Lasers

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Introduction

Study resources

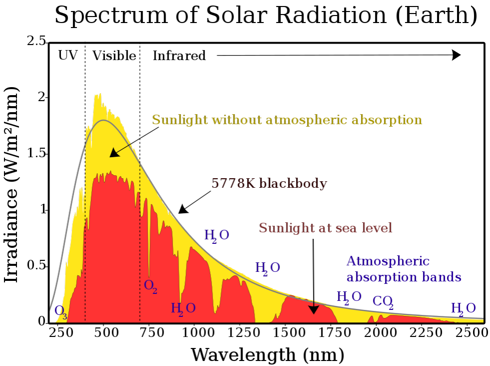
- "Optics" by Ajoy Ghatak, ISBN-10 : 9390113598 - Chapter 26
- `https://spie.org/Documents/Courses/OP-TEC/Course_1_Fundamentals_of_Light_and_Lasers_3rd_Edition_2018.pdf` - Module 6 contains material on lasers
- `https://ocw.mit.edu/resources/res-6-005-understanding-lasers-and-fiberoptics-spring-200 laser-fundamentals-i/`

What is a laser?

- LASER is an acronym for "Light Amplification by Stimulated Emission of Radiation"
- Laser is a special form of light
- Classically, light is an electromagnetic wave
- It is made out of electric and magnetic fields that obey the Maxwell equations
- https://www.youtube.com/watch?v=nt-A1Cr6Aao - Nice animation of how electric and magnetic fields look like in a light wave

Properties of Ordinary light

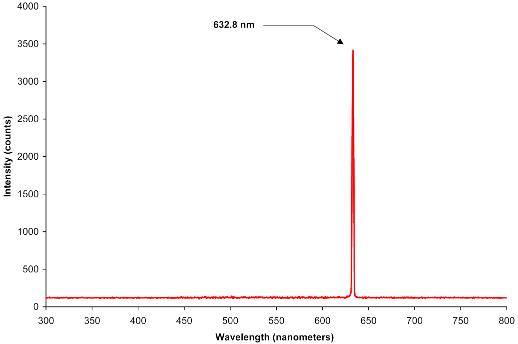
- Sunlight consists of well-known seven colors - its a blackbody spectrum



- Its a broadband-spectrum, spread out over a decade of wavelengths
- Similar is the light from torches, light-bulbs, lamps, neon lights, etc.

Narrow spectrum of a laser

- A laser light consists of light waves of a very specific wavelength, i.e., their spectrum is extremely narrow



- This is also called as monochromatic (single color)

Coherence

- Coherence refers to continuity of the waveform - both in time and space

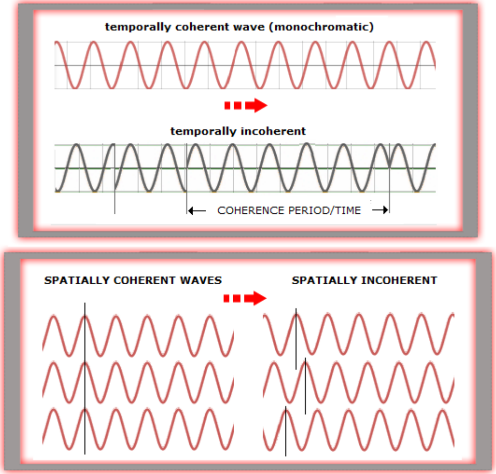


Figure: credit: www.telescope-optics.net

Coherence and beaming

- Lasers have a much higher spatial and temporal coherence compared to other light sources
- Laser have high directionality and very little divergence. A beam of laser will spread less than 10^{-5} radians

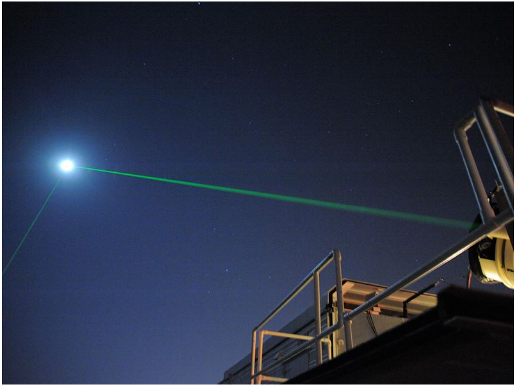


Figure: credit: GSFC NASA

Applications of lasers

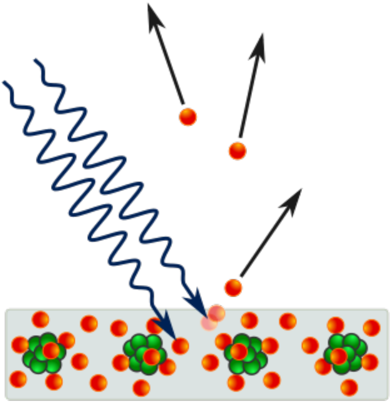
- Tumour and kidney stone removal
- Eye surgery
- Laser endoscopy
- Dental surgery
- Cosmetic surgery
- Fiber-optic communication
- Space and satellite communication
- Cutting glass and quartz
- Photolithography to manufacture microprocessors
- Production of industrial plasmas
- Barcode scanner
- Precision drilling
- Heat treatment in auto industry
- Spectroscopy, microscopy
- CD, DVD, Blu-ray
- Laser printers
- Detecting earthquakes and underwater blasts
- Range finders
- Radar
- Guidance systems
- Laser welding
- Precision metrology for railways, airways
- ...and many more...

Stimulated emission

Quantum nature of light

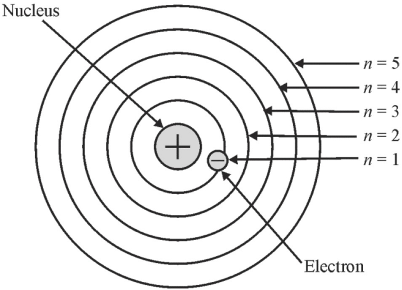
- Classically light is an electromagnetic wave
- When light is analyzed closely, it is found to consist of particles - called photons

  - This is demonstrated by the photoelectric effect - light shines on metals and excites electrons
  - The electrons are not emitted if the frequency of light is below a certain threshold, no matter how intense the light is
  - This implies that light is made up of small packets (photons) which can be absorbed wholly, not partially

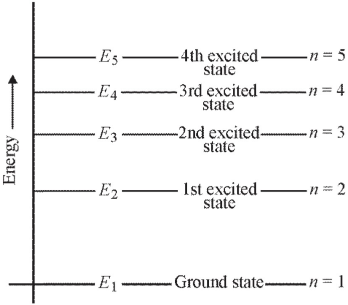


Energy levels

- The electrons in an atom can occupy only discrete energy levels, i.e., the energy levels are "quantized", as suggested by the Bohr model



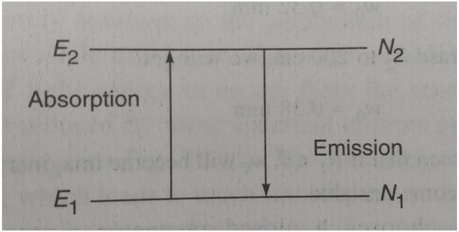
(a) Hydrogen atom with allowable electron orbits showing electron in the innermost orbit—the lowest energy level



(b) Ground state energy level and first four excited energy states for a hydrogen atom

- An electron can be excited by absorbing a photon, or it can de-excite be emitting a photon

Photon absorption and emission



- Consider a bunch of atoms interacting with a bath of photons
- Lets say the atoms have two energy levels E_1 and E_2. An electron in the lower level E_1 can be excited to the level E_2 if it absorbs a photon of light with frequency $\nu = \Delta E/h$
- Conversely, if the electron de-excites from E_2 to E_1 then it emits a photon of the same frequency
- $h = 6.63 \times 10^{-34} Js$ is the Planck's constant

Rate of stimulated absorption

- The process of excitation is called stimulated absorption, because it is stimulated by the absorption of a photon
- The rate of stimulated absorption is the number of photons absorbed per unit time per unit volume. It will be proportional to the number of atoms (per unit volume) N_1 in energy level E_1 and the number of photons present per unit volume.
- The number of photons present is proportional to the energy density of the light, which is $u(\nu)$. This represents the radiation energy per unit volume at frequency ν.
- Thus we can write the rate of change of atoms from state N_1 to N_2 due to stimulated absorption is

$$\left.\frac{dN_2}{dt}\right|_{\text{absorption}} = B_{12} N_1 u(\nu) \tag{1}$$

- B_{12} is the proportionality constant.

Spontaneous emission

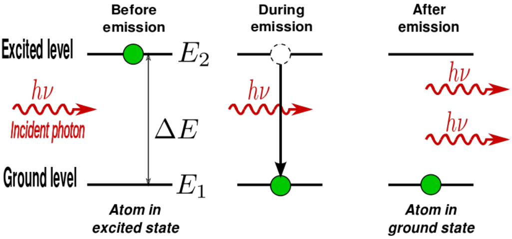
- If an atom is in excited state E_2 then it will spontaneously emit a photon and relax to state E_1. This is a random process and occurs spontaneously.
- The rate of this emission will depend only on how many atoms are there in state N_2, like the law of radioactive decay (as there is a fixed probability of decay of an excited state in a certain time, independent of other factors). So this rate can be written as

$$\left.\frac{dN_2}{dt}\right|_{\text{spontaneous emission}} = -A_{21}N_2 \tag{2}$$

- A_{21} is the proportionality constant. The negative sign indicates that N_2 will reduce due to emission of photons.

Stimulated emission

- In 1917, Albert Einstein proposed that there should be third process called "stimulated emission" (we will soon see why this process has to exist)
- In this process, an incident photon of appropriate frequency triggers an atom in the excited state to emit radiation
- Based on principles of time-reversal symmetry and also conservation of momentum it is predicted that the emitted photon will have the same direction and energy as the incident photon



$$E_2 - E_1 = \Delta E = h\nu$$

Rate of stimulated emission

- The rate of stimulated emission will also be proportional to the number of atoms present in excited state N_2 and the number of incident photons. This is given by

$$\left.\frac{dN_2}{dt}\right|_{\text{stimulated emission}} = -B_{21}N_2u(\nu) \tag{3}$$

- B_{21} is the proportionality constant. The negative sign again indicates that N_2 will reduce due to emission.
- Now if the gas of atoms and this bath of photons is in thermal equilibrium, then the number of atoms N_2 should not change, i.e.,

$$\left.\frac{dN_2}{dt}\right|_{\text{absorption}} + \left.\frac{dN_2}{dt}\right|_{\text{spontaneous emission}} + \tag{4}$$

$$\left.\frac{dN_2}{dt}\right|_{\text{stimulated emission}} = 0 \tag{5}$$

Einstein coefficients

- This implies

$$B_{12}N_1u(\nu)-A_{21}N_2 - B_{21}N_2u(\nu) = 0 \tag{6}$$

$$\implies u(\nu) = \frac{A_{21}}{B_{12}\frac{N_1}{N_2} - B_{21}} \tag{7}$$

- Now, according to the Maxwell-Boltzmann statistics of thermodynamics, the number of atoms in thermal equilibrium is proportional to $N \propto e^{-E/(k_B T)}$, where k_B is the Boltzmann constant
- This gives $N_1/N_2 = e^{(E_2-E_1)/(k_B T)} = e^{h\nu/(k_B T)}$. Plugging this back gives

$$u(\nu) = \frac{A_{21}}{B_{12}e^{h\nu/(k_B T)} - B_{21}} \tag{8}$$

Einstein coefficients

- Now we also know the Planck's law of energy distribution of photons in a black-body radiation is

$$u(\nu) = \frac{2h\nu^3 n_0^3}{c^3} \frac{1}{e^{h\nu/(k_B T)} - 1} \tag{9}$$

- where n_0 is the refractive index of the medium
- Comparing the 2 expressions of the photon energy density $u(\nu)$, we can conclude that

$$B_{12} = B_{21} \equiv B \tag{10}$$

$$\frac{A_{21}}{B} \equiv \frac{A}{B} = \frac{2h\nu^3 n_0^3}{c^3} \tag{11}$$

- A and B are called Einstein coefficients
- We see that if we had not taken the process of stimulated emission, i.e., $B_{21=0}$, then we will not get Planck's law. Thus stimulated emission was postulated by Einstein.

Population Inversion

Ratio of spontaneous to stimulated emission

- The ratio of spontaneous to stimulated emission is

$$\frac{dN_2/dt\Big|_{\text{spontaneous emission}}}{dN_2/dt\Big|_{\text{stimulated emission}}} = \frac{A}{Bu(\nu)} = e^{h\nu/(k_B T)} - 1 \qquad (12)$$

- Consider a normal light source which has temperature $T = 1000K$ and a wavelength of $6000\mathring{A}$. This gives $\nu = c/\lambda = 5 \times 10^{14} Hz$. So $A/(Bu(\nu)) = 3 \times 10^{10}$
- This in normal circumstances, the spontaneous emission will be much, much stronger than the stimulated emission.
- The spontaneous emission is random and so ordinary light is incoherent.

A coefficient

- The decay rate of state N_2 under spontaneous emission is

$$\left.\frac{dN_2}{dt}\right|_{\text{spontaneous emission}} = -AN_2 \implies N_2 = e^{-At} \tag{13}$$

- Lets call $A \equiv 1/t_{sp}$, then the decay due to spontaneous emission becomes $N_2 = exp(-t/t_{sp})$
- So A is the inverse lifetime of the upper level under spontaneous emission

Light energy distribution

- Often the energy levels have an uncertainty, due to a fundamental quantum mechanics uncertainty principle, $\Delta E \Delta t \geq \hbar$
- This implies that the frequency ν is not fixed but has a range
- To take care of this, we introduce a line shape function $G(\nu)$ which represents a probability distribution of energy in the laser light.
- The number of stimulated emission per unit time per unit volume is then

$$W_{21} = N_2 B G(\nu) U \tag{14}$$

- and the number of stimulated absorptions per unit time per unit volume is

$$W_{12} = N_1 B G(\nu) U \tag{15}$$

- U is the energy density of radiation

Intensity

- The intensity of light is energy per unit time per unit area. If a light beam has energy density U, then its intensity is

$$I = \frac{c}{n_0} U \tag{16}$$

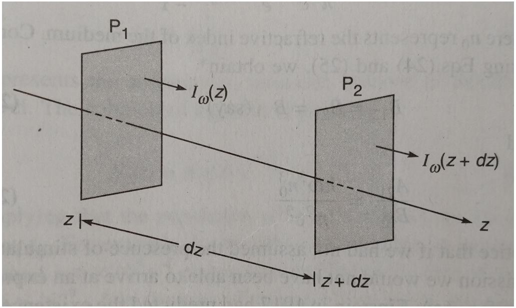
- This comes by considering the fact that a beam of light with cross section S will cover a volume $S(c/n_0)dt$ in time dt.
- Using this we get

$$W_{21} = N_2 B G(\nu) U = N_2 G(\nu) \frac{Ac^2}{2h\nu^3 n_0^2} I \tag{17}$$

$$W_{12} = N_1 B G(\nu) U = N_1 G(\nu) \frac{Ac^2}{2h\nu^3 n_0^2} I \tag{18}$$

Amplification

- Consider a beam of light with frequency ν passing through a medium of atoms



- It travels from z to $z + dz$. The volume it traverses is Sdz, where S is the area of the rectangle.
- The number of absorptions per unit time in this volume is $W_{12}Sdz$ and the number of stimulated emissions per unit time are $W_{21}Sdz$. Therefore, the change in energy per unit time is

$$dE/dt = (W_{21} - W_{12})Sh\nu dz \tag{19}$$

Amplification

- The change in intensity will be n

$$dI = dE/(Sdt) = (W_{21} - W_{12})h\nu dz \tag{20}$$

- We are ignoring the spontaneous emission assuming that it can be made negligible
- This gives

$$\frac{dI}{dz} = (W_{21} - W_{12})h\nu \tag{21}$$

$$= G_\nu \frac{Ac^2}{2h\nu^3 n_0^2} I(N_2 - N_1)h\nu \tag{22}$$

- the solution of this equation is

$$I(z) = I_0 e^{\gamma z} \tag{23}$$

- where $\gamma = G_\nu \frac{Ac^2}{2\nu^2 n_0^2}(N_2 - N_1)$

Population Inversion

- We see that the intensity of this beam can grow if $\gamma > 0$. For this we require $N_2 > N_1$
- In thermodynamic equilibrium, we have already seen that $N_2/N_1 = exp(-h\nu/(k_B T))$. This ratio will always be less than 1, so we will not get amplification in ordinary gas that is in thermal equilibrium
- For light amplification, we need population inversion, that means, $N_2 > N_1$. This will be a non-equilibrium system

Maser-Laser invention

- *“...Although I had considered molecules before, I had dismissed them because of certain laws of thermodynamics. But suddenly I recognized, ”Hey, molecules don’t have to obey such a law if they are not in equilibrium.” ..... Wow! It looked possible.”* - Charles H. Townes

The Nobel Prize in Physics 1964

Photo from the Nobel Foundation archive.

Charles Hard Townes

Prize share: 1/2

Photo from the Nobel Foundation archive.

Nicolay Gennadiyevich Basov

Prize share: 1/4

Photo from the Nobel Foundation archive.

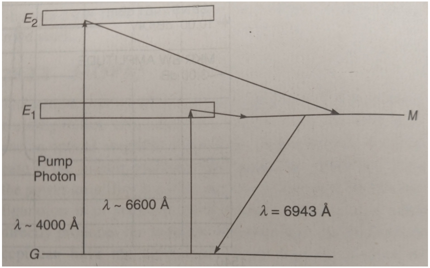
Aleksandr Mikhailovich Prokhorov

Prize share: 1/4

The Nobel Prize in Physics 1964 was divided, one half awarded to Charles Hard Townes, the other half jointly to Nicolay Gennadiyevich Basov and Aleksandr Mikhailovich Prokhorov "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle."

Metastable states

- The population inversion is done by means of a metastable state - this is an excited state which has a long lifetime to decay via spontaneous emission



- The first laser created by Theodore Maiman was a Ruby laser with the above energy levels

Metastable states

- Ruby crystal is Al_2O_3 with some Aluminum atoms replaced with Chromium
- The E_1 and E_2 energy levels have a lifetime of $10^{-8}s$, whereas the state M has a lifetime of $3 \times 10^{-3}s$
- The atoms are quickly excited to state E_1 and E_2 by optical pump
- They quickly decay to state M, but then they stay there for a long time. Since the Chromium atoms are isolated, this helps in keeping them excited for a longer time
- This creates population inversion and creates a gain medium where light is then amplified

Optical Resonators

Ruby Laser

- Construction of ruby laser - The flash light optically pumps and excites the Chromium atoms to excited states

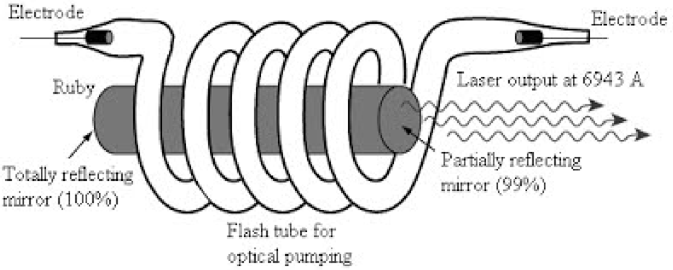
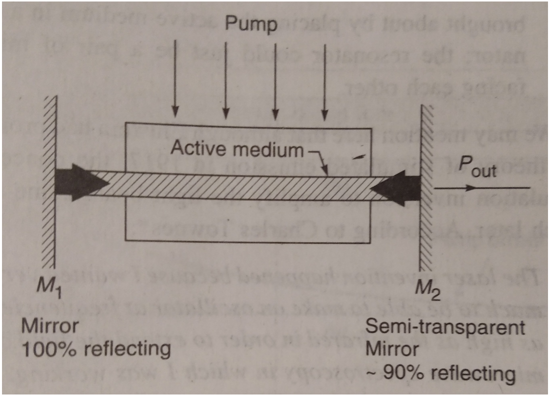


Figure: Prof. Amit Mourya

- The Ruby crystal is a cylinder with one end totally reflecting and another end partially reflecting - this is called a resonator so that light rays stay inside and get amplified
- Laser light leaks from one end of the partially reflecting mirror

Resonator



- The 3 components of a laser - the active medium (or gain medium), an optical resonator, & a pump to create population inversion

Resonant modes

- Consider a light beam that is reflected in a resonator. The condition for constructive interference is

$$\frac{2d}{\lambda} = m; \qquad m = 1, 2, 3, ... \tag{24}$$

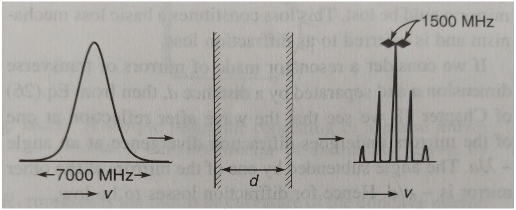
- Here d is the length of the cavity, so the light travels distance $2d$ to return to the same spot, which should be an integral multiple of the wavelength to interfere constructively
- The wavelength in the active medium would be $\lambda = \lambda_0/n_0$, where λ_0 is the wavelength in vacuum and n_0 is the refractive index of the active medium
- The resonant frequencies are

$$\nu = \frac{c}{\lambda_0} = \frac{cm}{n_0 2d} \tag{25}$$

Spectral width and resonant modes

- The frequency difference between the resonant modes is

$$\delta\nu = \frac{c}{n_0 2d} \tag{26}$$



- We earlier saw that the energy of the excited state will have some spread due to the uncertainty principle - this will cause a range of frequencies in the laser light
- Other factors will also broaden the frequency range - like Doppler broadening
- Due to the optical resonator, we will find only the resonant modes which lie within this frequency range in the laser light

Types of lasers

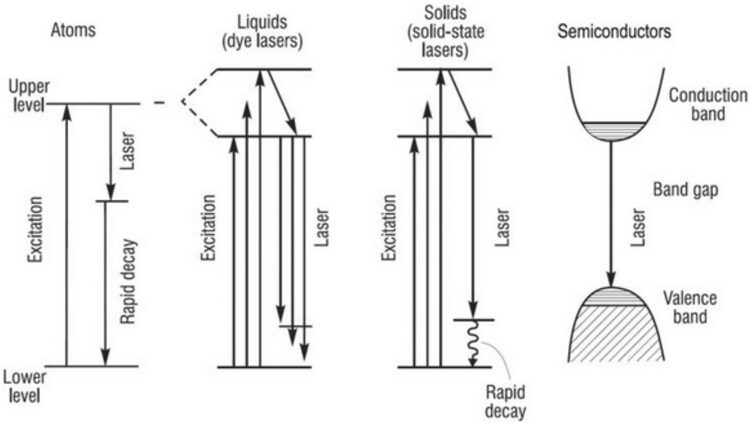


Figure: SPIE publications

Major types of lasers

- Gas Lasers - gain medium is a gas and population is inverted by applying a high voltage which drives electrons which then collide and excite the atoms
- Liquid-dye lasers - the gain medium is dye molecules dissolved in a solvent. Due to broad spectrum of electronic, vibrational, and rotational state, the wavelength can be fine tuned. Used for spectroscopic applications
- Semiconductor diode lasers - the gain medium is a semiconductor material. When large current is driven population can be inverted in the conducting band. Due to large difference in refractive index between semi-conductor material and air, the material itself can act as a resonator cavity. Very widely used lasers.
- Solid-state lasers - gain medium is impurities introduced in a solid medium like crystals. The solid medium protects the impurity atoms from losing their metastable states. Optically pumped
- Fiber lasers - The resonator is an optical fiber

Further courses

- EP3220 - Modern Optics
- EP3338 - Laser and Photonics
- EP4118 - Laser Spectroscopy