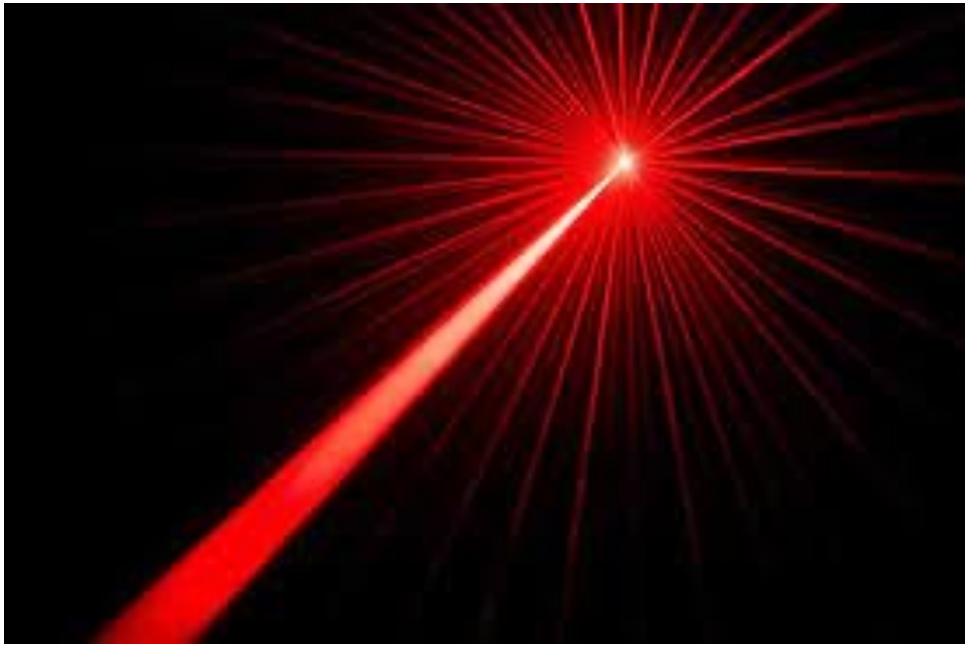
Principles of Laser

Textbooks

1. Lasers: foundation and applications, K. Thyagarajan, Chap.4-5.
2. Fundamentals of light sources and lasers, Mark Csele Chap.4-6

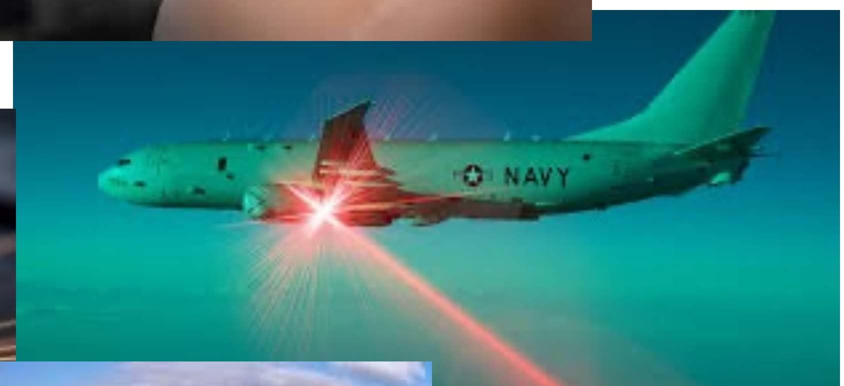
Laser



Laser is a special light source developed from quantum theory that has extraordinary properties not possessed by natural light sources, including (not limited to)

- Monochromatic
- Highly collimated
- Coherent
- High intensity

Applications of Laser



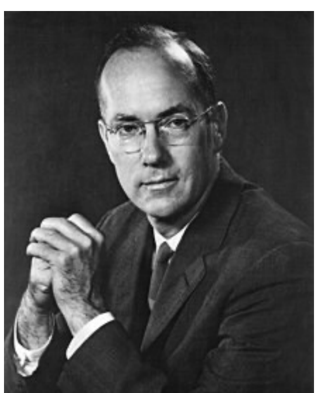
History of Laser

LASER: Light **A**mplification by **S**timulated **E**mission of **R**adiation

MASER: Microwave **A**mplification by **S**timulated **E**mission of **R**adiation

Year	Name	Development
1917	Einstein	Quantum mechanics of radiation
1953	Townes, Gordon, Zeiger	Built first MASER
1954	Townes et al	First publication
	Prokhorov, Basov	Publication and assembled MASER
1958	Townes and Schawlow	Proposal of Laser
1960	Maiman	First working laser
1964	Townes, Basov, Prokhorov	Nobel Prize in Physics

Townes



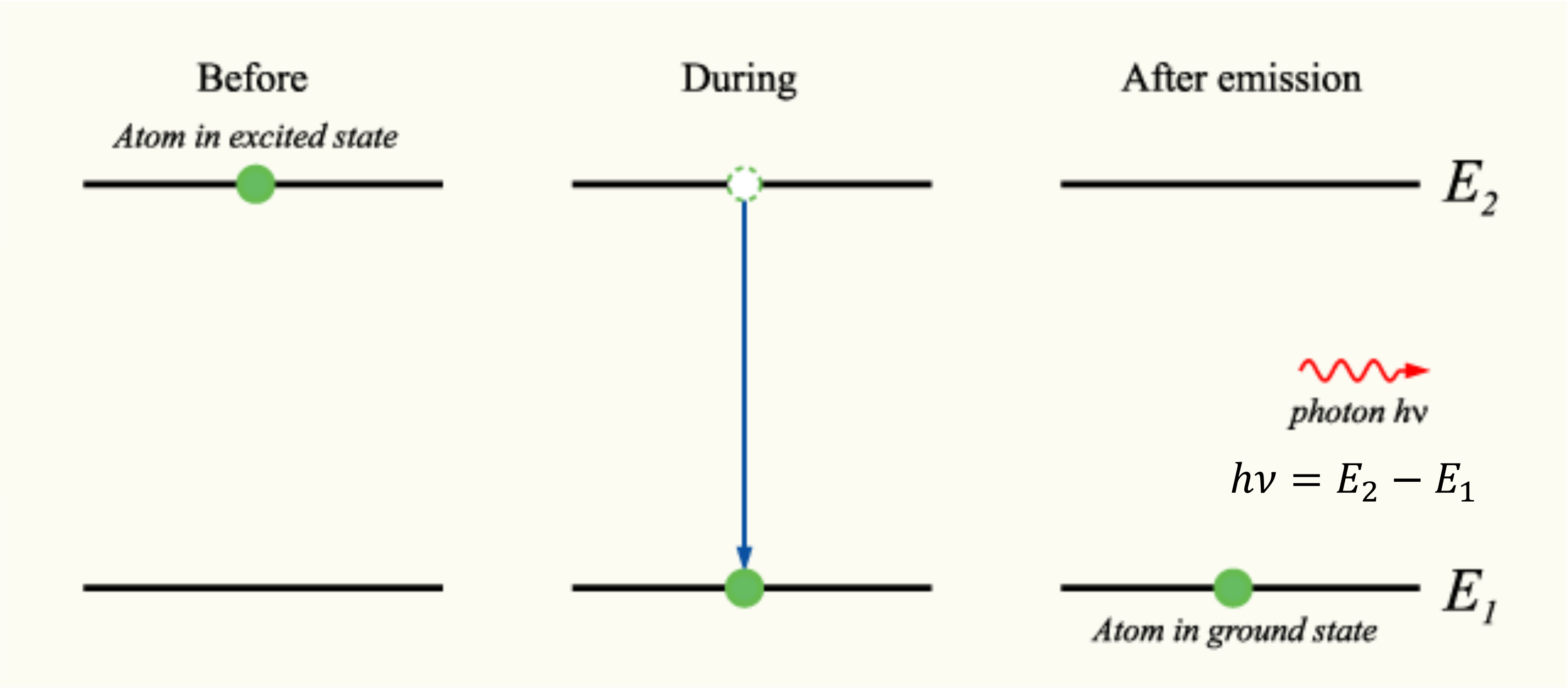
Basov

Prokhorov

Schawlow

Maiman

Spontaneous Emission



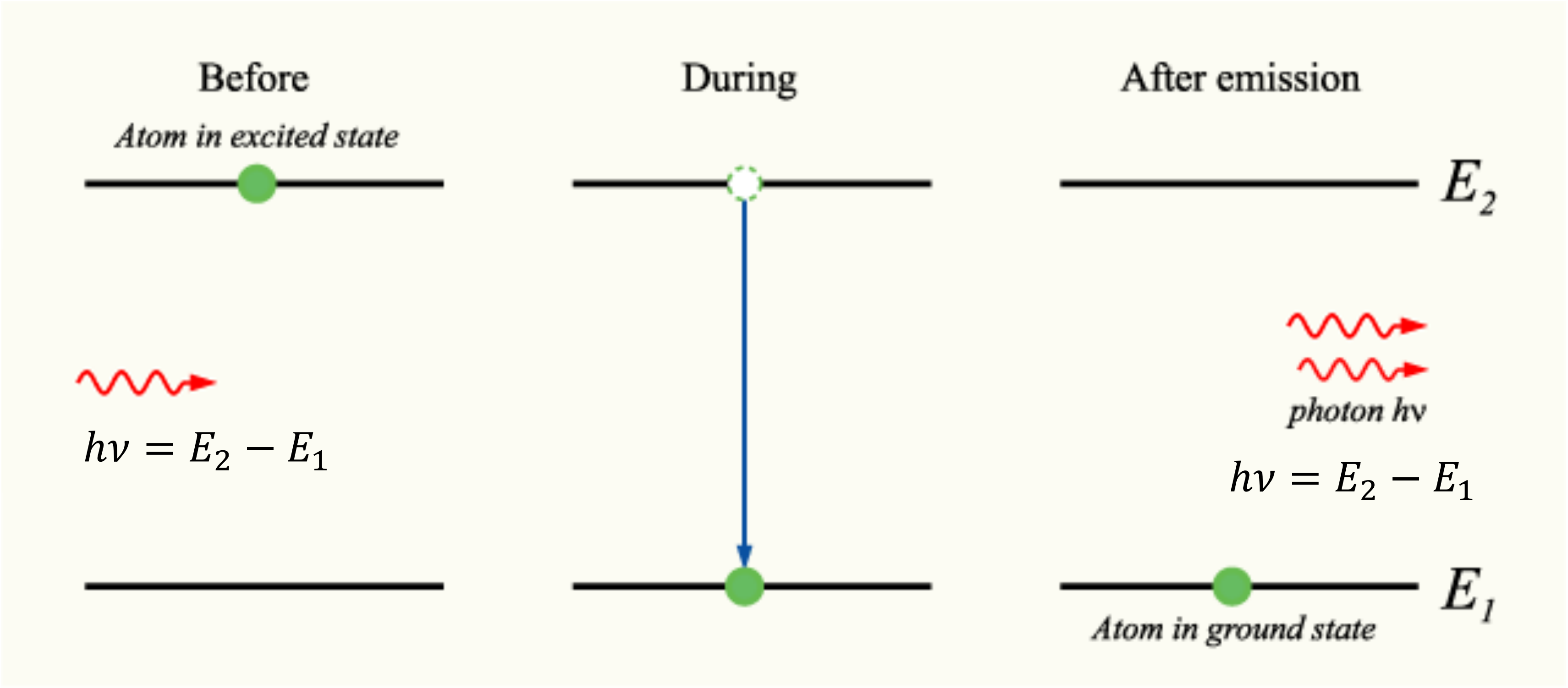
According to quantum theory, atoms can possess a range of discrete energy levels. When an atom at higher energy level transits to a lower energy level, it emits (not always happen, it could transit back to a lower energy level without emitting photons, called *nonradiative decay*) a photon with energy equal to the difference between the two energy levels. This is called spontaneous emission process.

Spontaneous Emission

Spontaneous emission is responsible for most natural light sources, such as fireflies, candles, incandescent light bulbs, and many luminescence phenomena (such as electroluminescence, chemiluminescence, photoluminescence etc).

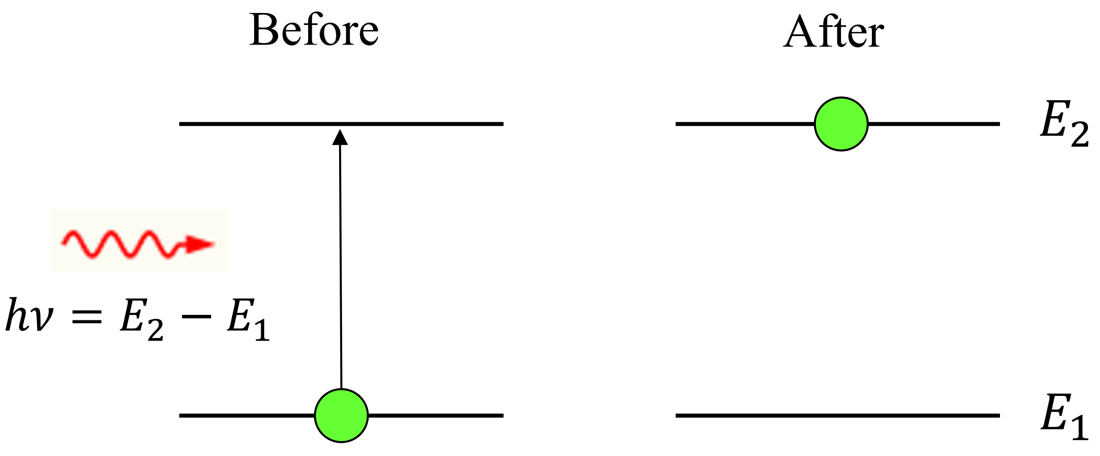
- The phase and direction of spontaneous emission are random, so is incoherent and divergent.
- Generally it involves a large collection of atoms with wide distribution of energy levels, so the emission spectrum is broad.

Stimulated Emission



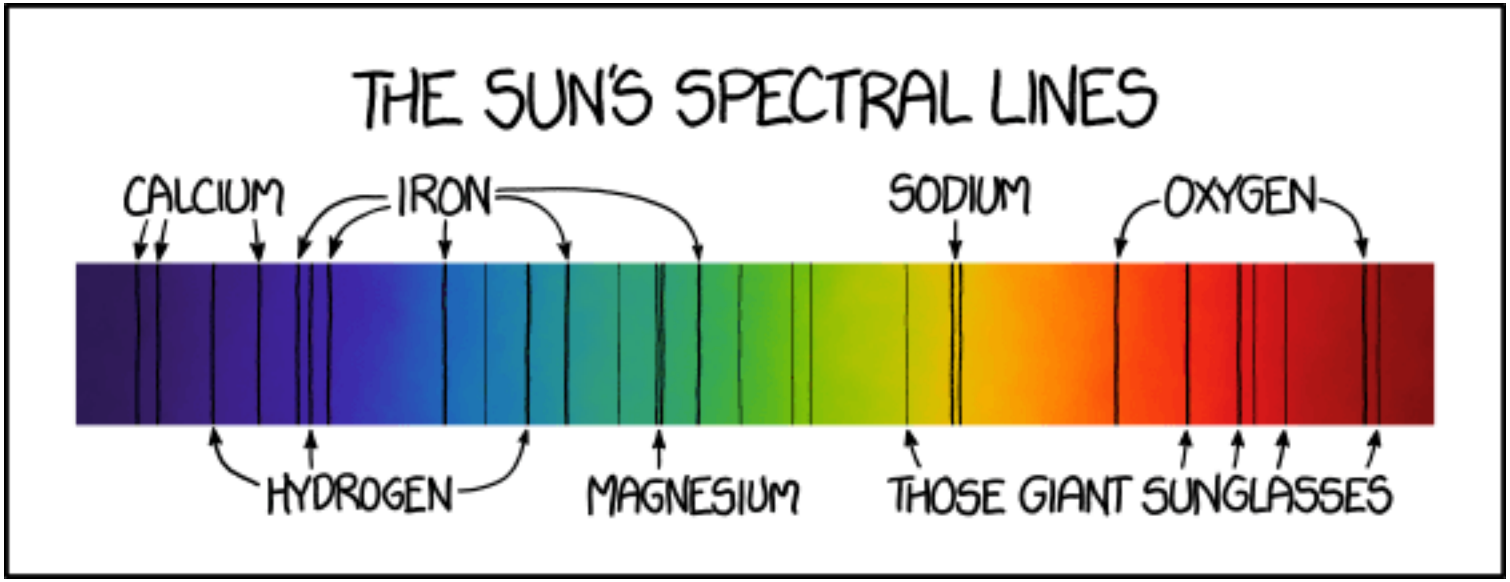
An incoming photon with energy equal to the difference between the high and low energy states can 'stimulate' the atom to transit back to the low energy state and emit a photon with identical energy, polarization, phase and propagation direction as the incoming photon. The incoming photon is unaffected. This process is called **stimulated emission**. This was first theoretically developed by Einstein.

Absorption



An incoming photon is absorbed by an atom at the groud state, pumping the atom to a higher energy state. The energy of the photon is equal to the energy difference between the high and ground state. This process is called **absorption**.

Absorption Spectrum



https://en.wikipedia.org/wiki/Fraunhofer_lines

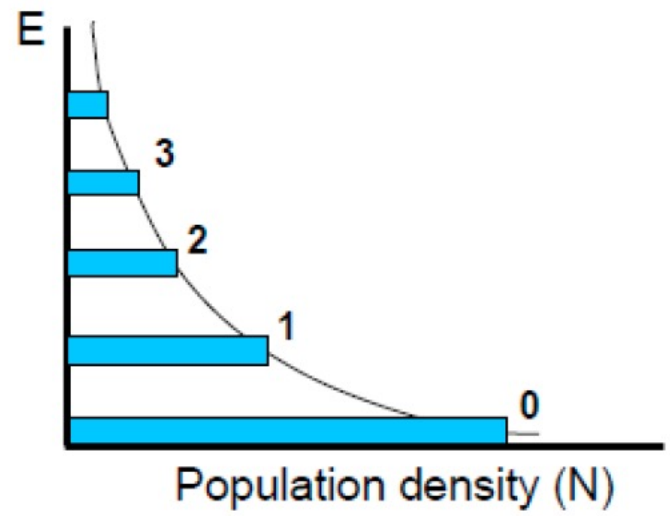
Each element in the Periodic Table has its own unique absorption spectrum. This can be used to identify the elemental composition in the gases of stars. The spectrum shown above is called Fraunhofer lines, which is the optical absorption spectrum of sun.

Population Distribution Law

At temperature T, the number of atoms at an energy level E is given by

$$N(E,T) = N_0 e^{-\frac{(E-E_0)}{k_B T}}$$

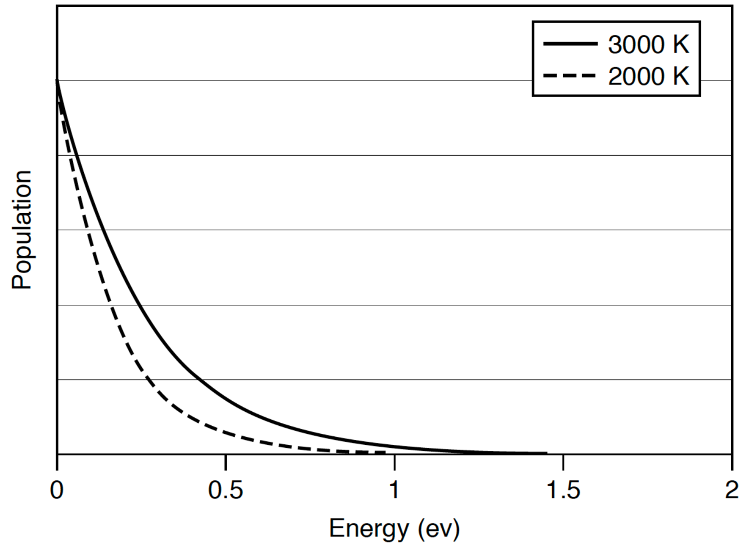
E_0: ground state energy
N_0: number of atoms at ground state



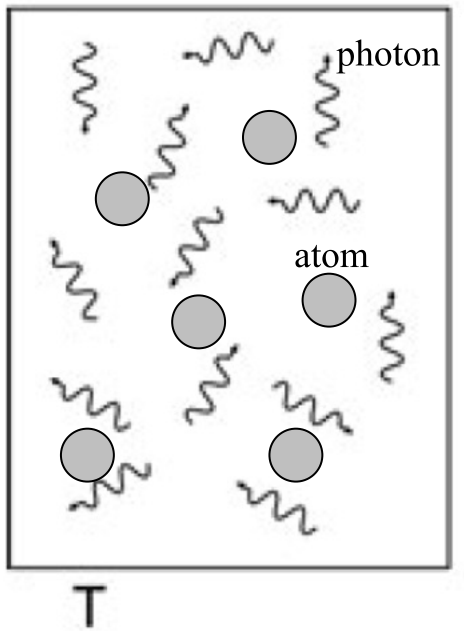
The ratio of atom population between any two energy levels is

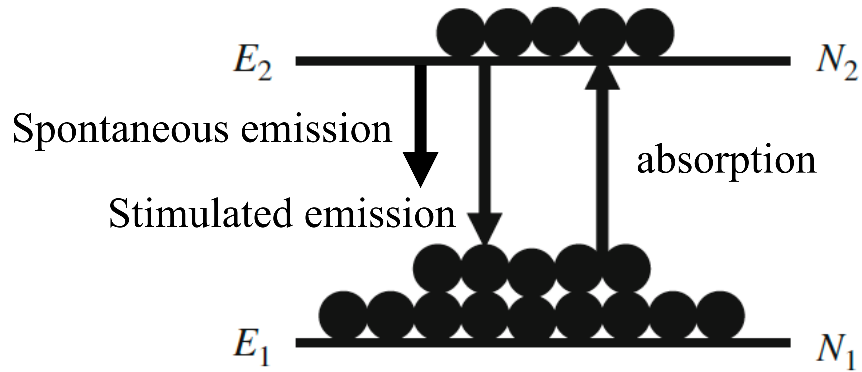
$$\frac{N_2}{N_1} = e^{-\frac{E_2-E_1}{k_B T}} = e^{-\frac{\Delta E_{21}}{k_B T}}$$

- Higher energy levels have less atoms
- Population increases with temperature



Einstein Coefficients





Einstein considered a system composed of a collection of atoms sealed in a vessel. The system is at thermal equilibrium at temperature T. *Absorption* transports atoms from low energy level to high energy level, while *spontaneous emission* and *stimulated emission* processes transport atoms back from high energy level to low energy level. As the system is at thermal equilibrium, at any time, the change rate of atom population at energy level 1 must equal to the change rate of atom population at energy level 2.

$$\frac{dN_1}{dt} = \frac{dN_2}{dt}$$

Einstein Coefficients

1. Absorption rate

$$\frac{dN_1}{dt} = -B_{12}\rho(\upsilon)N_1$$

2. Stimulated emission rate

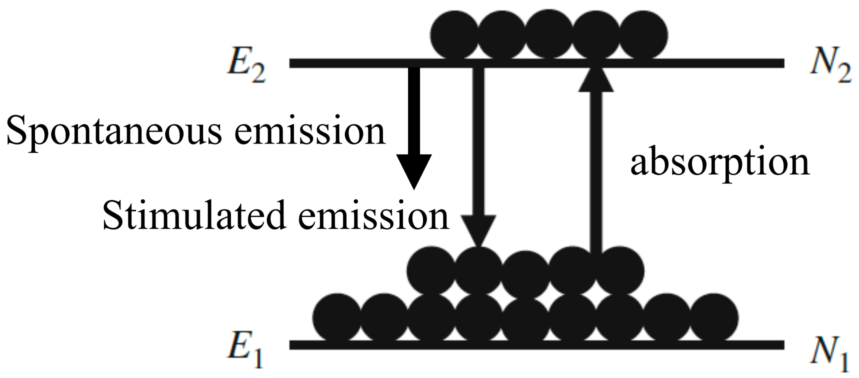
$$\left(\frac{dN_2}{dt}\right)_{St} = -B_{21}\rho(\upsilon)N_2$$

3. Spontaneous emission rate

$$\left(\frac{dN_2}{dt}\right)_{Sp} = -A_{21}N_2$$

B_{12}, B_{21}, A_{21}: Einstein coefficients

$\rho(\upsilon)$ is the spectral energy density



For the case of blackbody radiation, according to Planck's law:

$$\rho(\upsilon) = \frac{8\pi n^3 h\upsilon^3}{c^3}\frac{1}{e^{h\nu/k_B T} - 1}$$

n: refractive index of medium
h: Planck constant
c: speed of light
k_B: Boltzmann constant
T: temperature

Einstein Coefficients

Thermal equilibrium condition requires:

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = \left(\frac{dN_2}{dt}\right)_{sp} + \left(\frac{dN_2}{dt}\right)_{st}$$

$$B_{12}\rho(v)N_1 = A_{21}N_2 + B_{21}\rho(v)N_2$$

$$\rho(v) = \frac{A_{21}N_2}{N_1B_{12} - N_2B_{21}} = \frac{A_{21}}{\frac{N_1}{N_2}B_{12} - B_{21}}$$

$$= \frac{\frac{A_{21}}{B_{21}}}{\frac{B_{12}}{B_{21}}\frac{N_1}{N_2} - 1} = \frac{\frac{A_{21}}{B_{21}}}{\frac{B_{12}}{B_{21}}e^{h\nu/k_BT} - 1} \quad (1)$$

$$\frac{N_1}{N_2} = e^{\frac{E_2 - E_1}{k_BT}} = e^{h\nu/k_BT}$$

$$\rho(v) = \frac{8\pi n^3 hv^3}{c^3}\frac{1}{e^{h\nu/k_BT} - 1} \quad (2)$$

Comparing (1) and (2), we obtain

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

Einstein coefficients of absorption and stimulated emission are identical. Absorption is the reverse process of stimulated emission.

$$\frac{A_{21}}{B_{21}} = \frac{8\pi n^3 hv^3}{c^3}$$

Spontaneous Emission vs Stimulated Emission

Ratio between spontaneous emission and stimulated emission

$$R = \frac{A_{21}}{B_{21}\rho(\upsilon)} = e^{h\nu/k_B T} - 1$$

Example: $\lambda = 500\text{ nm}, \mathrm{T} = 1000\mathrm{K}$

$$h\nu = 6.626\times10^{-34}\times\frac{3\times10^{8}}{500\times10^{-9}} = 3.97\times10^{-19}\,J$$

$$k_B\,T = 1.38\times10^{-23}\times1000 = 1.38\times10^{-20}\,J$$

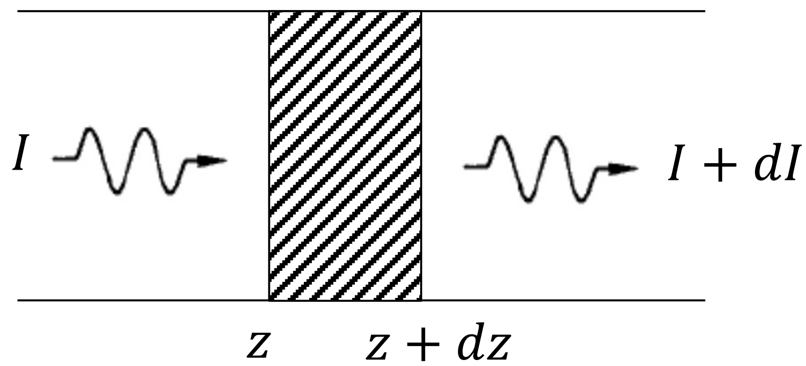
$$R = e^{h\nu/k_B T} - 1 \approx e^{28.7} \approx 3.16\times10^{12}$$

For $R = 1$

$$\frac{h\nu}{k_B\,T} = \ln 2 \Rightarrow T \approx 41{,}500\text{ K}$$

In normal circumstances, light emission is dominated by spontaneous emission, hence light from natural sources mostly originates from spontaneous emission process, with random phase, direction, and broad line width.

Light Amplification

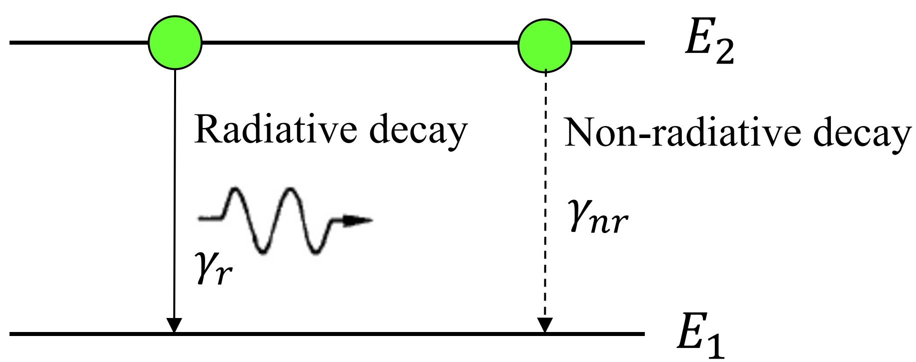


The increased light intensity dI after travelling a distance dz in the lasing medium is determined by the difference of stimulated emission and absorption, given by

$$dI \propto [B_{21}\rho(v)N_2 - B_{12}\rho(v)N_1] = B_{12}\rho(v)(N_2 - N_1)$$

To have amplification of light intensity, it requires $dI > 0$, however, generally $N_2 < N_1$, so $dI < 0$. This means in normal circumstances light is absorbed rather than amplified. To achieve amplification, we need $N_2 > N_1$, so called ***population inversion***.

Lifetime

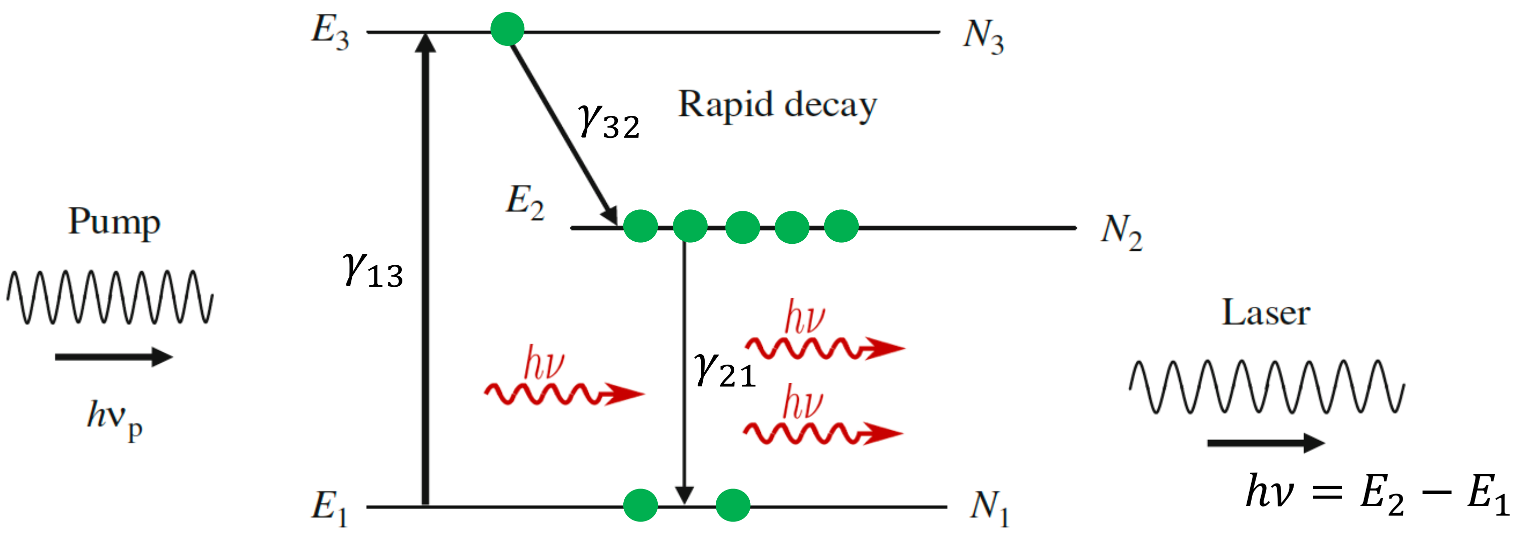


Atoms can stay at excited energy states for a short time. They will transit back to the ground state either by emitting a photon which is called radiative decay or without emitting a photon which is called non-radiative decay. The lifetime τ of atoms at an excited state is inversely proportional to the total decay rate (sum of radiative decay rate γ_r and the non-radiative decay rate γ_{nr}).

$$\tau = \frac{1}{\gamma_r + \gamma_{nr}}$$

Population Inversion

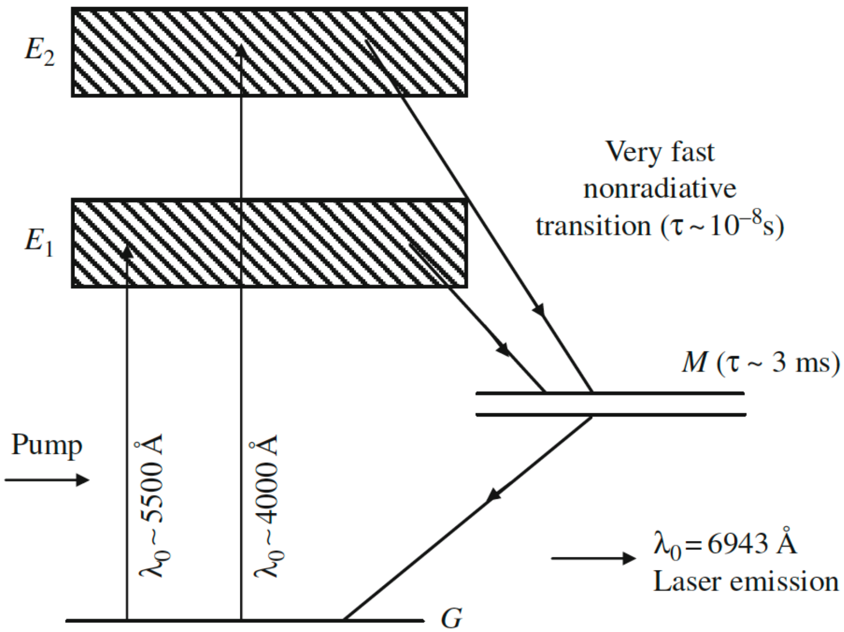
3-level lasing system



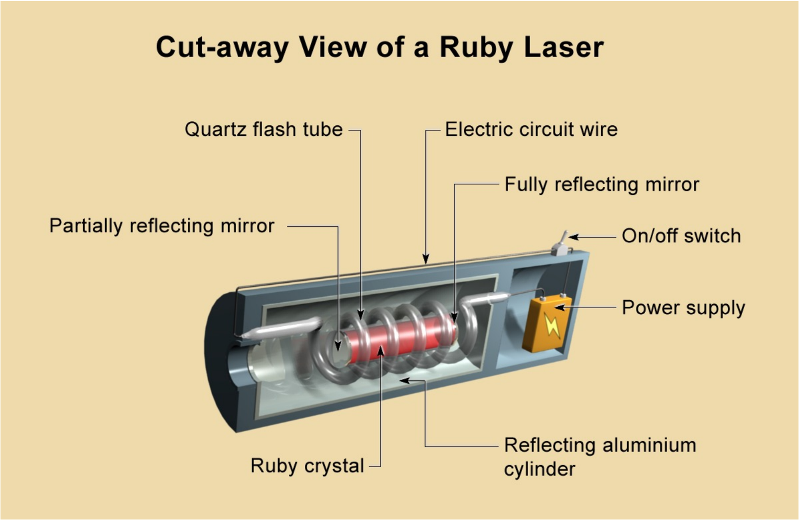
Population inversion can be achieved on a three energy-level system involving different lifetimes.

- Atoms are pumped onto the highest level 3 with an absorption rate γ_{13}.
- Atoms at level 3 quickly relax to level 2 without emitting photons with a decay rate γ_{32}.
- Atoms at level 2 transit to the ground state much more slowly with a decay rate γ_{21}.
- Under the condition $\gamma_{32} \gg \gamma_{13} \gg \gamma_{21}$, or lifetime $\tau_{32} \ll \tau_{13} \ll \tau_{21}$, more atoms will be accumulated at energy level 2 than at the ground state, achieving population inversion between level 2 and level 1.
- Lasing happens between level 2 and the ground state through stimulated emission, emitting photons of energy $h\nu = E_2 - E_1$.

The First Laser



Ruby: Alumina (Al_2O_3) doped with Chromium (~0.05 % by weight)



The world's first laser invented by Maiman in 1960 in principle is a 3-level lasing system (though it involves more than three energy levels). Atoms at the ground state are pumped onto bands of excited states (E_1 and E_2), then quickly (~10^{-8}s) transit to a metastable state (M). The transition from state M to the ground state has a much longer lifetime (~3 ms), thus achieving population inversion. Lasing happens between state M and the ground state with an emission wavelength of 694.3 nm.

<u>Key characteristic of 3-level lasing system</u>: lasing is between a metastable state and the **ground state**.
<u>Disadvantage</u>: requiring significant pumping power, as at least half of atoms at the ground state need to be pumped onto excited states.

Stimulated Optical Radiation in Ruby

Schawlow and Townes[1] have proposed a technique for the generation of very monochromatic radiation in the infra-red optical region of the spectrum using an alkali vapour as the active medium. Javan[2] and Sanders[3] have discussed proposals involving electron-excited gaseous systems. In this laboratory an optical pumping technique has been successfully applied to a fluorescent solid resulting in the attainment of negative temperatures and stimulated optical emission at a wave-length of 6943 Å.; the active material used was ruby (chromium in corundum).

A simplified energy-level diagram for triply ionized chromium in this crystal is shown in Fig. 1. When this material is irradiated with energy at a wave-length of about 5500 Å., chromium ions are excited to the $^4F_2$ state and then quickly lose some of their excitation energy through non-radiative transitions to the ^2E state[4]. This state then slowly decays by spontaneously emitting a sharp doublet the components of which at 300° K. are at 6943 Å. and 6929 Å. (Fig. 2a). Under very intense excitation the population of this metastable state (^2E) can become greater than that of the ground-state; this is the condition for negative temperatures and consequently amplification via stimulated emission.

To demonstrate the above effect a ruby crystal of 1-cm. dimensions coated on two parallel faces with silver was irradiated by a high-power flash lamp; the emission spectrum obtained under these conditions is shown in Fig. 2b. These results can be explained on the basis that negative temperatures were produced and regenerative amplification ensued. I expect, in principle, a considerably greater (~ 10[5]) reduction in line width when mode selection techniques are used[1].

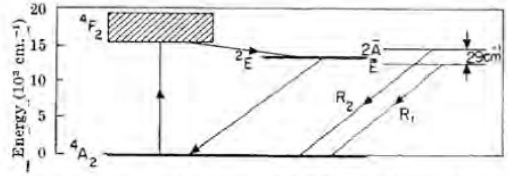


Fig. 1. Energy-level diagram of Cr^{3+} in corundum, showing pertinent processes

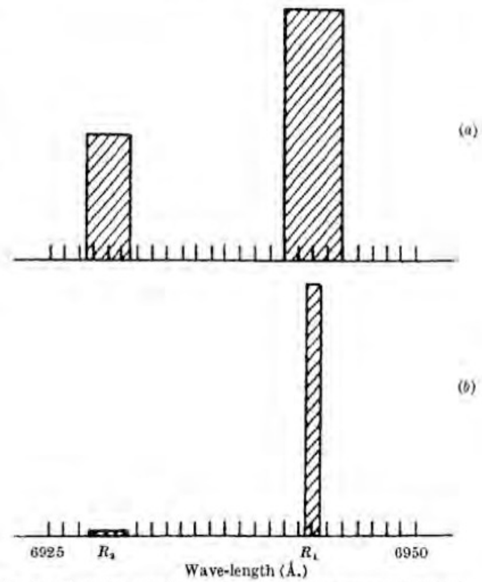


Fig. 2. Emission spectrum of ruby: *a*, low-power excitation; *b*, high-power excitation

I gratefully acknowledge helpful discussions with G. Birnbaum, R. W. Hellwarth, L. C. Levitt, and R. A. Satten and am indebted to I. J. D'Haenens and C. K. Asawa for technical assistance in obtaining the measurements.

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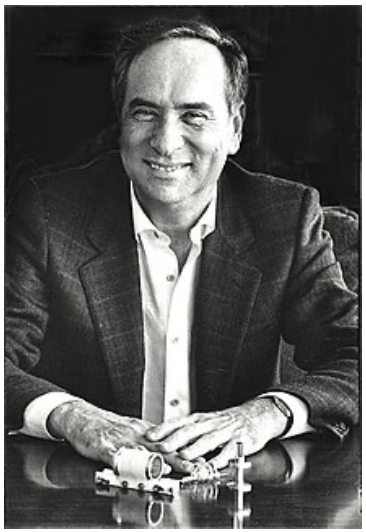
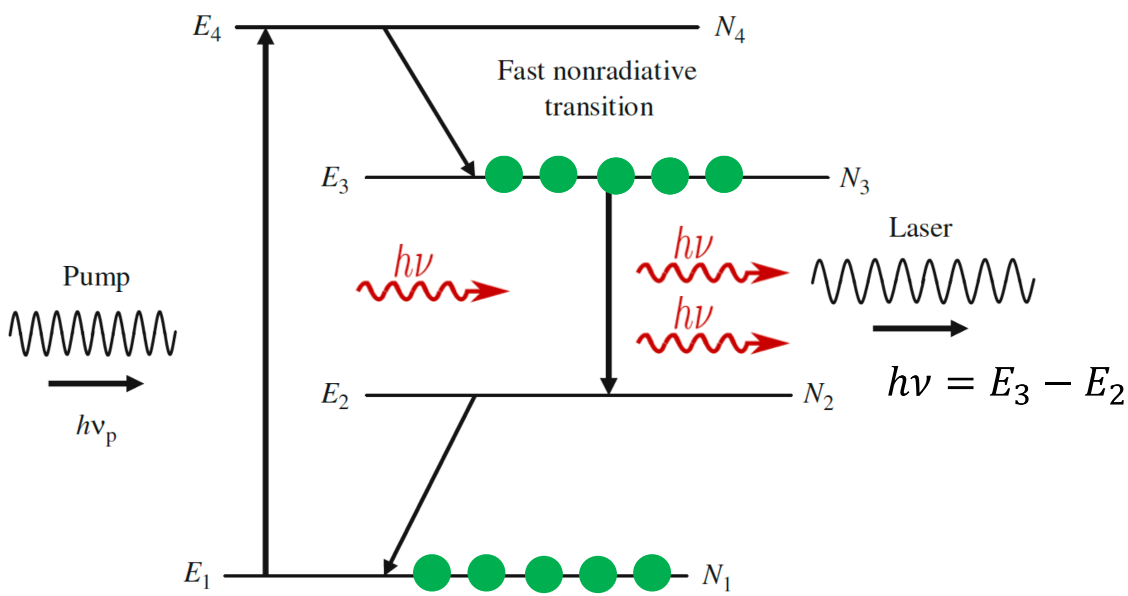
[1] Schawlow, A. L., and Townes, C. H., *Phys. Rev.*, **112**, 1940 (1958).
[2] Javan, A., *Phys. Rev. Letters*, **3**, 87 (1959).
[3] Sanders, J. H., *Phys. Rev. Letters*, **3**, 86 (1959).
[4] Maiman, T. H., *Phys. Rev. Letters*, **4**, 564 (1960).



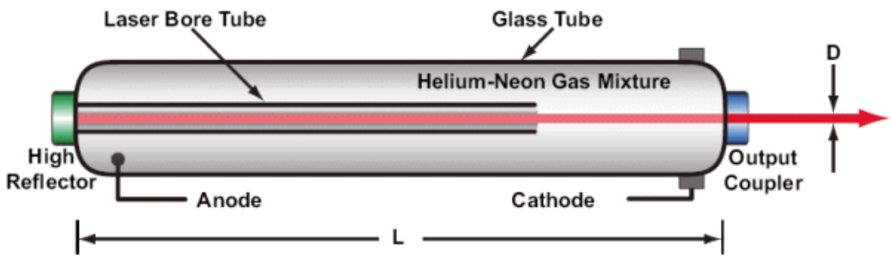
Theodor Maiman
(1927-2007)

Four Level Lasing System

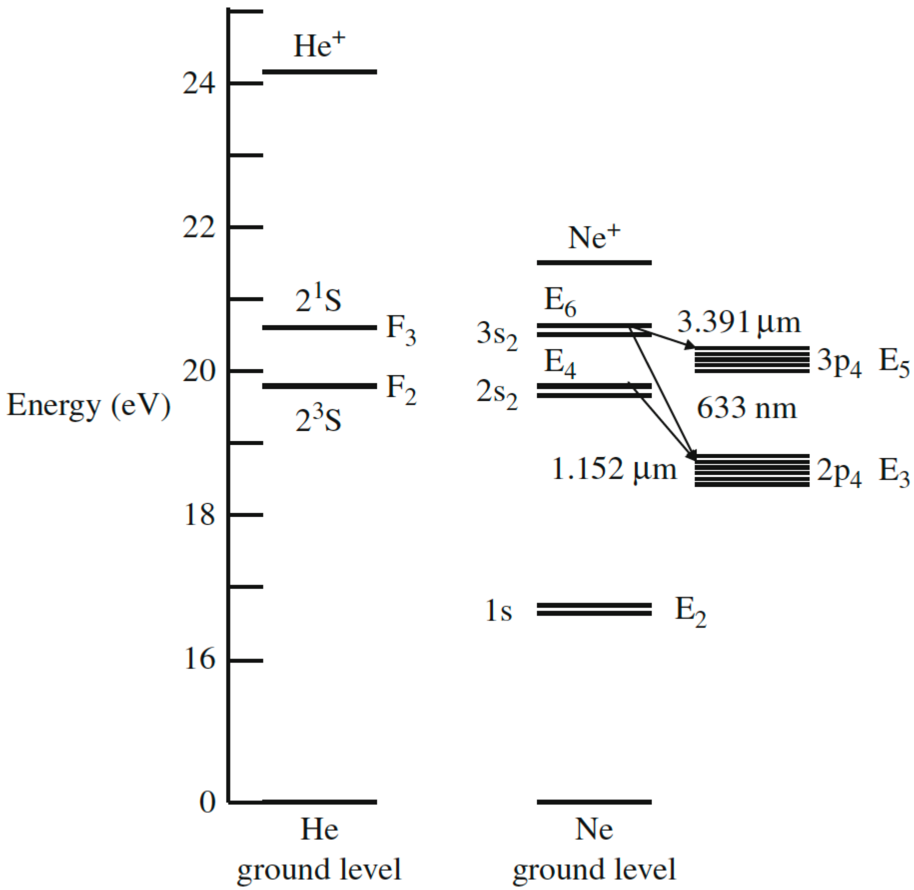


- Atoms at the ground state (level 1) are pumped to the highest level (level 4), which quickly relax to level 3 via nonradiative transition processes without emitting photons.
- The transition from level 3 to level 2 is a slow process, so atoms are accumulated at level 3.
- Transition from level 2 to level 1 is fast, so very few atoms remain at level 2, therefore achieving population inversion between level 3 and 2.
- As the ground state is not involved in lasing, there is no need to pump at least >50% atoms as the case in a 3-level system, hence a 4-level system can be more efficient than a 3-level lasing system.

He-Ne Laser

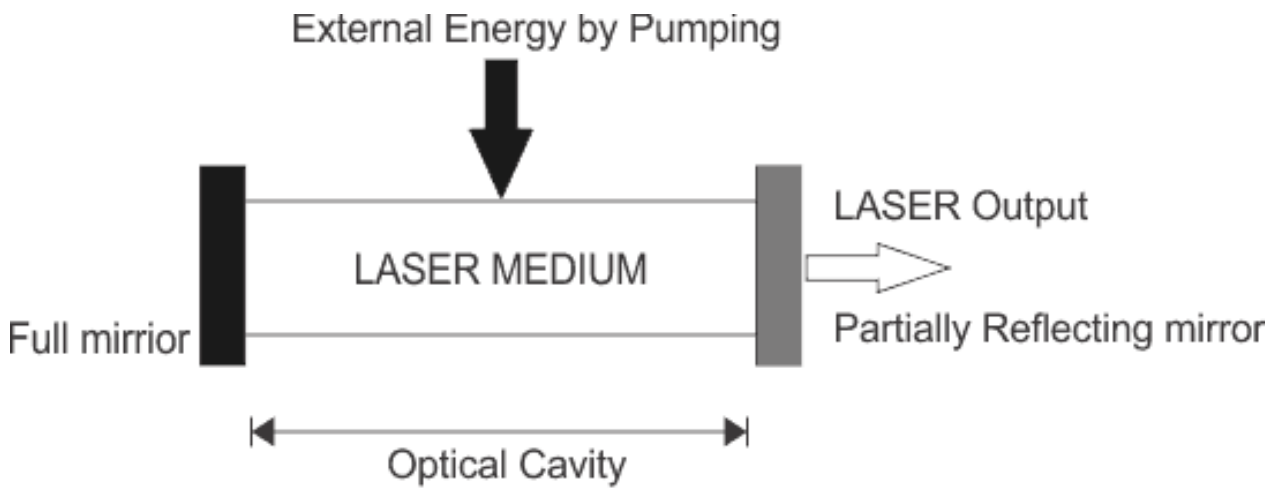


λ =632.8 nm



- A 4-level lasing system.
- Mixture of He and Ne gas at a ratio of 10:1 (1 torr and 0.1 torr, respectively).
- He atoms are excited to long lifetime (10^{-6}~10^{-4} s) states F2, F3, which excite Ne atoms to E4, E6 states through collision.
- Transition between E6 and E3 produces the emission of 632.8 nm laser line.
- E3 to E2 is a fast process with lifetime of ~ 10^{-8}s, much shorter than the lifetime of E6, so steady population inversion can be achieved between E6 and E3.

Structure of Laser

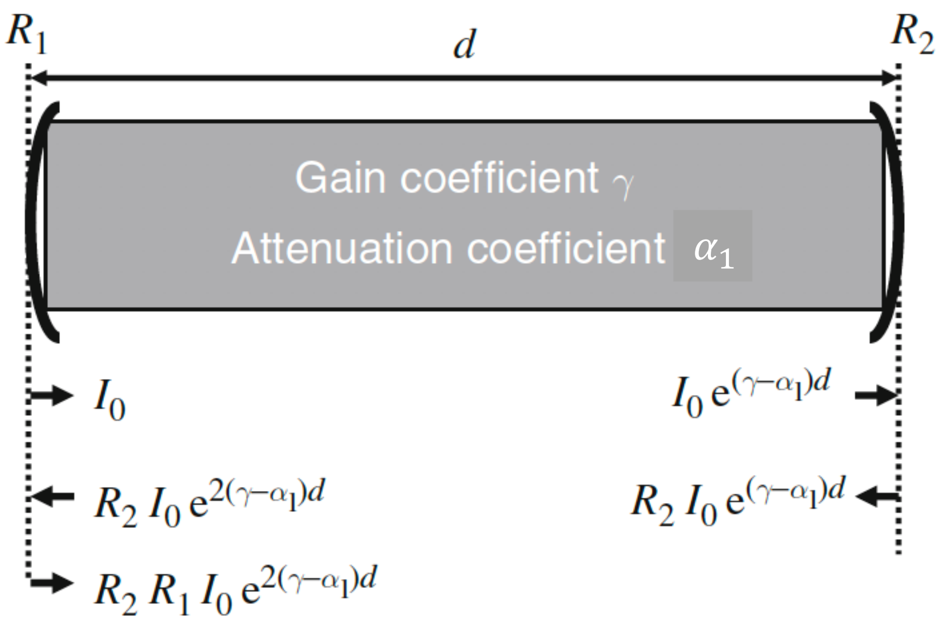


Components of LASER

A laser has three basic elements:

- A pump source: input energy to pump atoms from ground states to excited states. Common pumping techniques include optical pumping (flash lamp or other lasers) and particle pumping (through particle collision, mostly adopted in gas lasers)
- A gain (lasing) medium
- An optical resonator cavity: a pair of reflective mirrors to reflect laser beam back and forth inside the cavity many many times to increase the gain. One mirror is partially reflective to allow the output of some portion of energy.

Threshold Condition



After one complete round trip inside the resonator cavity, the intensity of the reflected beam after mirror 1 is enhanced by a factor of $R_1R_2e^{2(\gamma-\alpha_1)d}$. For light amplification to happen, this factor needs to be greater than 1.

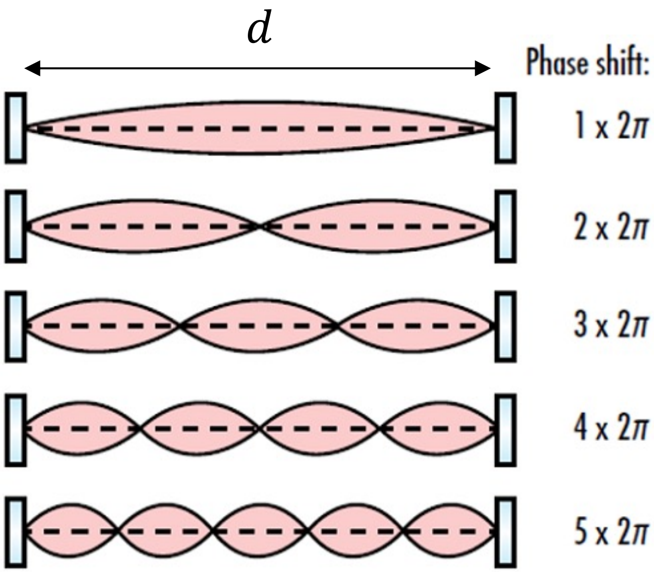
$$R_1R_2e^{2(\gamma-\alpha_1)d} \geq 1$$

Threshold condition for lasing

Example: A He-Ne laser, at 632.8 nm
Gain coefficient $\gamma = 0.1/m$
Loss: 0.5% per round trip
$R_1 \approx R_2 = 99.9\%$
$d = 20\ cm$

$$R_1R_2e^{2(\gamma-\alpha_1)d} \approx 1.013 > 1$$

Longitudinal Cavity Mode



In order to have maximum amplification effect, the phase change of a complete round trip should be integer multiples of 2π so that light is constructively interfered. This means the cavity length should be multiples of half wavelength of light in the lasing medium.

$$d = n\left(\frac{\lambda_{max}}{2}\right) \rightarrow \lambda_{max} = \frac{2d}{n}$$

n is an integer, λ_{max} is the wavelength of emission light inside the lasing medium that will have maximum amplification.

Longitudinal Cavity Mode

<u>Longitudinal cavity modes</u>

The frequencies of maximum amplification laser lines are

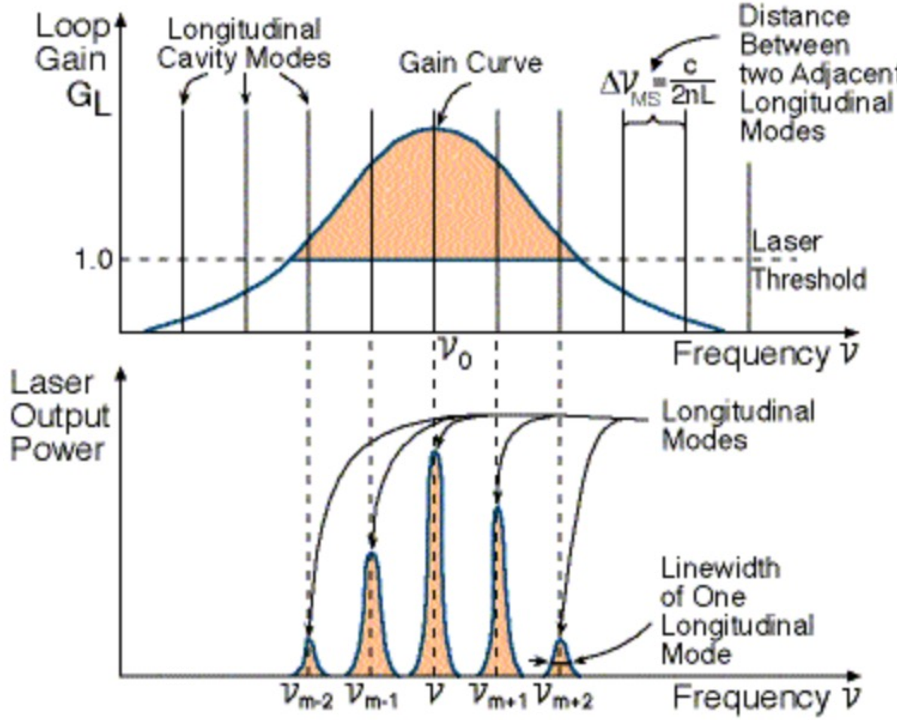
$$\nu_n = \frac{c}{\eta\lambda_{max}} = \frac{nc}{2\eta d}$$

η: refractive index of lasing medium

<u>Frequency separation:</u>

$$\Delta\nu_{sp} = \nu_{n+1} - \nu_n = \frac{(n+1)c}{2\eta d} - \frac{nc}{2\eta d} = \frac{c}{2\eta d}$$

Constant frequency separation

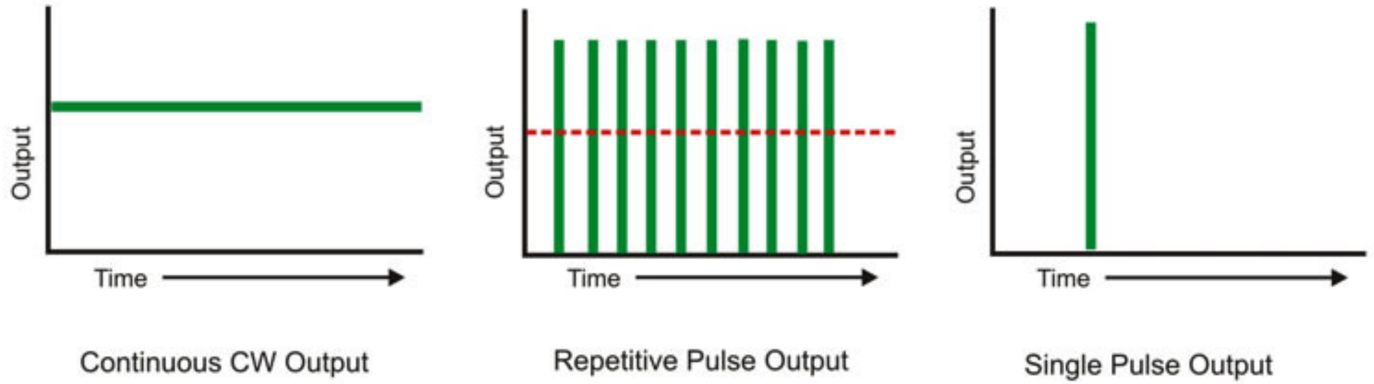


Types of Lasers

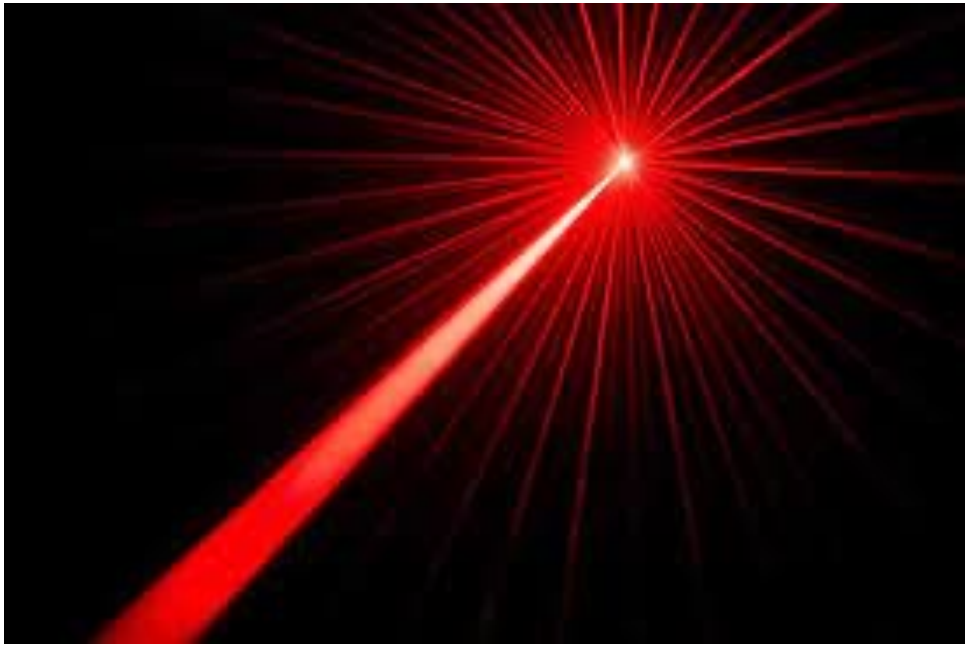
Lasing medium and structure: gas laser, dye (liquid) laser, solid state laser, semiconductor laser, fiber laser, photonic crystal laser, surface plasmon laser, free electron laser

- Gas laser: HeNe, CO_2 (up to hundreds of kilowatts, 9.6 and 10.6 μm), excimer lasers (F_2, ArF, KrCl, KrF, XeCl etc, UV light), Argon ion lasers (visible range).
- Liquid laser: dye lasers (320-1200 nm, CW or pulsed, can be very powerful).
- Solid state laser: ruby laser, Ti:Sapphire laser, Nd YAG laser
- Free electron laser: very broad frequency range from teraHz to soft x-ray.

Mode of operation: continuous wave (CW) operation, pulsed operation



Properties of Lasers

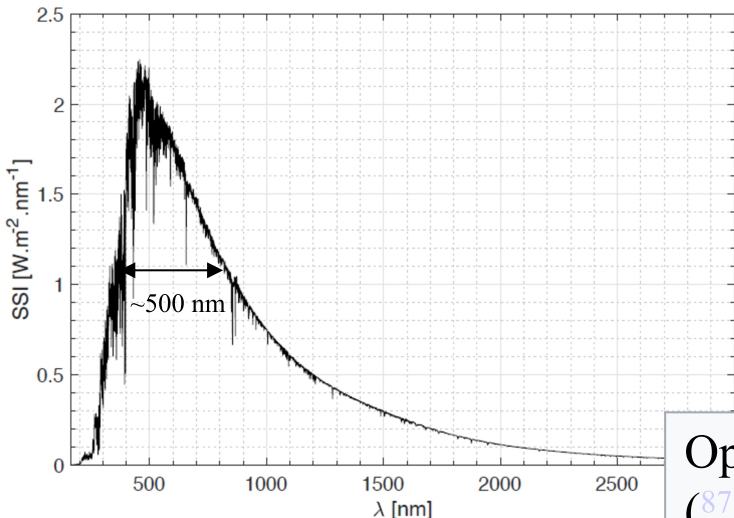


Laser is a special light source developed from quantum theory that has extraordinary properties not possessed by natural light sources, including (not limited to)

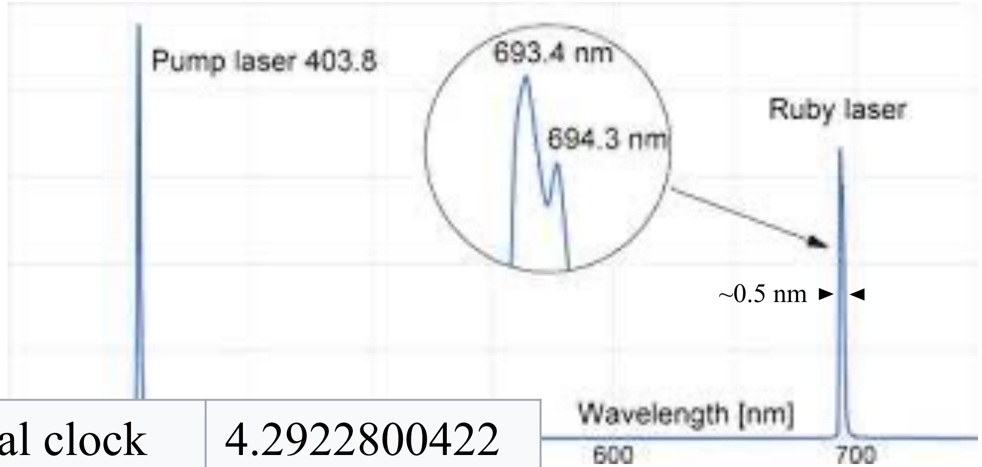
- Monochromatic
- Highly collimated
- Coherent
- High intensity

Monochromaticity

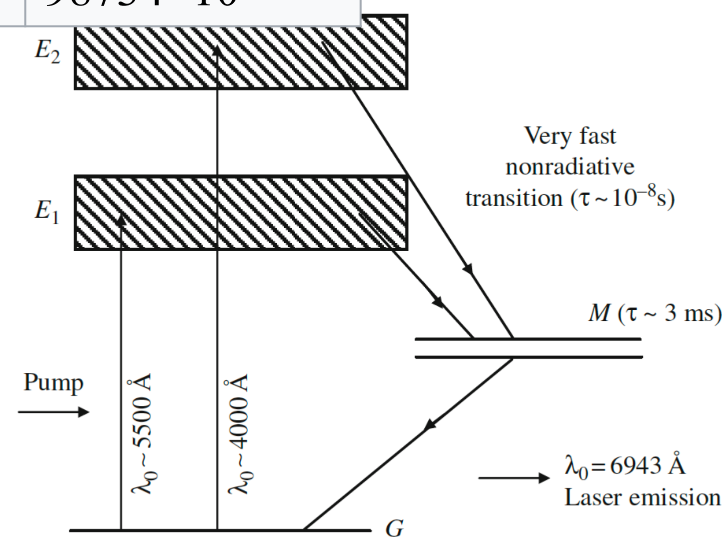
Solar spectrum



Emission line of Ruby laser



Optical clock (^{87}Sr)	$4.2922800422\,98734\times10^{14}$

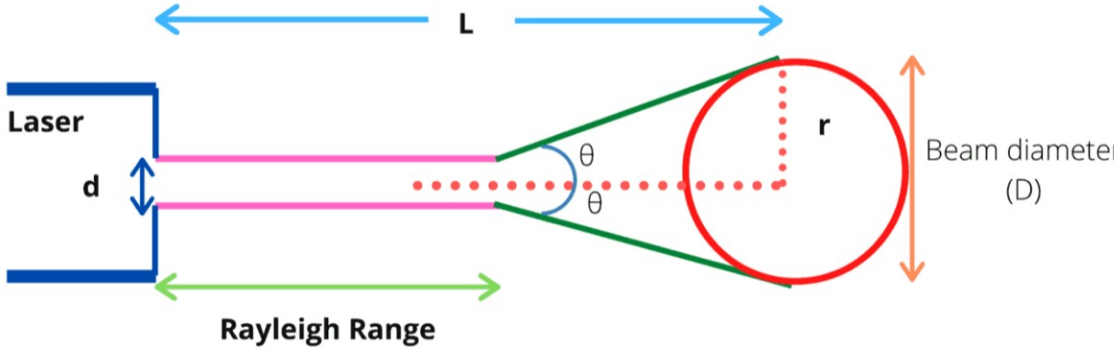


- Laser emission is due to the transition between two discrete quantum states of well-defined energies, hence can have very narrow linewidth.
- Today's lasers can have linewidth < 1 Hz (corresponding to ~10^{-21} nm for visible light).
- Applications: atomic clock, spectroscopy, interferometer etc

Optical clock (^{87}Sr), $\upsilon = 4.29228004229873 4\times10^{14}$Hz

Accuracy~1 part in 10^{16}

Directionality



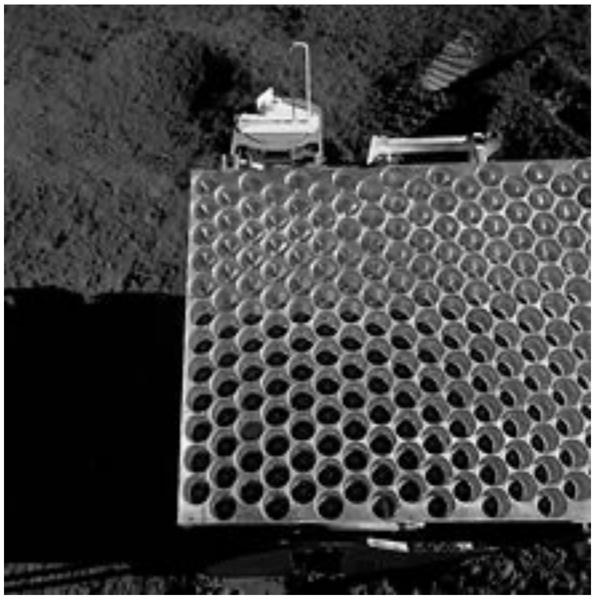
- Laser beams are highly directional with very small divergence.
- Laser beam can travel a distance near the laser source almost without any divergence. This distance is given by $\frac{d^2}{\lambda}$, called Rayleigh range.
- After the Rayleigh range, laser beam has a divergent angle $\theta \approx \frac{\lambda}{d}$, d is aperture or diameter of laser beam.
- After traveling distance L, the beam diameter is $D \approx 2L\theta = \frac{2L\lambda}{d}$

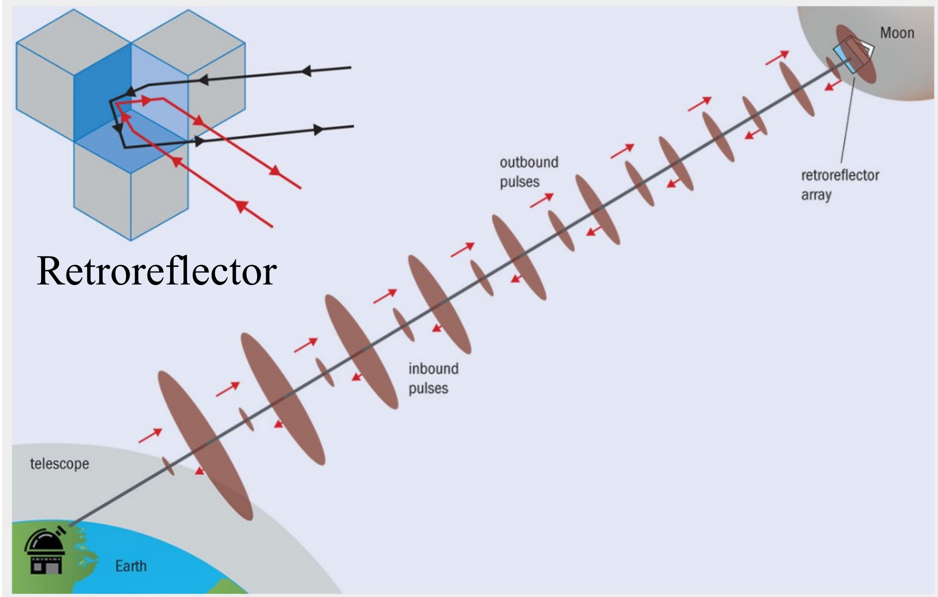
Example: $\lambda = 632$ nm, $d = 1$ mm, $L = 1$ km

Rayleigh range $= \frac{d^2}{\lambda} = 1.58$ m, $\theta \approx \frac{\lambda}{d} = 6.32\times10^{-4}$ rad, $D = \frac{2L\lambda}{d} = 1.26$ m

Lunar Laser Ranging Experiment

Apollo 15 LRRR





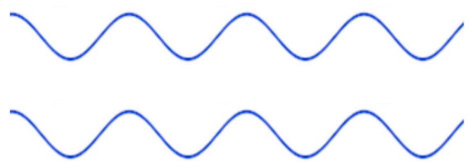
- By sending pulsed laser shots to retroreflector installed on moon and measuring the round-trip time, the distance between moon and earth can be measured.
- Beam size on moon ~ 2 km. Return beam size on earth ~15 km.
- Accuracy up to millimeter for a distance of ~ 384,400 km, ~2 parts in 10^{12}.

Tests of gravitation physics and investigation of moon properties

- Moon is moving away from earth at a rate of 3.8 cm/yr
- Moon probably has a liquid with radius of ~ 350 km
- Gravitation constant change rate $\frac{dG}{dt}/G < 10^{-12}$/yr

Coherence

- Coherence is an important property of waves, which quantifies the correlation between physical quantities of a single wave, or between several waves or wave packets.
- Two waves are coherent if the fields have definite phase difference.



$$E_1 = A_1 e^{i\varphi_1}$$

$$E_2 = A_2 e^{i\varphi_2}$$

$$\Delta\varphi = \varphi_2 - \varphi_1$$

- Coherent: $\Delta\varphi$ has a definite value, φ_1 and φ_2 are corelated
- Incoherent: $\Delta\varphi$ is random, φ_1 and φ_2 are unrelated

When two waves meet, the total electric field is the sum of the electric fields of the two waves

$$E = E_1 + E_2 = A_1 e^{i\varphi_1} + A_2 e^{i\varphi_2}$$

Intensity

Intensity $$I = \langle EE^* \rangle = \left\langle \left(A_1 e^{i\varphi_1} + A_2 e^{i\varphi_2}\right)\left(A_1 e^{-i\varphi_1} + A_2 e^{-i\varphi_2}\right) \right\rangle$$

$$= A_1^2 + A_2^2 + A_1 A_2 \left(\left\langle e^{i(\varphi_1 - \varphi_2)} \right\rangle + \left\langle e^{i(\varphi_2 - \varphi_1)} \right\rangle \right)$$

$I_1 = A_1^2, I_2 = A_2^2$ $$= I_1 + I_2 + A_1 A_2 \left(\left\langle e^{i(\varphi_1 - \varphi_2)} \right\rangle + \left\langle e^{i(\varphi_2 - \varphi_1)} \right\rangle \right)$$

Incoherent waves: $\varphi_1 - \varphi_2$ is unrelated. $\left\langle e^{i(\varphi_1 - \varphi_2)} \right\rangle = \left\langle e^{i(\varphi_2 - \varphi_1)} \right\rangle = 0$

$$I_{incoherent} = I_1 + I_2$$

Coherent waves: $\varphi_1 - \varphi_2 = \delta$ is a definite value. $\left\langle e^{i(\varphi_1 - \varphi_2)} \right\rangle + \left\langle e^{i(\varphi_2 - \varphi_1)} \right\rangle = 2\cos\delta$

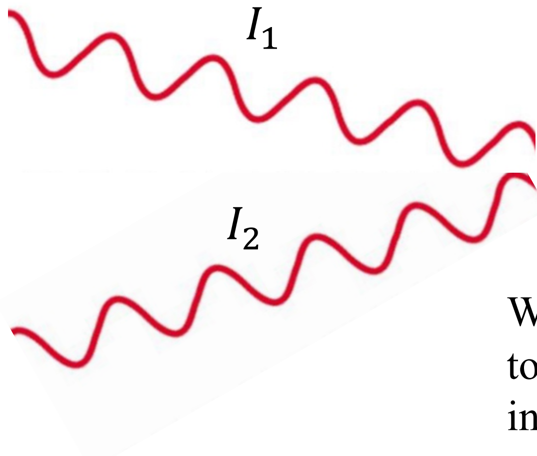
$$I_{coherent} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\delta$$

$I_{max} = I_1 + I_2 + 2\sqrt{I_1 I_2}$, when $\delta = 0$, constructive interference

$I_{min} = I_1 + I_2 - 2\sqrt{I_1 I_2}$, when $\delta = \pi$, destructive interference

Interference

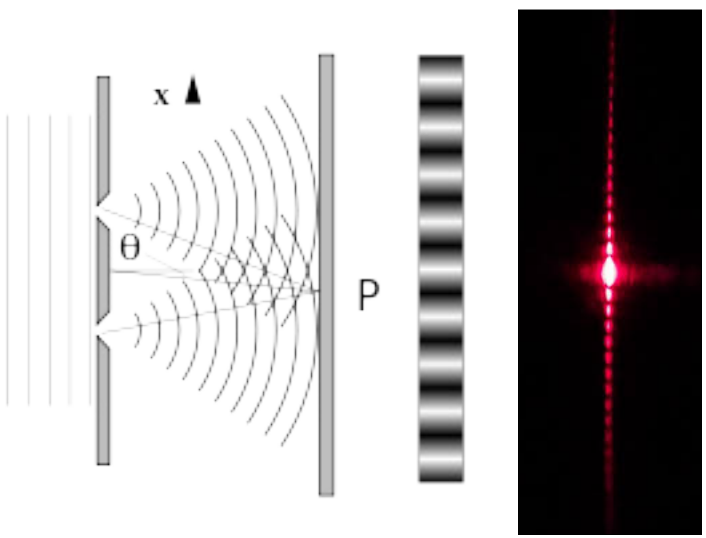
Incoherent light source



$I = I_1 + I_2$

When two incoherent beams meet, the total intensity is the sum of the intensity of two individual beams.

Coherent light source



Double slits experiment

When two coherent beams meet, the total intensity is dependent on the phase difference between the two beams, forming interference fringes.

Coherence Length and Time

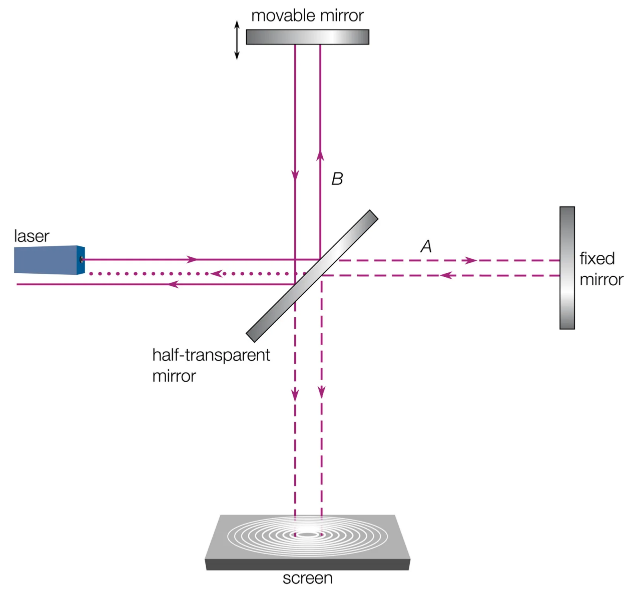
Coherence length: the propagation distance of a coherent wave over which it maintains a specified degree of coherence

$$L_c = \frac{\lambda^2}{\Delta\lambda}$$

$\Delta\lambda$: linewidth of laser

Coherence time: the time elapse over which a coherent wave maintains a specified degree of coherence

$$T_c = \frac{L_c}{c} = \frac{\lambda^2}{c\Delta\lambda}$$



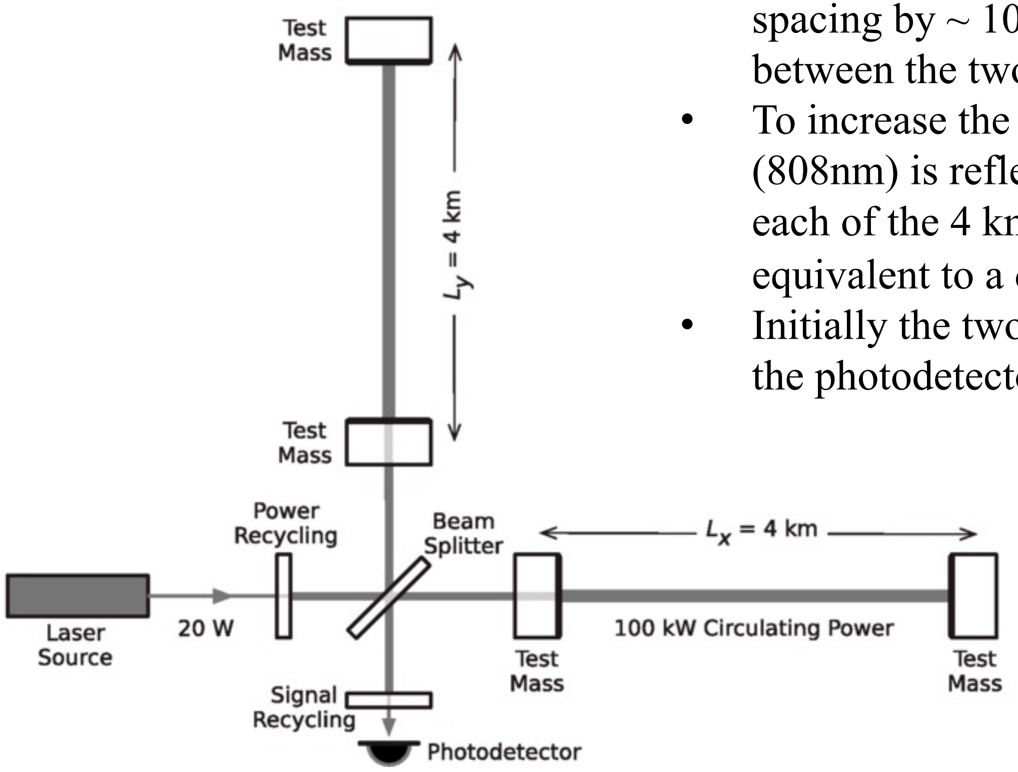
If the path difference of the two beams in an interferometer is longer than the coherence length, the visibility of interference fringes will degrade.

Examples:

- He-Ne laser $\lambda = 632.8$ nm, $\Delta\lambda \approx 0.001$ nm, $L_c \approx 40$ cm
- Sun light: $\lambda \approx 500$ nm, $\Delta\lambda \approx 500$ nm, $L_c \approx 500$ nm

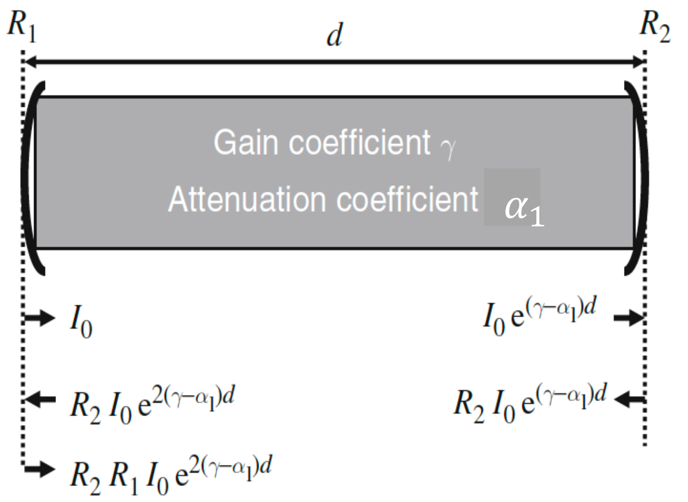
LIGO

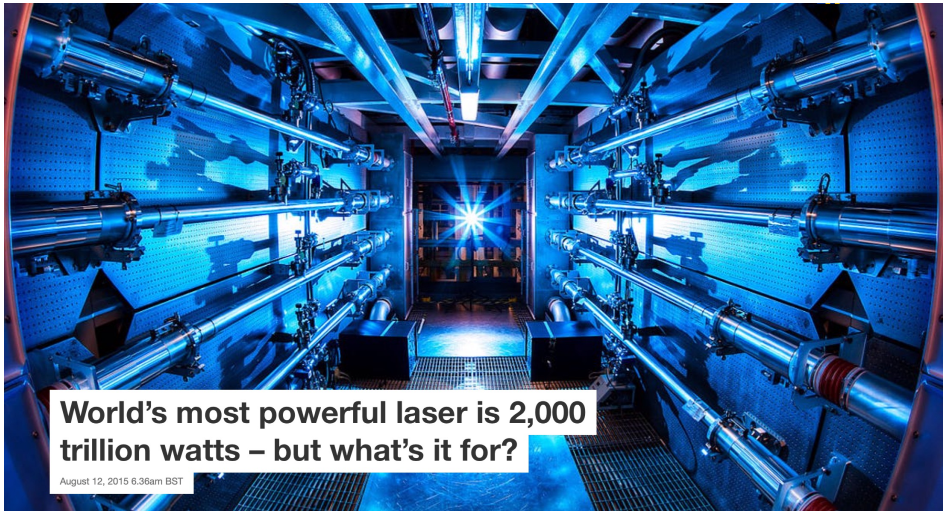
Laser Interferometer Gravitational-Wave Observatory (LIGO)



- Gravitation waves are expected to distort the 4 km mirror spacing by ~ 10^{-18} m. This will induce a phase difference between the two beams.
- To increase the phase difference, high power laser (808nm) is reflected forth and back for 280 round trips in each of the 4 km arm before merging in the detector, equivalent to a distance of 1120 km.
- Initially the two beams were tuned to be out of phase at the photodetector, so no signal was recorded.
- When gravitation waves arrive, it distorts the space, the two beams are not out-of-phase anymore, so the photodetector will record some signals.
- On 11 February 2016, first observation of gravitation waves was announced, due to the merge of two black holes.
- In 2017, Nobel Prize in Physics was awarded to Weiss, Thorne and Barish for '*decisive contributions to the LIGO detector and the observation of gravitational waves*'.

High Power





The amplification after one round trip

$$g = R_1 R_2 e^{2(\gamma-\alpha_1)d} > 1$$

After N round trips, intensity

$$I = I_0 g^N$$

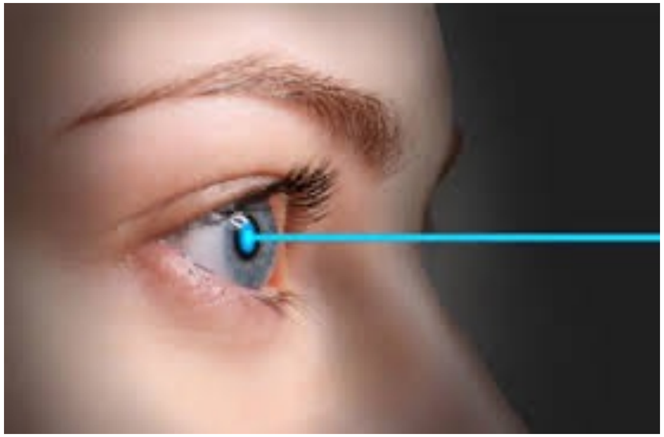
If only g and N are large enough, the power can be very high

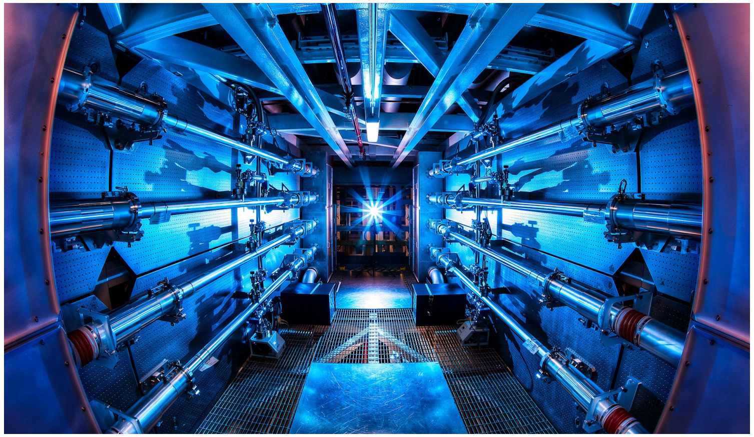
- Up to 100s kW cw lasers are commercially available
- US navy developed a Mid-Infrared Advanced Chemical Laser (MIRACL) with output cw power over megawatts, λ =3.8 μm, over 70s duration.
- EU's Extreme Light Infrastructure (ELI) project develops pulsed laser with peak power up to 10 PW (10,000,000,000,000,000 Watt). Pulse duration: ~24 fs.

Applications of High Power Lasers

<u>Applications of high power laser</u>

- Industrial application: cutting, welding, materials processing
- Surgery
- Plasma physics
- Nuclear Fusion
- Military





Laser fusion
National Ignition Facility
192 pulsed lasers, 1.9 MJ, <4 ns

Laser Safety

Due to the high power and low divergency of beam, lasers can potentially cause significant damages to eyes and even skins.

Class	Basis for Classification
Class 1 Laser Inherently Safe Visible/non visible	Lasers which are safe under reasonably foreseeable conditions of operation.
Class 1 Laser product Safe as long as not modified	A product that contains a higher class laser system but access to the beam is controlled by engineering means.
Class 2 Low Power Visible only	For lasers, protection of the eyes normally provided by natural aversion blink response which takes approx. 0.25s. Theses lasers are not intrinsically safe. AEL = 1 mW for a CW laser
Class 1M Safe without viewing aids 302.5 to 4000nm	Safe under reasonably foreseeable conditions of operation. Beams are either highly divergent or collimated but with a large diameter. May be hazardous if user employs optics with the beam.
Class 2M Safe without viewing aids Visible only	Protection of the eyes is normally provided by natural aversion blink response which takes approx. 0.25s. Beams are either highly divergent or collimated but with a large diameter. May be hazardous if user employs optics with the beam.
Class 3R Low/medium power Visible / non-visible	Risk of injury is greater than for the lower classes but not as high as for class 3B. Up to 5 times the AEL for Class 1 and Class 2.
Class 3B Medium / high power Visible / non-visible	Direct intrabeam viewing of these devices is always hazardous. Viewing diffuse reflections is normally safe provided the eye is no closer than 13 cm from the diffusing surface and the exposure duration is less than 10 seconds. AEL = 500mW for a CW laser
Class 4 High power Visible / non-visible	Direct intrabeam viewing is dangerous. Specular and diffuse reflections are hazardous. Eye, skin and fire hazard. TREAT CLASS 4 WITH CAUTION