{\partial t} = R_{21} = B_{21} \cdot \rho(\nu) \cdot N_2$, B_{21}- Einstein Coefficient; $\rho(\nu)$ - energy density of incident radiation, N_2- number of electrons in the excited state
2) **(photon/time):**$P_{21} = B_{21} \cdot \rho(\nu)$, B_{21}- Einstein Coefficient; $\rho(\nu)$ - energy density of incident radiation

The atom is less excited, the process is similar to the damping effect

3. Spontaneous Emission

When an excited molecule emits a photon independent of the external field. It depends only on the structure of the molecule, E_2 to E_1 transition.

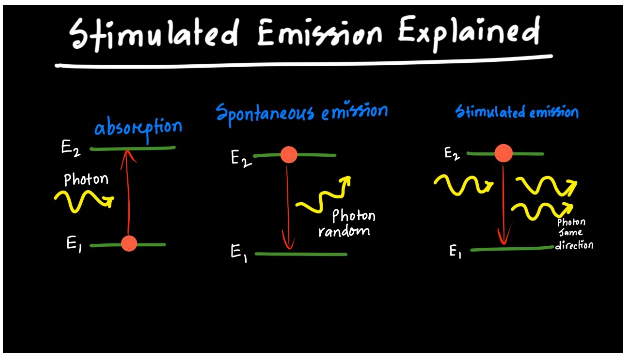
Rate of spontaneous emission:

1) **(electron/time):**$\frac{\partial N_1}{\partial t} = R_{12}\ (spontaneous) = A_{12} \cdot N_2$, A_{12} - Einstein Coefficient, N_2- number of electrons in the excited state
2) **(photon/time):** $P_{12}\ (spontaneous) = A_{12}$, A_{12} - Einstein Coefficient

*What is the source force of spontaneous emission?
The Vacuum field/ Boson field there is a probability to jump without an external force.

**Dominant @ short wavelengths (gamma to IR radiation). At large wavelengths (micro, radio wave region) spontaneous emission is of no importance, only induced emission (and absorption) dominates.

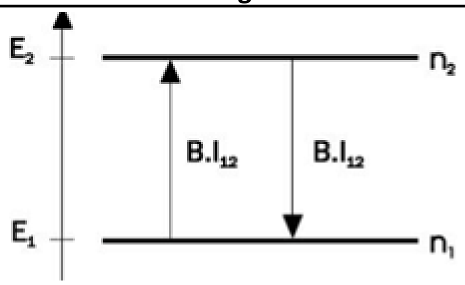
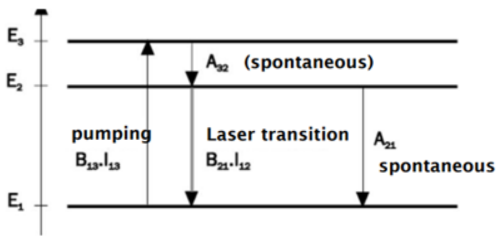
Stimulated Emission	Spontaneous Emission
Excited atom is **induced** to return to the ground state by external e/m field, thereby resulting in **two photons** of same frequency (incident + new)	Excited atom returns to the ground state thereby emitting a **photon**, **without** any external e/m field
Emitted photons move in the **same direction**	Emitted photons move in **all directions and are random**
Radiation is highly intense and coherent (waveform and frequency are identical).	**Radiation is less intense and is incoherent**

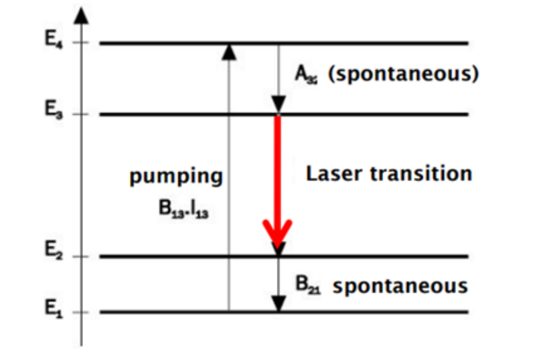


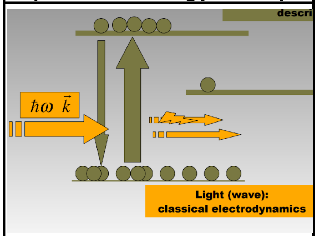
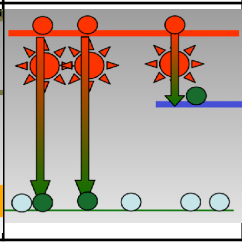
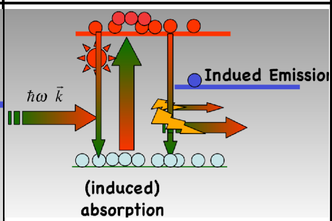
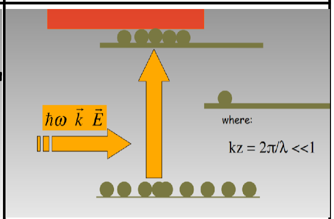
Part 3: Summary

Phenomena	External E field required?	Level of Interaction	Einstein Coefficients
Induced Absorption	YES	E1⟶ E2 UP	B_{12}
Induced Emission (coherent)	YES	E2⟶ E1 DOWN	B_{21}
Spontaneous Emission (incoherent)	NO	E2⟶ E1 DOWN	A_{21}

Part 4: Three energy levels system

Levels	Image	Einstein Coefficients	Pumping
2		$B_{12} = B_{21}$	Intensive illumination. Same amount in the levels n_2=n_1.
3		$B_{13}\,\rho(\nu)$= Pumping A_{32} = Spontaneous $B_{21}\,\rho(\nu)$ = Laser Transition A_{21}=Spontaneous	**Population inversion!!** Performed at a wavelength other than the lasing wavelength.

4		$B_{13}\rho(\nu)$= Pumping A_{32}= Spontaneous B_{21}= Spontaneous	Decoupling the lower laser level from the ground state. Most lasers (e.g., Nd: YAG, CO_2 laser) are of this type.

Semiclassical Approach (Discrete energy levels)	Three level system	Three level system	Dipole interaction
			
Where: k ⟶ Wavevector of the photons, w ⟶ Angular frequency of the incoming wave $(2\pi\nu)$ $\hbar$⟶ *Reduced Planck's Constant* $(h/2\pi)$, E ⟶ Electric field			
$h\omega, \bar{k}$	$h\omega, \bar{k}$	$h\omega, \bar{k}$	$h\omega,\ \bar{k},\ E$
From E1 to E2 Various eigenstates that the electron can occupy based on the Schrodinger Equation **Always more particles at the ground state.**	From E2 to E1, provided that there is a transmission via a dipole moment. Only spontaneous emission.	When there are **more electrons in ground state than in E2**	**The electric field is constant amongst the interaction.**

Rate equation:

Description of the <u>incoherent transition</u> of the system from Boltzmann's thermodynamic equilibrium to the time-independent state of equilibrium under the action of radiation.

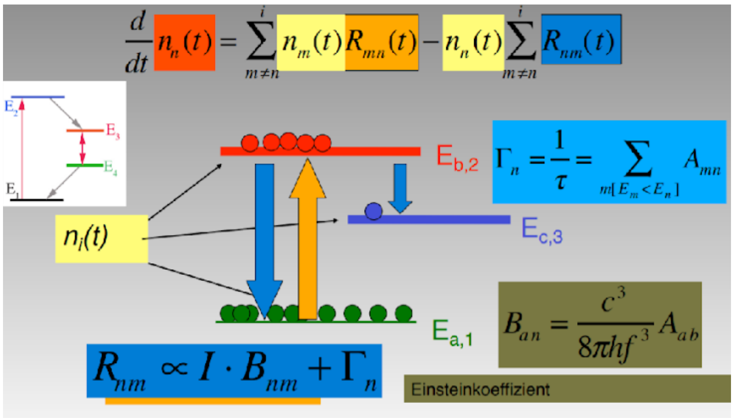
*<u>The incoherent case corresponds to the classic superposition of the measurable quantity</u>, i.e. <u>here the population of the different energy levels (with electrons)</u>. Possible interferences of the states (wave functions) are neglected from the start.

Characteristics:

- <u>Used for steady state (if we wait long enough, which may not be reachable for pulse-lasers)</u>

- Operates with “measurable“ occupation numbers (*number of electrons at different energy levels*)
- Numerical solution possible

n(t) - the probability to find electron in a definite energy state:



Part 5: Components of a LASER

LASER = Light Amplification by Stimulated Emission of Radiation
*Invented by Charles H. Townes and Arthur L. Schawlow @ USA

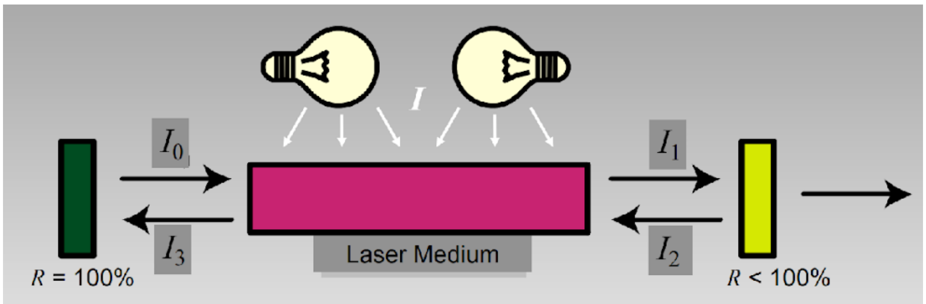
- Smallest → only visible with a microscope → thousands can be built on semiconductor chips.
  Example: Femtosecond range laser
  Example: Optical tweezers → manipulate organelles inside a living cell //
  Slow down the high-speed motion of atoms to hold them into traps.

- Medium: Material processing (laser cleaning of corroded coins, wavelength is relevant). Example: 532 nm (8ns) laser

- Biggest → able to consume the electricity of an entire small town.
  Ex: Free electron laser

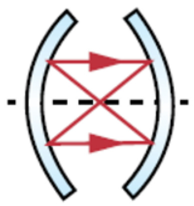
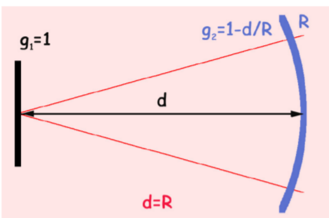
Properties of laser:

- Capable of material alteration:
  - Industrial procedures (car painting)
  - Medical Applications (eyes and cutting and coagulation scalpel)
- Unsurpassed medium for communication (all communication signals in the world could be packed in one laser beam)
- Optical precision → often used by the military to “target” a weapon aim



a) <u>Optical Resonators</u>: Two opponent parallel or curved mirrors. It couples and amplifies the light radiation
b) <u>Laser Medium</u> *(Gain is a function of the medium)*: Determines the spectral emission of the radiation (similar to tuning an instrument)
   - *Broadening of the medium could be due to the natural linewidths*
c) <u>Energy Pump: (flash lamp, gas discharge, or another laser) generates an occupancy of one or more energy levels in the laser medium that deviates extremely from the thermal equilibrium Brings the laser to population inversion</u>
d) <u>Amplifying Medium (Gain Medium)</u>: 3 to 4 level system to induce light emission after population inversion (crystals, ceramics, mixture of gases, semiconductors, and others)

STABLE AND UNSTABLE RESONATORS:

Type of Resonator	**Optics Geometry**	**Implications**
STABLE  	2 parallel perfectly reflecting mirrors (to increase reflection coatings can be used) -> in reality perfectly parallel mirrors not feasible Or two curved mirrors Or curved and parallel mirror (d=R **(radius of curvature)**)	Light on-axis will <u>remain in the resonator</u> after multiple bounces. And the ones slightly off the axis will be reflected in a direction to bring them back towards the center of the bore. *morden lasers have slightly concave mirrors
UNSTABLE **d>R (radius of curvature)**	1 flat, 1 tilted mirror	Light rays regardless to their initial direction, will <u>eventually leave</u> the

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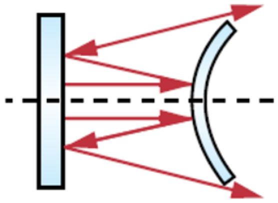
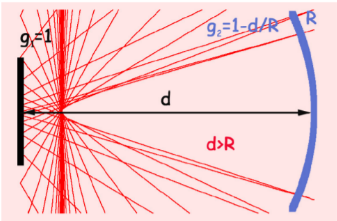
<td>

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<td></td>
<td>resonator:
a) Through a clear area in the output coupler
b) Clear area or hole in the middle or around the bouncing area

They can cause damage (overheating)

Only possible for lasers with high amplification</td>
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<tr>
<td colspan="3">Stability range</td>
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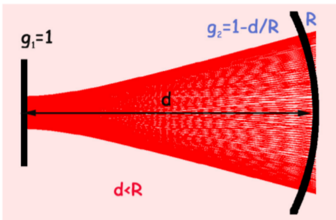
<tr>
<td>d≤R (radius of curvature)

</td>
<td>1 flat, 1 curved</td>
<td>If the <u>distance between the reflection plates is reduced</u>, the resonator configuration would <u>remain stable</u></td>
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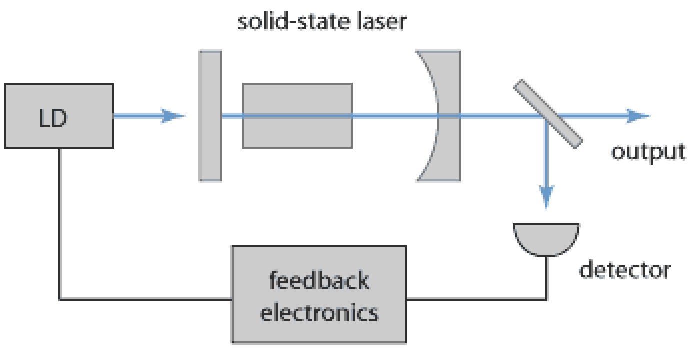
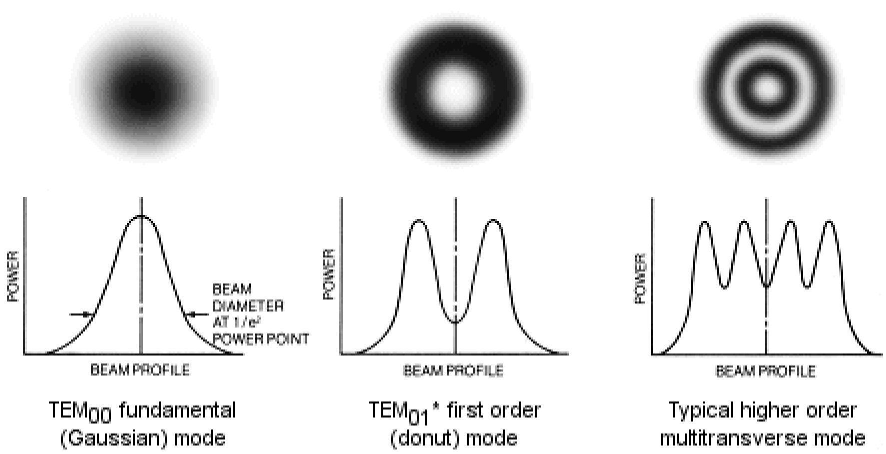
How to get a stable laser output?

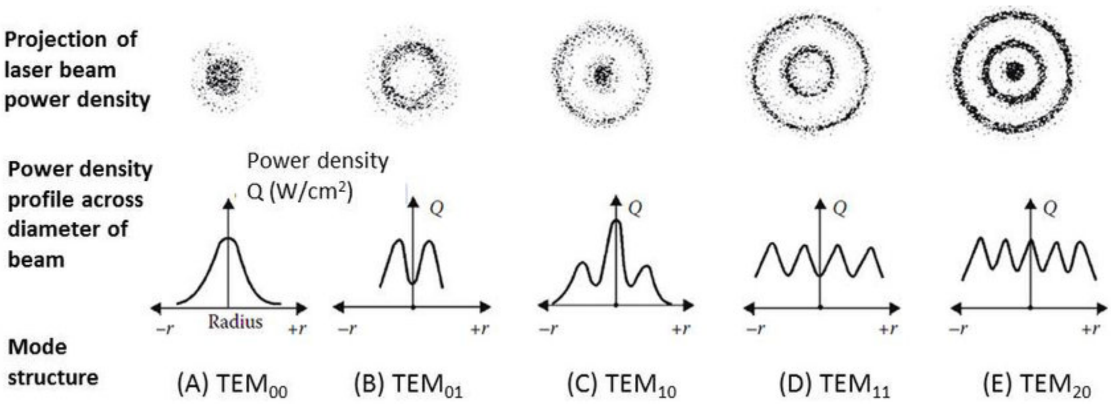
- By modulating the energy pump via a control system (feedback electronics) that is regulated by a photodiode (to count the losses of the resonator).



Transversal mode (classical geometrical optics):

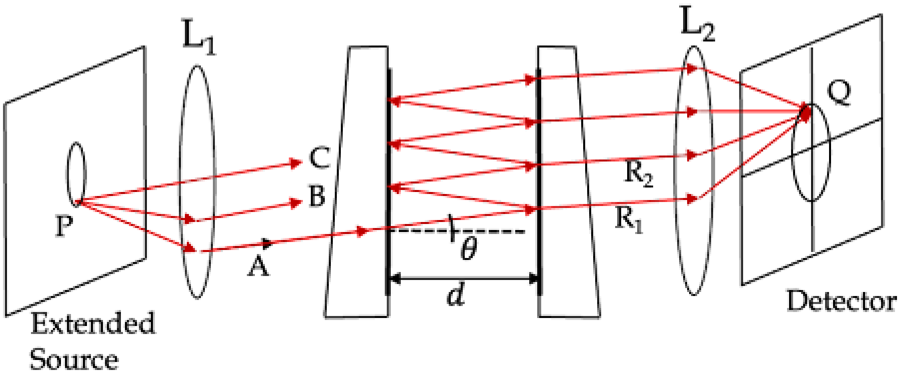
- The distribution of the radiation intensity beam across the cross sectional area perpendicular to the optical laser axis.
- They depend on the position of the mirror



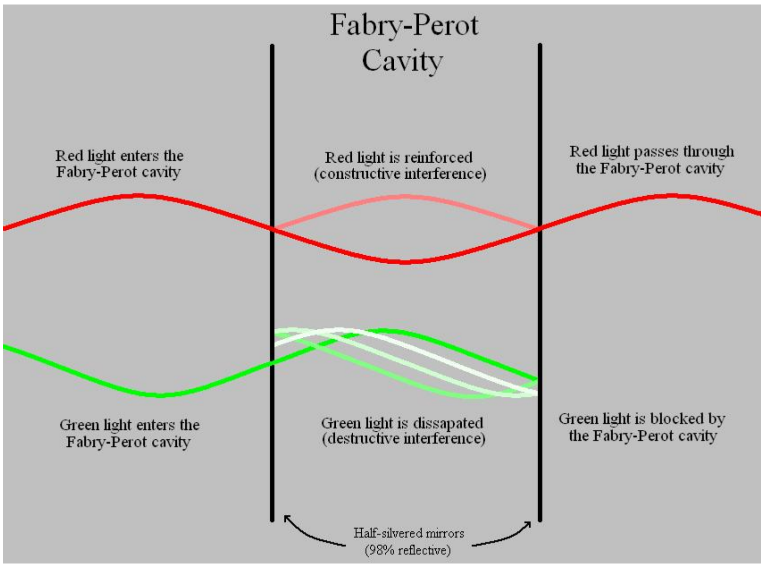


Longitudinal mode (classical geometrical optics):

- **Fabry Perot interferometer (active element):** extremely high-resolution spectrometer. In laser spectroscopy it is often used as an analyzer and a wavelength meter.
- 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.



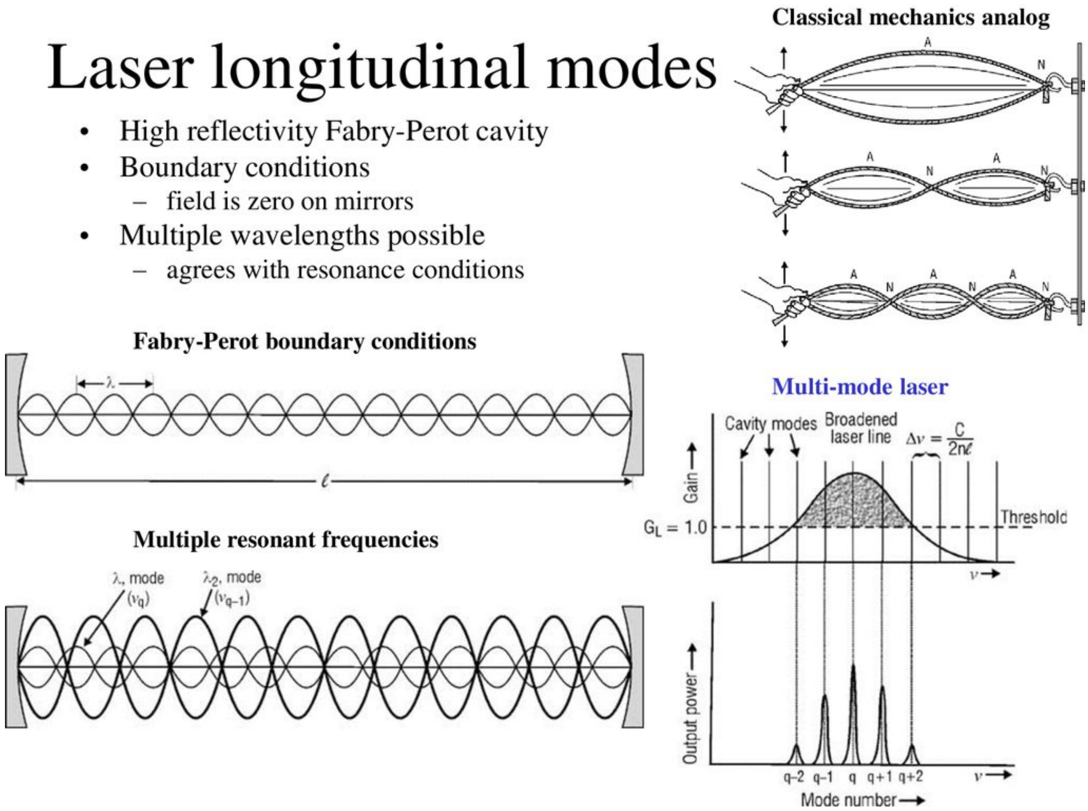
- Simplest implementation: a glass plates in the beam path



Condition for longitudinal modes (standing waves):

$$L = q\frac{\lambda}{2}$$

where L - distance between two mirrors, lambda - wavelength of e/m waves, q - integer values (number of modes)



Gaussian beam Profile:

Due to refraction effects, plane waves in open resonators cannot lead to steady field distributions, since the diffraction losses are greater at the edge of the mirror.

Diffraction effects cause plane waves to steady field distributions, due to diffraction losses.

Spatial field strength changes with each reflection inside the medium.

** Filed distribution is not a "top hat" ; it is a gaussian profile with a divergent angle!**

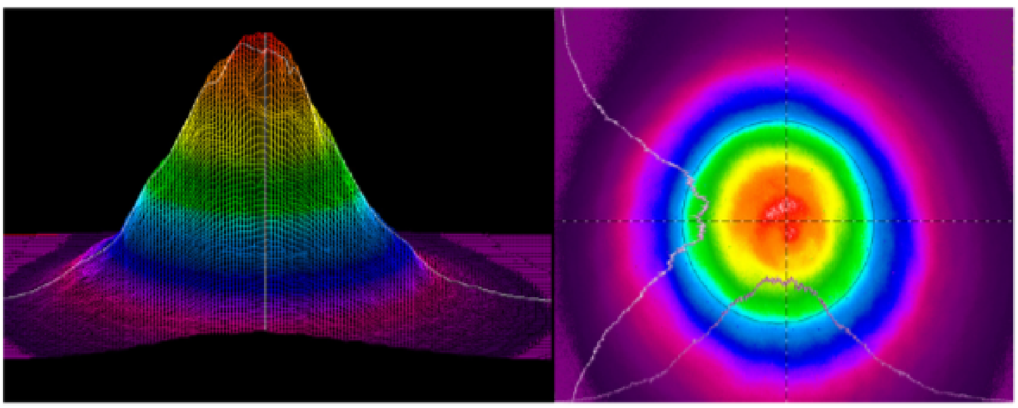


Figure 3.12. Measured Gaussian profile of a laser beam.

Experimentally: Diffract positions and different intensities (smaller at the edges and high at the center).

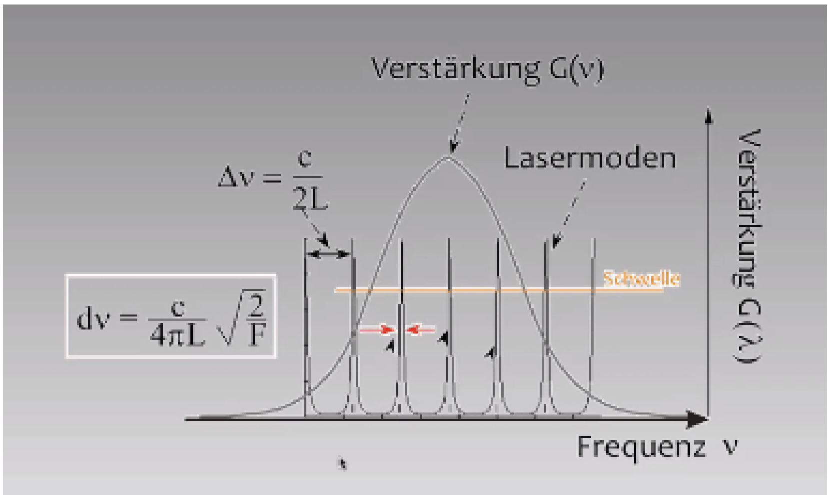
If the gaussian (beam constant) highly depends on the original prorogation, of the wavelengths is focused, you will get a certain area where the intensity stays more-less the same. It stays constant over the Z direction (very relevant in 3D printing).

Gain Profile:

- Wave-lenght dependent (frequency)
- Decreases with increasing light intensity.

Active vs. Passive Resonators:

Active	Passive
Amplifier in the resonator	
Distance d between the reflective layers is generally large (infinite FPI)	
Light is not coupled from the outside	
Distance between adjacent longitudinal modes: $\Delta v = c/2L$	



What does a frequency spectrum of a LASER look like?
Which consequences it may have?

- Several modes-multi mode spectrum within gain profile.
- Single mode operation-narrow, but finite frequency spectrum corresponding to one mode of FPI.

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

- 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.

Broadening	Trend Origin	Elements
Homogeneous	Laser medium	
Inhomogeneous	Doppler effect	Different types of molecules/atoms

Beam broadening:

Answer 1: Main effect: Doppler effect. Usually, we have a medium (a gas). We have many atoms here. 10 to the power of 20 - the amount of molecules. Let's assume that they don't move (have fixed positions). Then let's assume that they have only 2 energy levels and let's excite them (induced absorption, then after some time emission). BLOW HORNS story (example of Doppler effect). If the atom moves in relation to the incident e/m, which has its own frequency = the same situation.

$\gamma = \frac{1}{\tau}$ → The shorter the time the broader the spectra.

Doppler shift formula: V0=(1+-v/c) ????

Atoms don't move:

Assume that the medium emits visible light 10^14 Hz +- 10^8 Hz Lorentzian shape (if atoms don't move)
Half-width (caused by spontaneously emitted photons) is given by the natural lifetime. width = gamma is proportional to 1/t (t = 10^(-8) sec), so the delta frequency is 10^8 Hz

Atoms move: + ADDITIONAL BROADENING

→ Molecules emit some frequency spectrum but because they move (randomly in all directions) higher (when moving towards us) and lower frequencies (when moving away) are introduced by the Doppler-effect. These shifts are symmetric around zero -> frequency spectrum does not shift but broadens
(Rosa)

Part 6: Training

1. Which of the following statements are correct?

A. **Amplification of light is based on stimulated emission between two energy levels of an atomic system.**
B. In most cases, a laser will produce continuous (permanent) emission of light (c.w. laser)
C. The most important feature of any laser is the monochromatic light it produces.

D. **The process of stimulated emission produces emission of coherent light.**
E. Energy levels in a system (atom, molecule, solid, etc) which allow dipole transition between them can always be used for amplification.
F. **Spontaneous emission is an essential step in the process of any laser**

2. Explain what we understand under transversal and longitudinal modes of laser:

a) **TRANSVERSAL WAVES**: Waves that are oscillating perpendicularly (at a right angle) to the direction of propagation.

TRANSVERSAL MODE: (Wiki) Electromagnetic radiation is a particular electromagnetic field pattern of radiation measured in a plane perpendicular (i.e., transverse) to the propagation direction of the beam.

- Occurs because of boundary conditions imposed on the wave by the waveguide (resonator).
- Shows the intensity pattern of the beam
- The beam has a Gaussian distribution, centered in the direction of the beam output.

b) **LONGITUDINAL WAVES:** Waves that are oscillating parallelly to the direction of propagation.
LONGITUDINAL WAVES (mechanical wave, for example, sound): Waves in which the displacement of the medium is in the same (or opposite) direction as the direction of propagation of the wave.

LONGITUDINAL MODE: Happens when a particular standing wave pattern is formed by waves confined in the cavity. They correspond to the wavelengths of the wave which are reinforced by constructive interference after many reflections from the cavity's reflecting surfaces. All other wavelengths are suppressed by destructive interference.

3. Select the section of the laser textbook without errors:

The constant factor $B_{12,}$ the Einstein coefficient of induced absorption, depends on the electronic structure of the atom, i.e., on its electronic wave functions in two levels 1 and each absorbed photon of energy hv decreases the number of photons in one mode of the radiation field by one.

The radiation field can also induce molecules in the excited state E2 to make a transition to the lower state E1 with simultaneous emission of a photon of energy hv. This process is called induced or stimulated emission. **The induced photon of energy hv is emitted into the same mode (frequency and direction) that caused the emission.**

Key: Induced/stimulated emission is coherent.

4. In the following statements concerning rate equations, check which are correct and if the equation is displayed, check which one describes a correct rate equation (a possible realistic case).

a) The rate equation describe the exact physics of light interacting with an atomistic system

b) The rate equations yield the probability to find the system in a specific energy state as a function of time.

c) The rate equations yield the wave function of the system in a specific energy state as a function of intensity.

d) The rate equations yield the probability to find the system in a specific energy state as a function of intensity.

$$\frac{d}{dt}n_n(t)=\sum_{m\neq n}n_m(t)\cdot I\cdot B_{mn}-n_n(t)\sum_{m\neq n}I\cdot B_{mn}-n_n(t)\sum_{m[E_m<E_n]}A_{mn}$$

(with external e/m field presented)

$$\frac{d}{dt}n_n(t)=-n_n(t)\sum_{m[E_m<E_n]}A_{mn}$$

(no external e/m field presented)

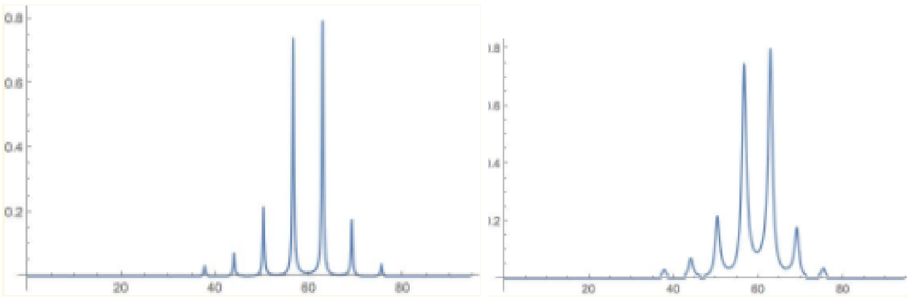
Key: Has to include all 3 processes (rate equation) and the first order derivative!

5. One of the most important parameters of light produced by a laser concerns its wavelength spectrum. In the following several statements are listed, which ones are correct?

Does the following picture display a correct frequency (wavelength) spectrum of a laser?

X= Frequency (1/s), wavelength (m), or energy (Joule) of the e/m waves

Y= Intensity (Watt/m^2)



- **The wavelength spectrum of a laser depends on the frequency dependent amplification of the amplifier medium and the resonator parameters.**
- **A laser is never monochromatic in the sense that the emitted light can be described by a sine wave with exactly one frequency.**

6. The most fundamental description of light is (must be used i.e., if we want to add the effect for two light sources): The electric field

7. Spontaneous Emission:

Mark all the statements that are correct (various answers)

- is initiated by an external light field.
- is the basis of light amplification as realized in a LASER
- **produces an exponentially decaying light field with a typical halfwith τ**
- the emission of many spontaneously emitted photons produces light into a defined direction
- **the emission of many spontaneously emitted photons produces light statistically distributed in all directions**
- produces coherent light
- **is the origin of basically any light in nature**
- produces an infinity short (delta-function like) light field

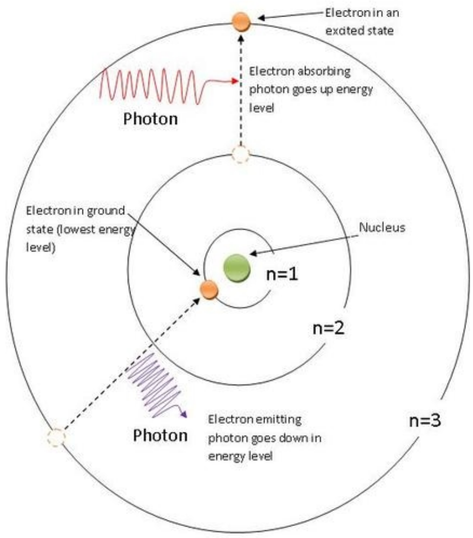
8. How does a laser start to emit light (Spontaneous and Stimulated emission, and how light gets amplified)?

A dipole moment + population inversion + energy transitions must occur, so a laser can emit light

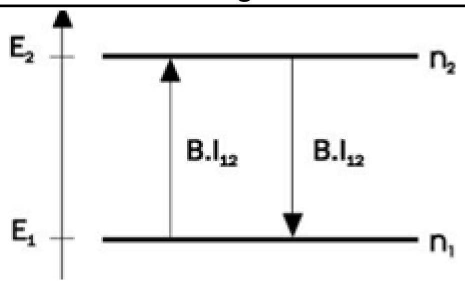
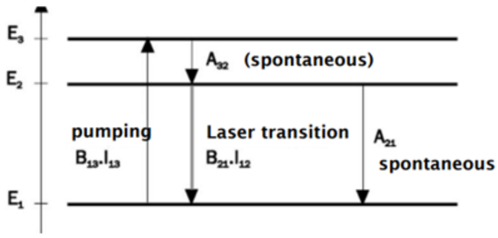
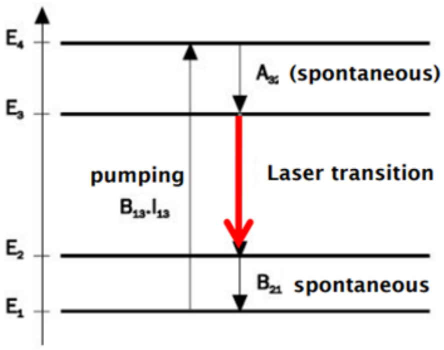
Phenomena	External E field required?	Level of Interaction	Einstein Coefficients	Amplification
Stimulated/ Induced Emission (coherent)	YES	E2⟶ E1 DOWN	B_{21}	Optically amplified in the gain medium
Spontaneous Emission (incoherent)	NO	E2⟶ E1 DOWN	A_{21}	

9. What happens inside the atom?

- Emission is the process of elements releasing different photons of color as their atoms return to their lower energy levels.
- Atoms emit light when they are heated or excited at high energy levels.
- Absorption occurs when electrons absorb photons which causes them to gain energy and jump to higher energy levels.



10. Energy levels (Niveau) and how they're distance between each other affects the emission of photons

Levels	Image	Einstein Coefficients	Pumping
2		$B_{12} = B_{21}$	Intensive illumination. Same amount in the levels n_2=n_1.
3		$B_{13}\,\rho(\nu)$= Pumping A_{32} = Spontaneous $B_{21}\,\rho(\nu)$ = Laser Transition A_{21}=Spontaneous	****Population inversion!**** Performed at a wavelength other than the lasing wavelength.
4		$B_{13}\,\rho(\nu)$= Pumping A_{32}= Spontaneous B_{21}= Spontaneous	Decoupling the lower laser level from the ground state. Most lasers (e.g., Nd: YAG, CO_2 laser) are of this type.

11. Which items are required for producing ultra-short laser radiation?

A. Farby Perot for mode selection.
B. Strong mode competition
C. Pump laser of population inversion media
D. Self-phase modulation
E. Mode locking
F. Laser resonator
G. Q switching device

12. Describe the principle of ultra-short laser radiation (explain and sketch!) and comment on the formula below:

- Laser emission in the range of femtoseconds to ten picoseconds.
- The first step in generating ultrashort pulses is to exploit the mode structure of the laser. 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

$$E_{aus} = E_0 e^{i2\pi\nu_0 t} \frac{\sin[(\Delta\nu_{Mode} N t)/2}{\sin[(\Delta\nu_{Mode} t)/2}$$

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

14. What is a plane wave?

A wave or field constant over any plane that is perpendicular to a fixed direction in space.

15. Explain and give a mathematical description of a one-dimensional plane wave.

A(z,t)= A0*cos(ωt - kz)
Where:
A0 ⟶ maximal amplitude
w⟶ frequency (2*pi*f) (Hz)
t⟶ time (s)
k⟶ wave number (2*pi/lambda) (1/m)
z⟶ propagation in space (m)

16. Explain the formulas (equations):

α **-->Absorption/Amplification Coefficient**

Can be +/- (positive exponent in Beer's Law ⟶ increase intensity) depending on the medium

$$\alpha(\nu) = [n_i - n_k] \cdot (\frac{\hbar w_{ik}}{c} B_{ik})$$

What is it?

★ Describes the specific coefficient for absorption/amplification
★ Depends on the frequency of the wave.
★ Depends on the probability of absorption (Proportional to B)

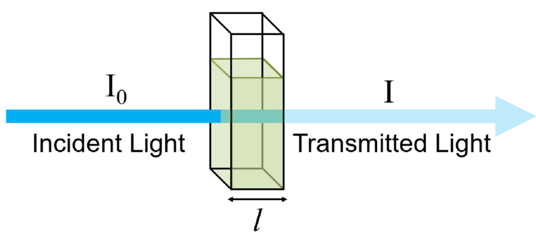
Where:
i=upper, k= lower levels of the medium
ν⟶ in terms of the photon described by: $\nu = c/\lambda$
$n_i - n_k$ ⟶ Population numbers of the two states i & k
$\hbar$⟶ Reduced Planck's Constant ($\hbar = h/2\pi$) ⟶ 6.626 070 15 x 10e-34 J Hz-1
c⟶ Speed of Light ⟶ 299 792 458 m/s
w_{ik}⟶ Oscillation Frequency of the Theoretical Dipole
B_{ik} ⟶ Einstein Coefficient for Induced Absorption (emission).

17. Beer's law of absorption

Traveling in the z direction (z)

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

Where:
z - the length of the matter (the length of path inside the matter)
I - Attenuation, Final Intensity of light
I_0- Initial Intensity



α = Absorption/Amplification coefficient along the attenuation path (in many cases proportional to the imaginary part of the refractive index)

What is it?

- ★ *Describes the attenuation/amplification in a medium.*
- ★ *Depends on the initial intensity* I_0 and the specific α Absorption/Amplification coefficient along the attenuation path

- *It also has a frequency dependence in the vicinity of the oscillator natural frequency for molecules at rest, which is described by a Lorentz profile for n − 1 ≪ 1*

18. Light interacts with a medium, which at the beginning is found in its lower state (the electrons). The wavelength of the light is in resonance with an oscillating dipole due to levels i, k of the medium. Amplificacion, absorption of the light can be described by the following equation:

$$\alpha(\nu) = [n_i - n_k] \cdot \left(\frac{\hbar \omega_{ik}}{c} B_{ik} \right)$$

Consequently, the intensity of a laser beam traveling in the medium in the z-direction is given by:

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

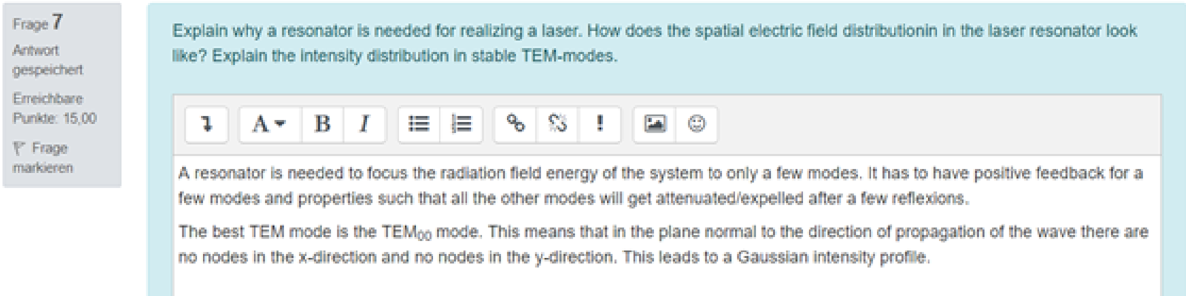
i,k stands for (i) lower and (k) upper levels of the medium

19. Which statements below are correct?

A. Let's assume that for a specific medium the lower level i is identical with a measurable state above the ground state. In this case we can always achieve amplification.
B. **Let's assume that for a specific medium the lower level i is identical with the ground state. In this case we can easily achieve amplification of the light**.
C. Absorption will always dominate.
D. **Absorption can go to zero. In this case the medium becomes transparent for light of this wavelength**.
E. The case where ni>nk (for all times) represents the most probable situation.

20. In order to treat the interaction of light with "matter", in many cases the so-called semiclassical approach is used.
Choose one or more answers:

A. In this treatment the solution is always obtained via solving the time dependent Schrodinger Equation.
B. "Laser-light-Matter Interaction" as well as "Conventional Light-Matter Interaction" can be both related with the semiclassical approach.
C. A two-level energy scheme can be sufficient to describe matter (in this context).
D. A three-level energy scheme is always sufficient to describe "matter" interaction.
E. A two-level energy scheme is always sufficient to describe "matter" in this context.
F. In this treatment (semiclassical approach) the solution is obtained via rate equations.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Explain why a resonator is needed for realizing a laser. How does the spatial electric field distributionin in the laser resonator look like? Explain the intensity distribution in stable TEM-modes.

A resonator is needed to focus the radiation field energy of the system to only a few modes. It has to have positive feedback for a few modes and properties such that all the other modes will get attenuated/expelled after a few reflexions.

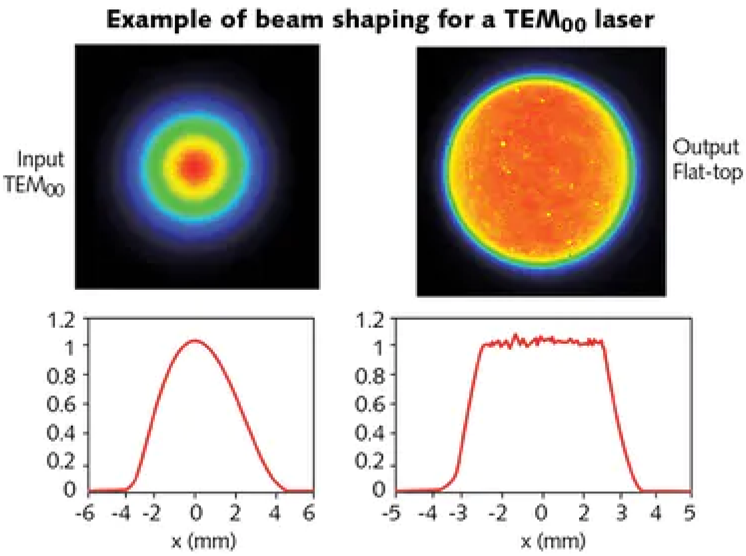
The best TEM mode is the TEM_{00} mode. This means that in the plane normal to the direction of propagation of the wave there are no nodes in the x-direction and no nodes in the y-direction. This leads to a Gaussian intensity profile.

21. Explain why a resonator is needed for realizing LASER:

- A resonator is required to build up the light energy in the beam
- The shape of a laser beam is determined by the resonator cavity in which the laser light is amplified in a gain medium.

22. How does the spatial electric field distribution in LASER resonator look like?

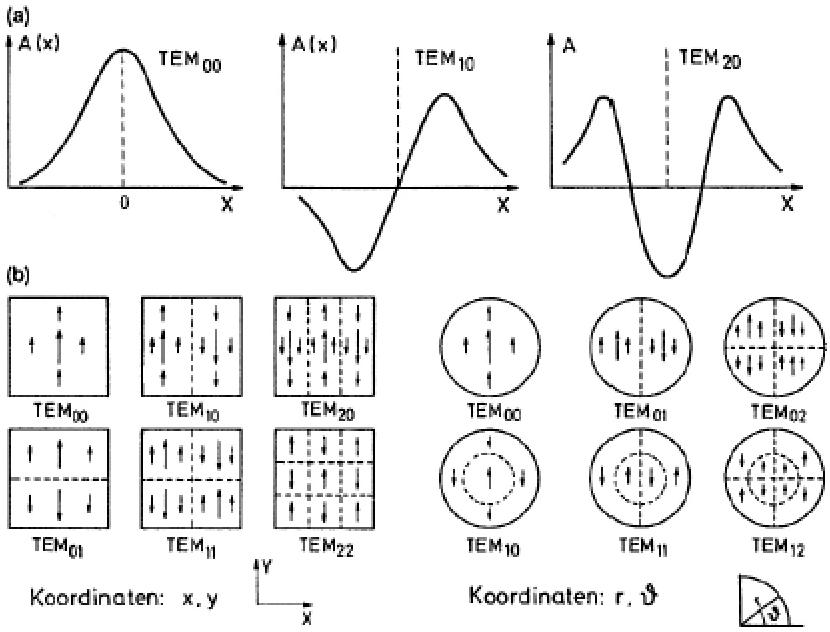
- Fundamental nodes (TEM00) have a radially symmetrical Gaussian intensity profile.



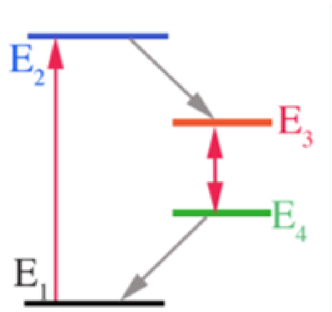
23. Explain the intensity distribution via TEM-modes.

TEM-modes → possible field distributions in stable resonators

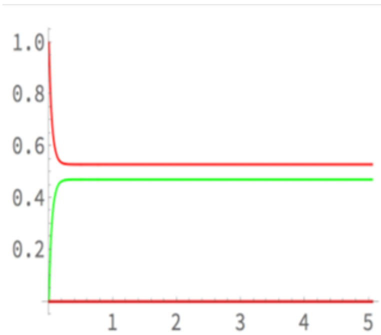
- Focused at the centre. only for certain modes, eg TEM00 apparently yeah....:-)https://www.laserglow.com/content/Laser-Beam-Profiles more info here! :)
- A stationary field distribution occurs when the spatial field strength distribution over the resonator cross section remains constant during the reflection.
- The absolute field energy naturally decreases over time due to the losses that occur if the lost energy is not replenished.
- Stationary field distributions are the modes of the open resonator, analogous to the modes of the closed resonator → represented by plane waves.
- The mode structures of an open resonator can be calculated using an iterative method using Kirchhoff-Fresnel's diffraction theory.



24. A typical energy level scheme of a laser medium is shown below:



Before the energy pump (light source with frequency corresponding to the transition E1 to E2) is turned on all electrons are found in level E1. The following solution of the rate equations yields a time dependence of n1 (red) and n2 (green curve:



25. Which of the Einstein Coefficients of the Laser Medium shown above have been set different from zero in the simulation leading to the result?

B21, A21

Which ones have to be set to nonzero to obtain a real laser medium "ready to go" for amplification?

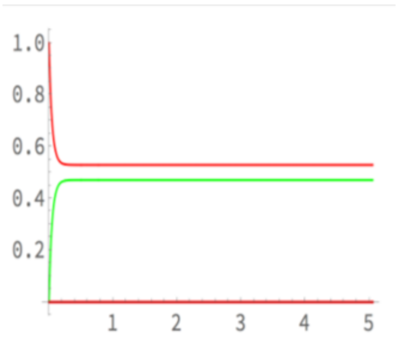
A23, A24

B34, A34

A41

26. Setting the parameter(s) to nonzero reflects which kind of physics?
It describes the discrete energy changes via the Eigenstates/values of the atom → Quantum Physics.

27.



Y axis: Percentage of the whole population of electrons on all the levels, 1.0 = 100 %,
X axis: Time, units of time
Red line: Amount of electrons over time on the Ground level (E1)
Green line: Amount of electrons over time on the Excited level (E2)

Process	Pumping	B21 - Induced Emission A21 - Spontaneous Emission
Influence on the number of electrons	N2 Rises	N1 Rises

28. Suppose we have light with the wavelength lambda=548,42 nm. What is the frequency of the corresponding electromagnetic field?
(With units!) Result: Value and units in the form: number+unit without blank)
Speed of light → c=2.99e108 m/s

$$f = c/\lambda$$
$$f = 2.99x10^{8}\ m/s\ /\ 5.4842x10^{-7}m$$
$$f = 545,2025x10^{12}\ s^{-1}$$ or Hz