PH 301

ENGINEERING OPTICS

Lecture_Optical Sources_17

LASER definition

L: LIGHT

A: AMPLIFICATION by

S: STIMULATED

E: EMISSION of

R: RADIATION

Laser Inventors

Invention: 1960

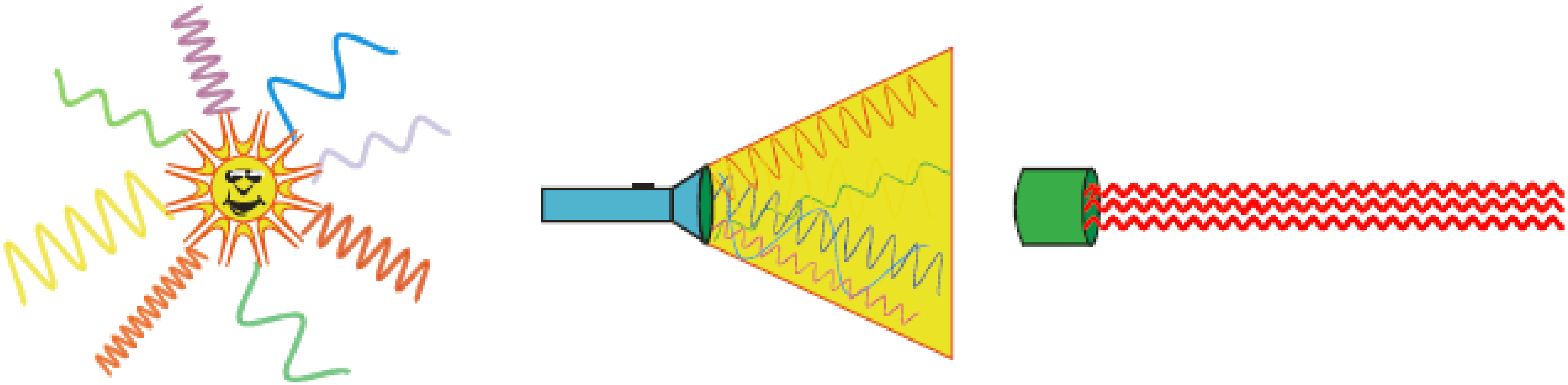
Nobel Prize: 1964

Charles Hard Townes
28.07.1915 – 27.01.2015
USA

Nicolay Gennadiyevich Basov
14.12.1922 – 01.07.2001
Russia

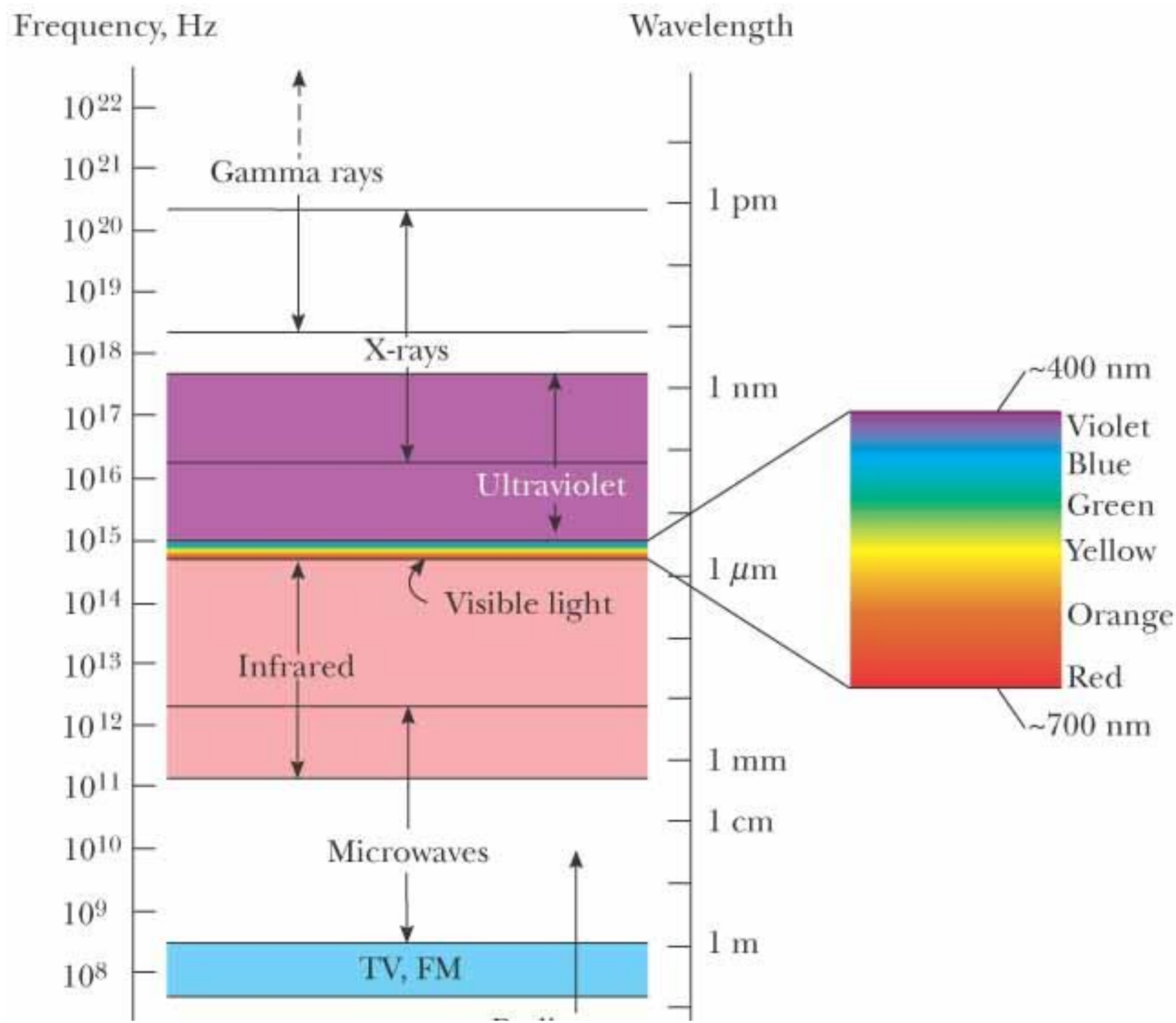
Alexander Prokhorov
11.07.1916 – 08.01.2000
Russia

Light sources



Sun Flashlight L.A.S.E.R.

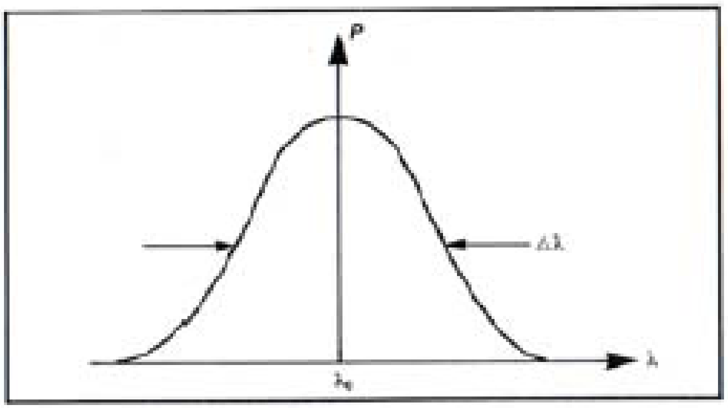
Light source	Light Power	Power density
Sun	10^{26} Watt	5×10^{2} W/cm^2
100 W Filament-lamp	3 Watt	10^{-2} W/cm^2
He-Ne- Laser	1 mWatt	4×10^{4} W/cm^2
CO_2 Laser	60 Watt	5×10^{6} W/cm^2
Pulsed Laser	1 GWatt	10^{14} W/cm^2



Frequency, Hz
Wavelength
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
Gamma rays
X-rays
Ultraviolet
Visible light
Infrared
Microwaves
TV, FM
1 pm
1 nm
1 μm
1 mm
1 cm
1 m
~400 nm
Violet
Blue
Green
Yellow
Orange
Red
~700 nm

Properties of LASER light

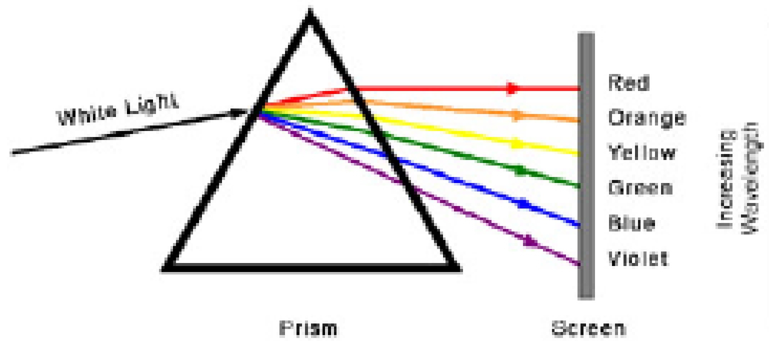
Monochromaticity:

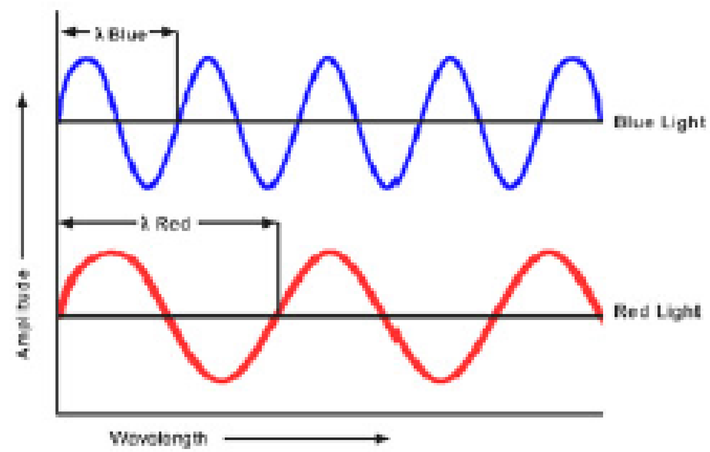


Nearly monochromatic light

Example:

He-Ne Laser	Diode Laser
$\lambda_0 = 632.5$ nm	$\lambda_0 = 900$ nm
$\Delta\lambda = 0.2$ nm	$\Delta\lambda = 10$ nm

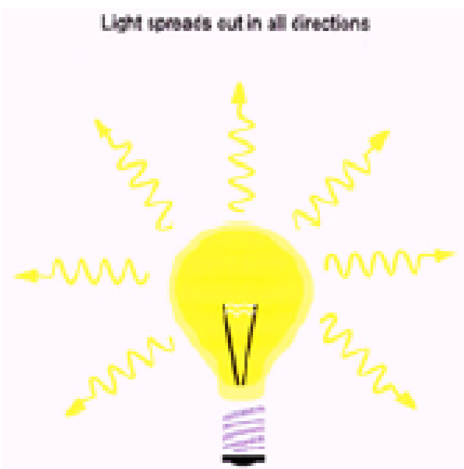




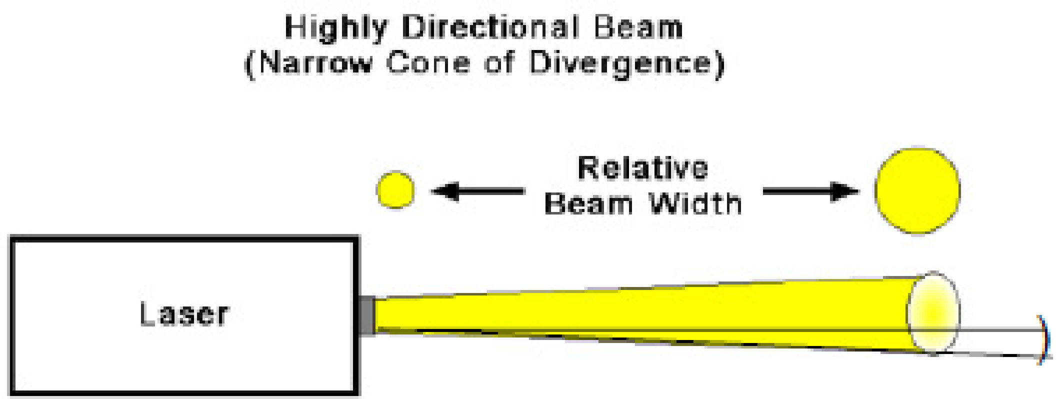
Comparison of the wavelengths of red and blue light

Properties of LASER light

Directionality:



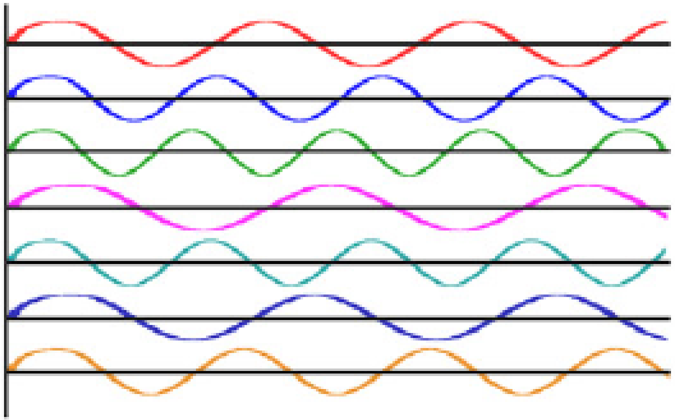
Conventional light source



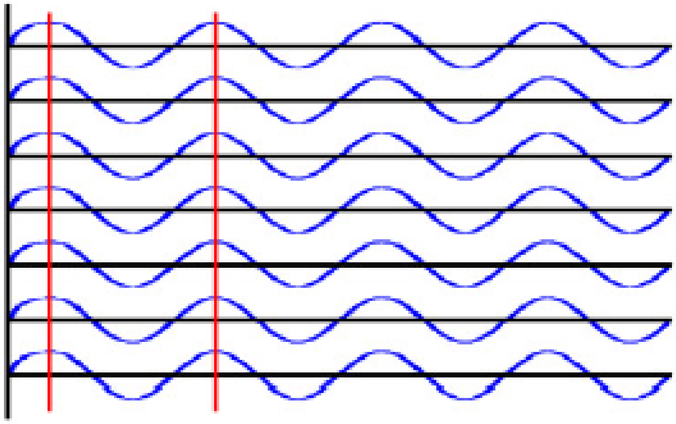
Divergence angle (θ_d)

Properties of LASER light

Coherence:



Incoherent light waves



Coherent light waves

Coherence

Dictionary meaning:

- Quality or state of cohering or sticking together, especially a logical, orderly, & aesthetically consistent relationship of parts.
- Property of being coherent, as of waves. Constant phase difference in two or more waves over time.
- Existence of correlation between phases of two or more waves.
- Property of moving in unison.
- Logical or natural connection or consistency.

Properties of laser light

Laser light cannot:

- be perfectly monochromatic
- be perfectly directional
- have perfect coherence

However…

Laser light is far more coherent than light from any other source.

History of LASER

- Invented at Bell Laboratories, USA.
- Based on Einstein's idea of "**particle wave duality**" of light, more than 30 years earlier.
- Originally called **MASER** (Microwave Amplification by Stimulated Emission of Radiation).
- MASER is similar to LASER but produces only **microwaves**.
- **First patent in 1958**.

Wave-Particle Duality of Light

- Evidence for Wave Nature of Light

  Diffraction & Interference

- Evidence for Particle Nature of Light

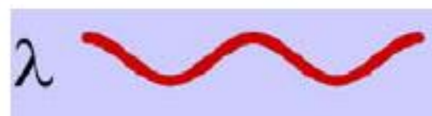
  Photoelectric effect & Compton effect

When UV light is shone on a metal plate in a vacuum, it emits charged particles (Hertz 1887), which were later shown to be electrons by J.J. Thomson (1899).

- In 1923 Prince Louis de Broglie postulated that ordinary matter can have wave-like properties, with wavelength *λ* related to momentum *p* in same way as for light.

Particles have a momentum

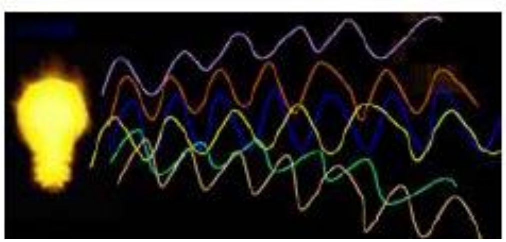
The momentum can be also classified by the wavelength

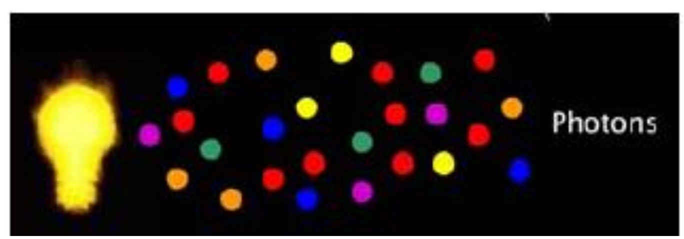


↓

Louis de Broglie(1923) :

$$\boxed{\lambda = h/\ m\cdot v = h/p}$$



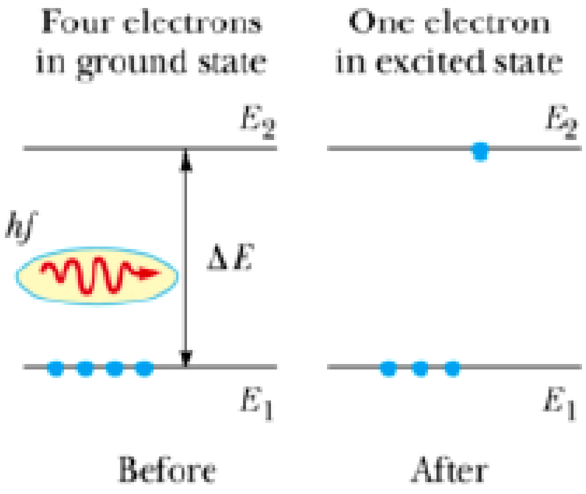


Atomic transitions

Almost all electronic transitions that occur in atoms that involve photons fall into one of three categories:

Stimulated absorption

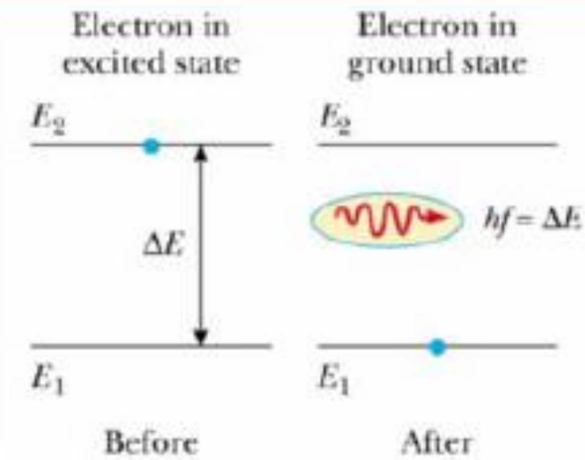
$\Delta E = hf$



Atomic transitions

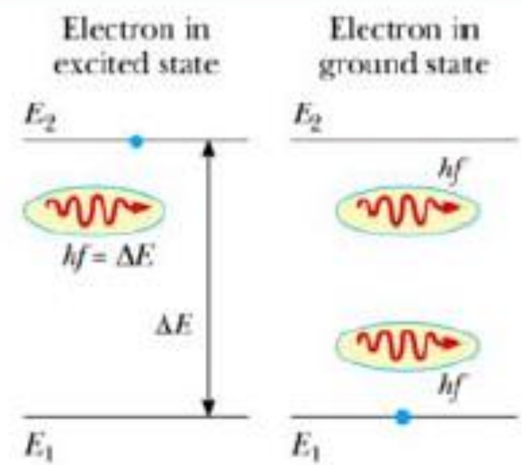
Spontaneous emission

Energy of the emitted photon = $hf = \Delta E$



Stimulated emission

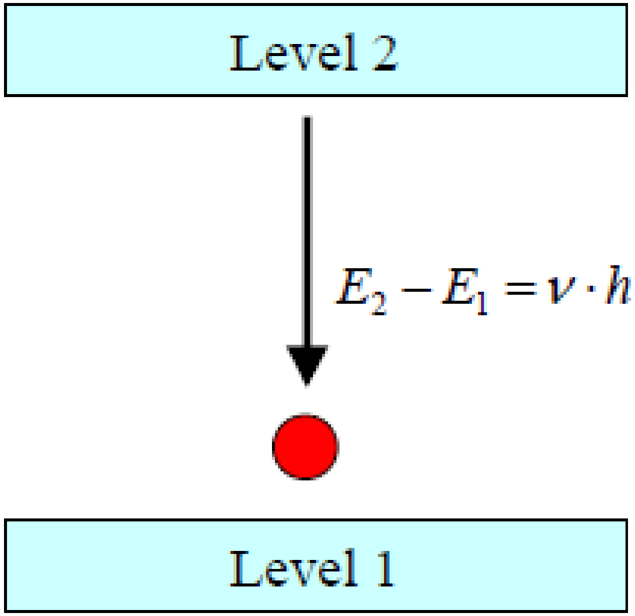
1 Photon with $\Delta E = hf$ produces two photons with the same energy



Atomic transitions

The frequency of the emitted photon going from Level 2 to 1 is given by:

$$\nu = \frac{E_2 - E_1}{h}$$



Defining *Ni* as the electron population of level *i* and considering the Boltzman equation which describes the relation between the electrons in level 1 and 2 at thermal equilibrium:

$$N_2 - N_1 = \exp\left(-\frac{E_2 - E_1}{k_B T}\right)$$

(k_B = Boltzman constant)

giving that $E_2 > E_1$ and $T > 0 \Rightarrow N_1 > N_2$!

Atomic transitions

To amplify light, the stimulated emission must by stronger than the absorption ($N_2 > N_1$)… but how is this possible???

An electromagnetic wave with frequency ν traveling in z-direction through the media with 2 atom levels is normally exponentially absorbed:

$$I = I_0 \exp(-\mu z)$$

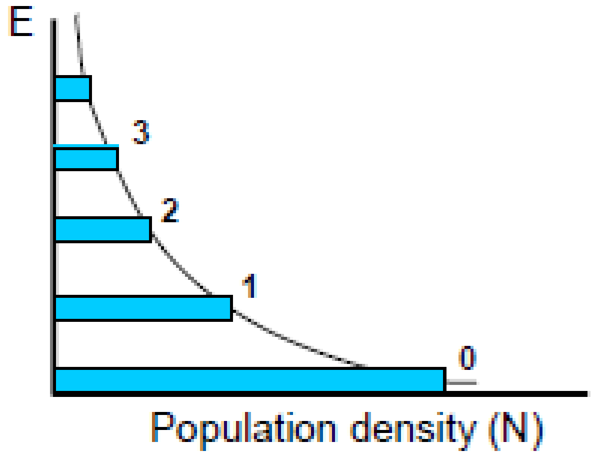
$\mu > \mathbf{0}$ is the lineal Absorption coefficient.

It can be demonstrated that $\mu \sim N_1 - N_2 > 0$

The amplification of light is only possible if $N_1 - N_2 < 0$ (=> $\mu < \mathbf{0}$)

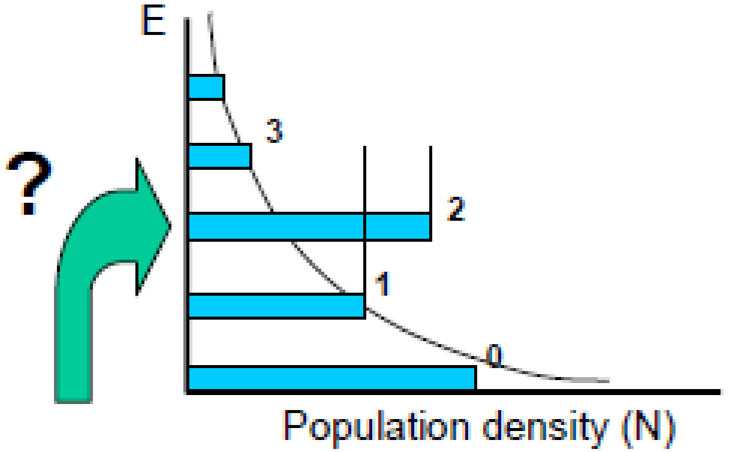
That means… **THE MEDIA IS ACTIVE**!

Inversion of energy levels



$$N_2 - N_1 = \exp\left(-\frac{E_2 - E_1}{k_B T}\right)$$

$$N_2 - N_1 < 0$$



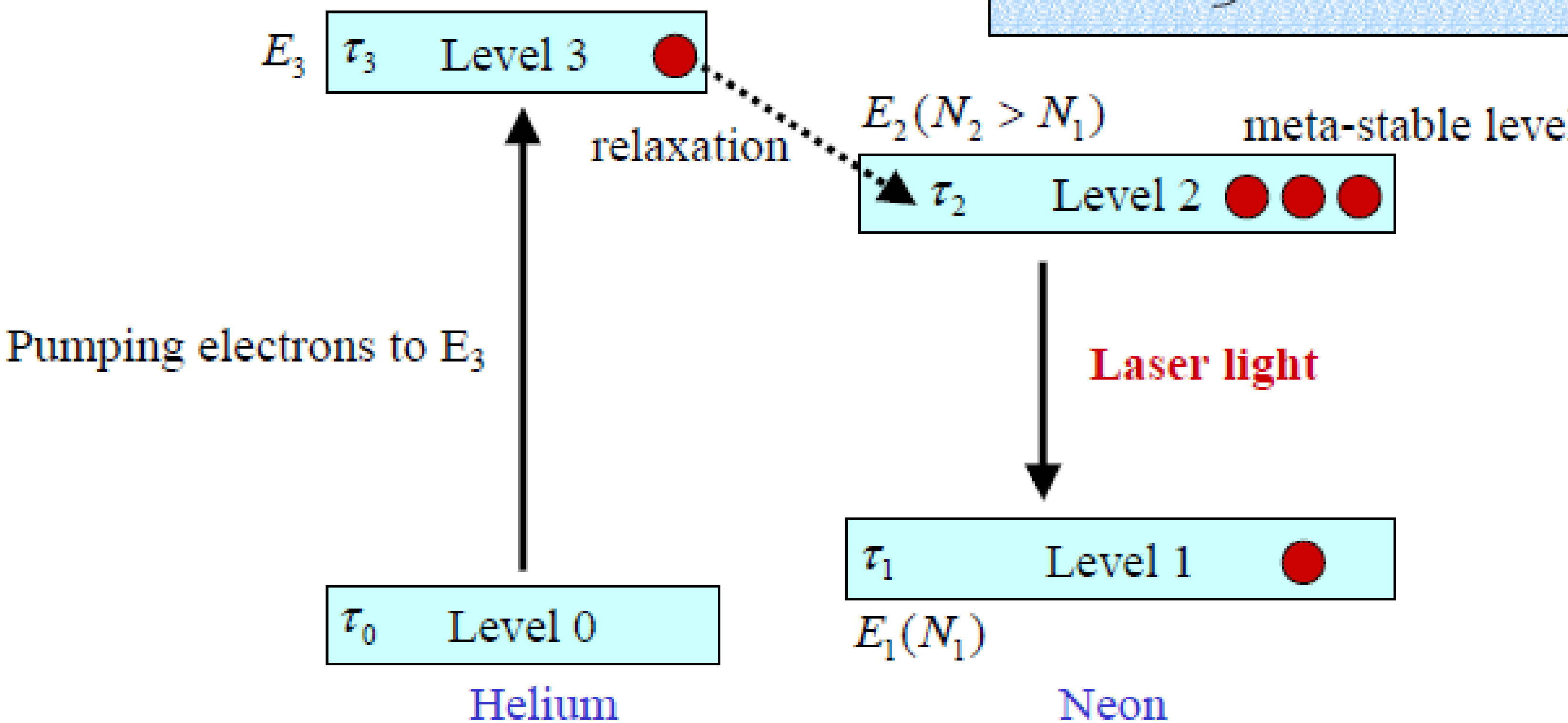
$$\Delta N = N_2 - N_1 > 0$$

$$\Delta E = h\gamma = hc / \lambda$$

Inversion of energy levels

One solution to this problem is to use three energy levels (example He-Ne laser):

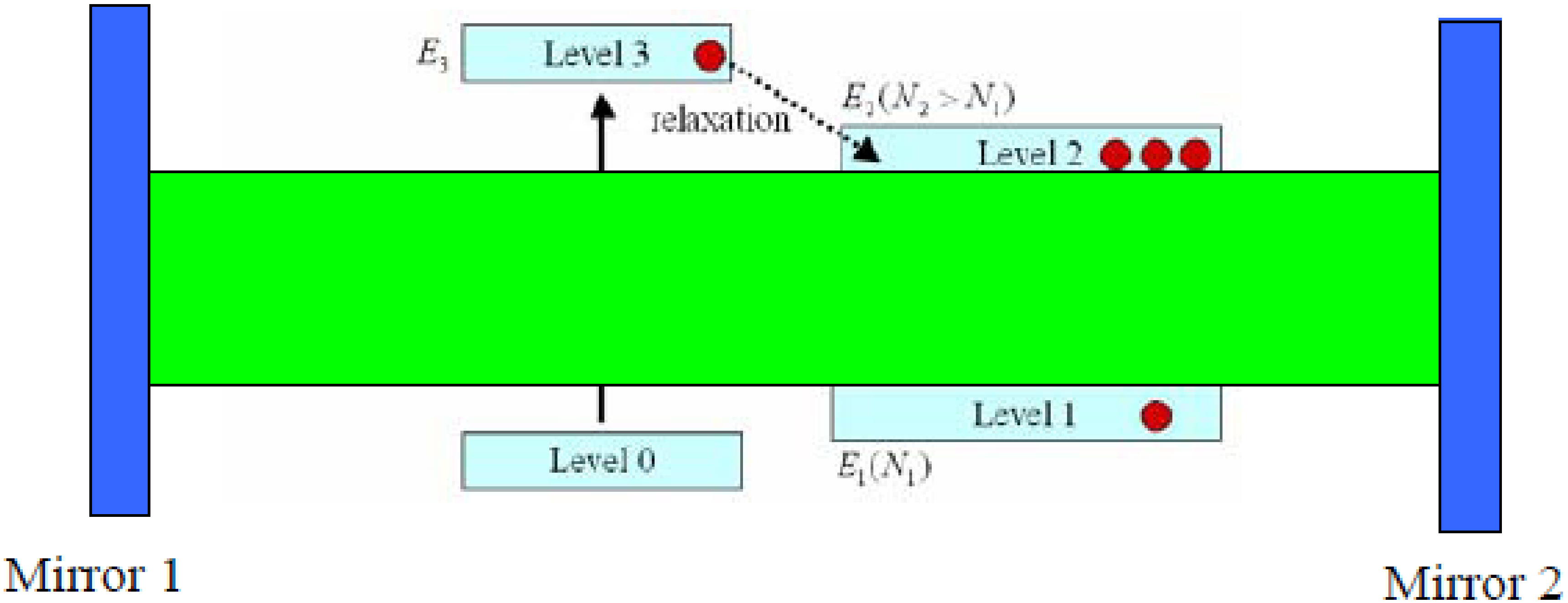
$$\left.\begin{array}{l} \tau_2 > \tau_3 \\ \tau_2 \quad long \\ \tau_1 \quad short \end{array}\right\} N_2 > N_1!!!$$



Stimulated emission

Now $N_2 > N_1$, however… we must amplify the intensity of our beam!

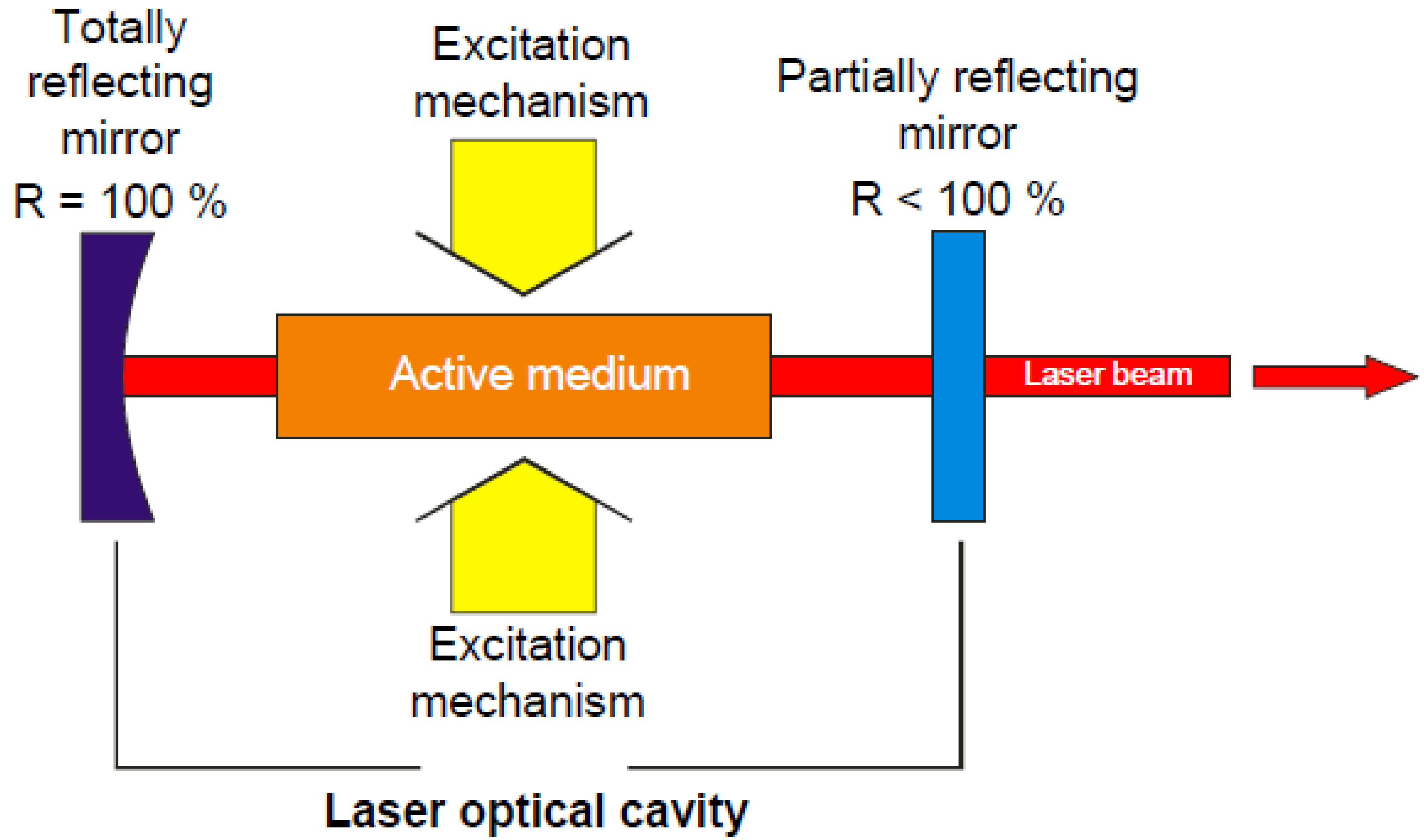
➔ We must build a LASER resonator!



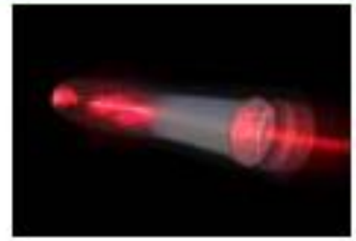
However, with this set-up the intensity will grow up to infinite!

What can we do to obtain the LASER beam?

Elements of a laser



Types of Lasers



Gas Lasers

Solid State Lasers

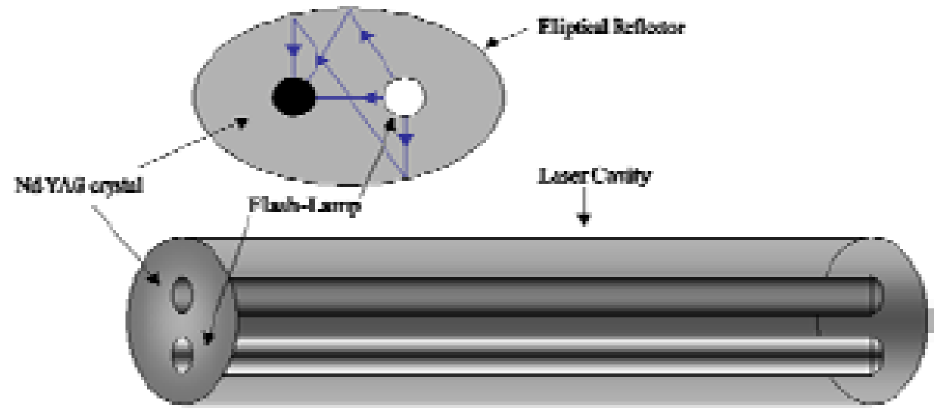
Semiconductor Lasers

Excimer Lasers

etc etc

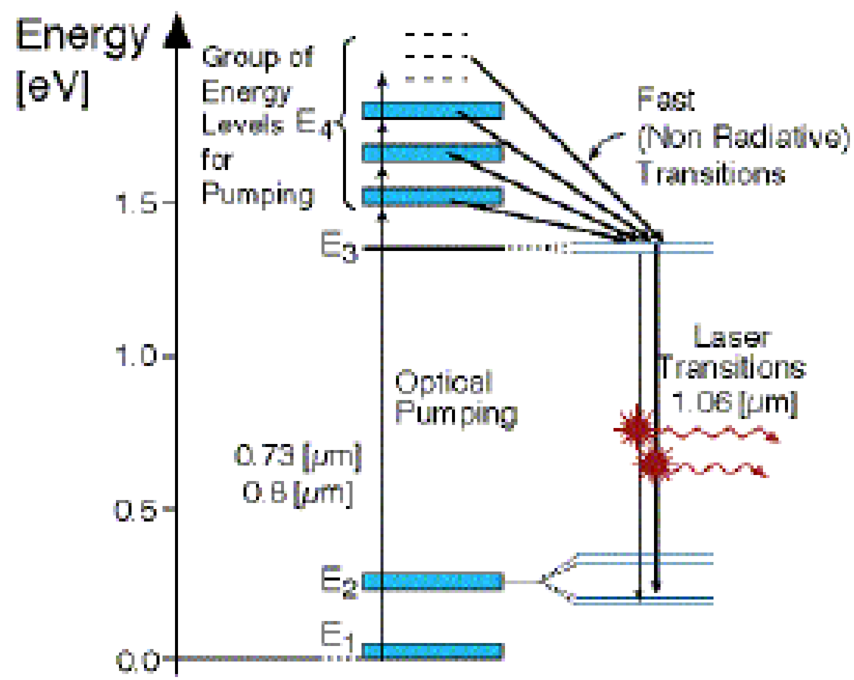
Solid State Lasers

Nd:YAG Laser:
$\lambda = 1.064\ \mu m$



• YAG = Yttrium-Aluminium-Garnet ($Y_3Al_5O_{12}$), it is transparent and colourless.

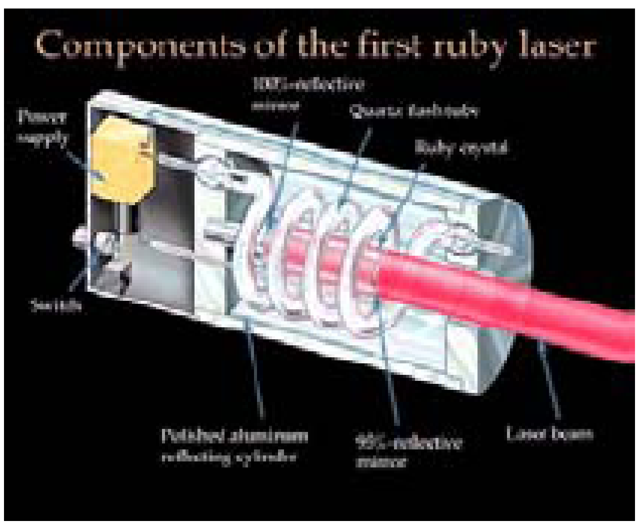
•Nd:YAG Laser is doped with about 1% Nd3+ ions into the YAG crystal. The crystal color then changed to a light blue color.

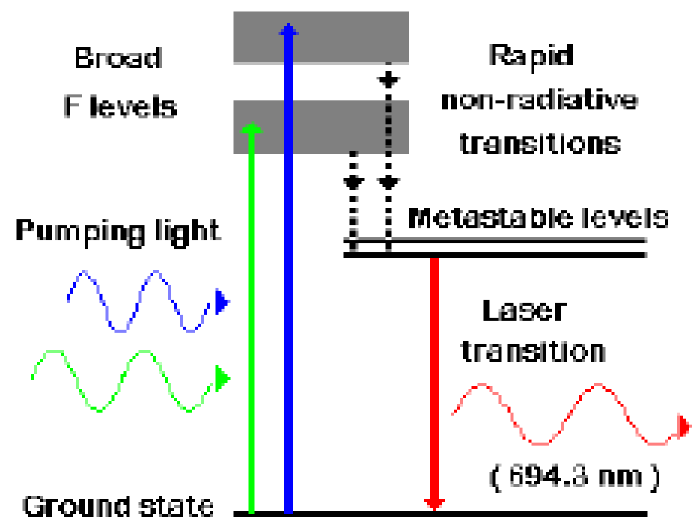


Solid State Lasers

Ruby Laser:
$\lambda = 694.3$ nm

- First laser invented (1960).
- Ruby: Al_2O_3 in which some of the Al atoms have been replaced with Cr.
- Cr gives its characteristic red color and is responsible for the lasing behavior of the crystal.
- Cr atoms absorb green and blue light and emit or reflect only red light.





Energy levels of chromium ions in ruby

Kumar Patel with a flowing-gas CO_2 laser in 1967