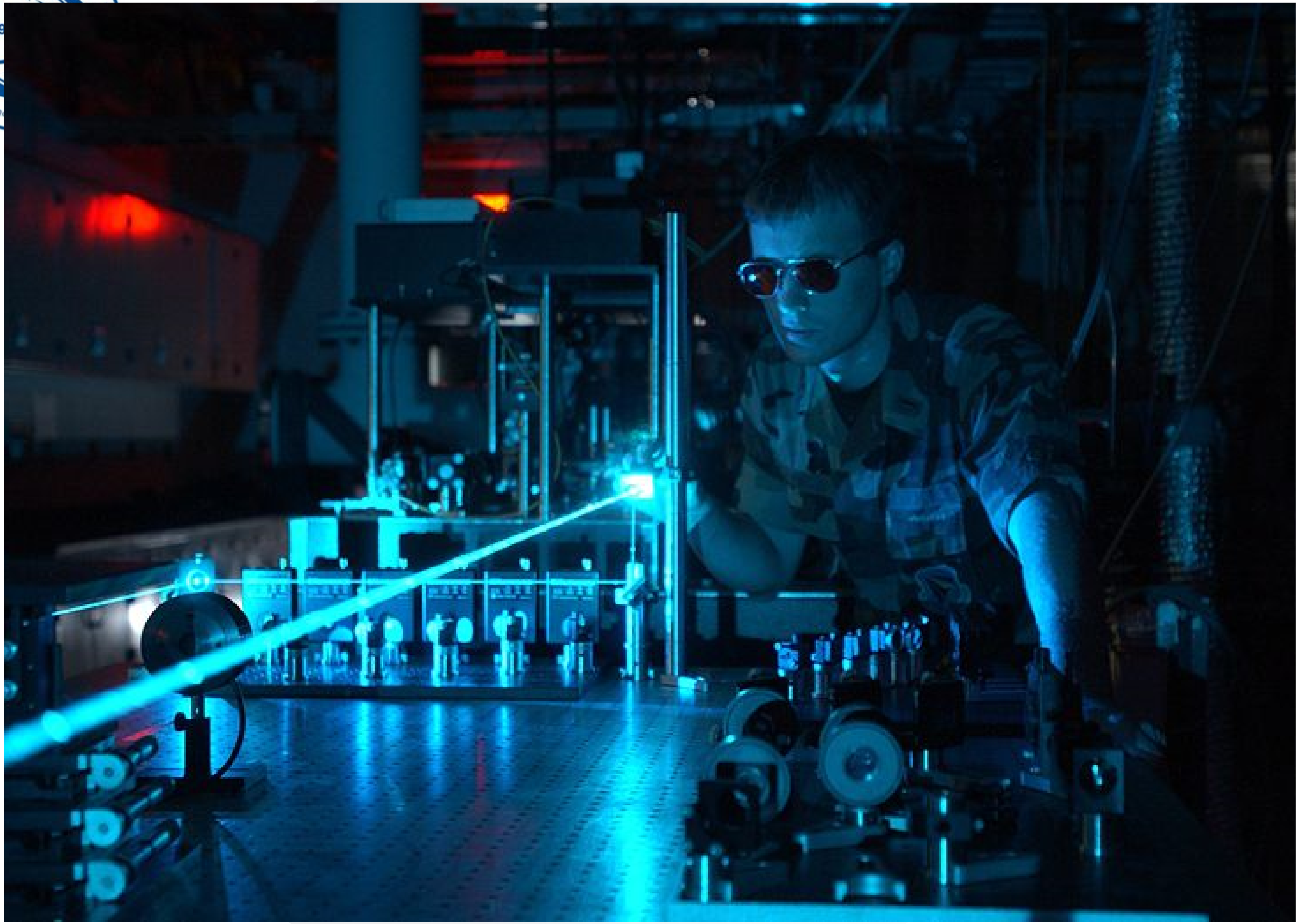
Lecture 5:
Introduction to Lasers



http://en.wikipedia.org/wiki/Laser

History of the Laser

- Invented in 1958 by Charles Townes (Nobel prize in Physics 1964) and Arthur Schawlow of Bell Laboratories
- Was based on Einstein's idea of the "particle-wave duality" of light, more than 30 years earlier
- Originally called MASER (m = "microwave")

History of the Laser

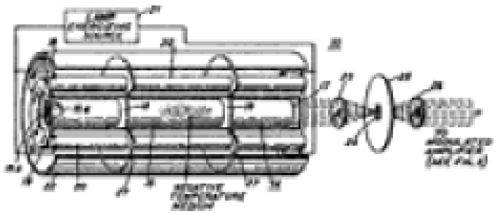
2,929,922

MASERS AND MASER COMMUNICATIONS SYSTEM

Arthur L. Schawlow, Madison, N.J., and Charles H. Townes, New York, N.Y., assignors to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

Application July 30, 1958, Serial No. 752,137

11 Claims. (Cl. 250—7)



1. A communications system for operation in the infrared, visible, or ultraviolet regions of the electromagnetic wave spectrum comprising a monochromatic maser generator, a coherent modulated maser amplifier, a modulating source, and a detector; said generator comprising a chamber having end reflective parallel members and transparent side members, a negative temperature medium disposed within said chamber, and means arranged about said chamber for pumping said medium; said amplifier comprising a chamber having end reflective parallel members and transparent side members, a negative temperature medium disposed within said chamber, means arranged about said chamber for pumping said medium, and coupling means for abstracting from one end of said chamber an amplified counterpart of the energy transmitted into the other end thereof and for directing said amplified counterpart at said detector.

The first patent (1958)

MASER = Microwave Amplification by Stimulated Emission of Radiation

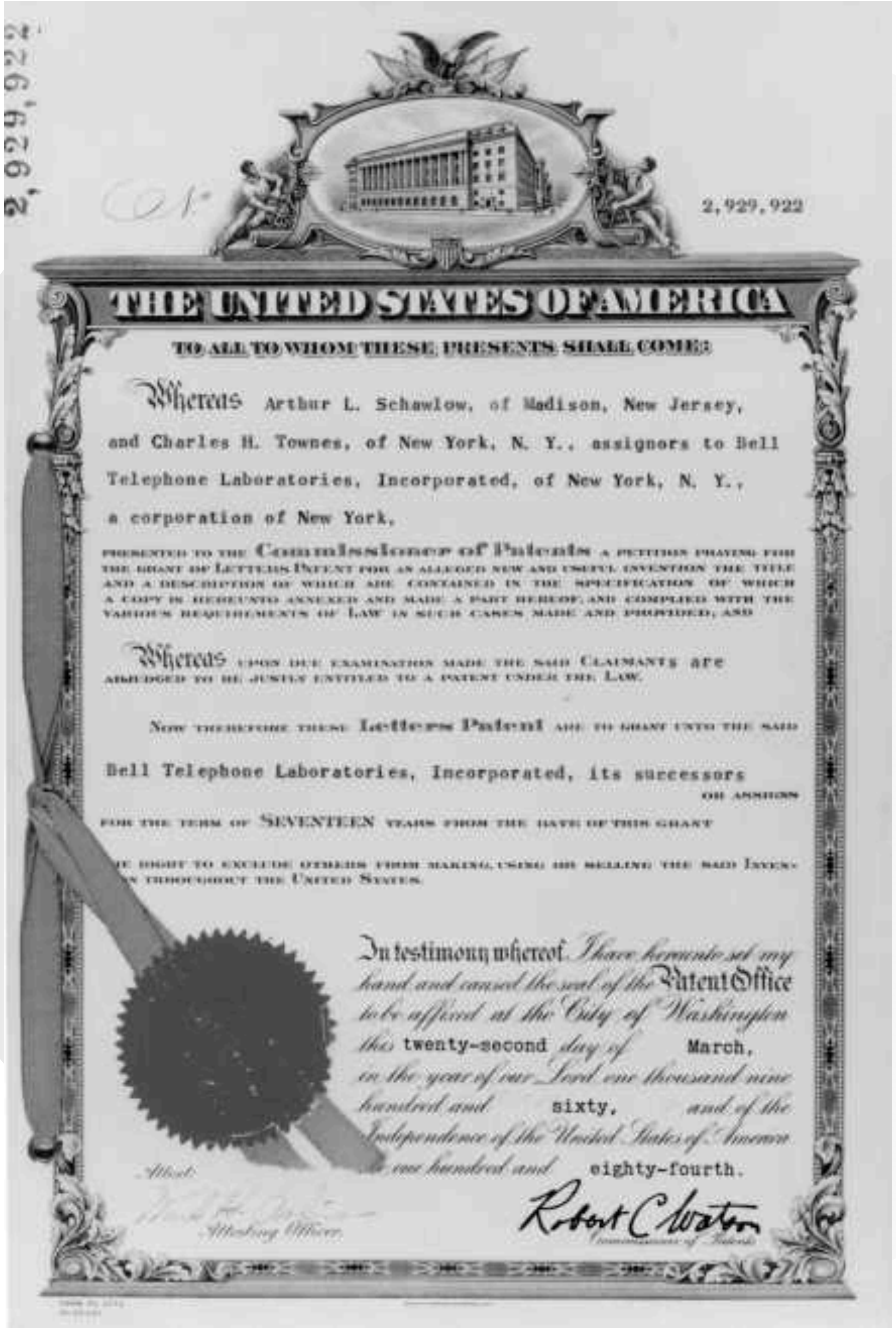
The MASER is similar to the LASER but produced only microwaves

History of the Laser

April 1959: Gould and TRG apply for laser-related patents stemming from Gould's ideas.

March 22, 1960: Townes and Schawlow, under Bell Labs, are granted US patent number 2,929,922 for the optical maser, now called a laser. With their application denied, Gould and TRG launch what would become a 30-year patent dispute related to laser invention.

1961: Lasers begin appearing on the commercial market through companies such as Trion Instruments Inc., Perkin-Elmer and Spectra-Physics.



2,929,922

No. 2,929,922

THE UNITED STATES OF AMERICA

TO ALL TO WHOM THESE PRESENTS SHALL COME:

Whereas Arthur L. Schawlow, of Madison, New Jersey, and Charles H. Townes, of New York, N. Y., assignors to Bell Telephone Laboratories, Incorporated, of New York, N. Y., a corporation of New York,

PRESENTED TO THE Commissioner of Patents A PETITION PRAYING FOR THE GRANT OF LETTERS PATENT FOR AN ALLEGED NEW AND USEFUL INVENTION THE TITLE AND A DESCRIPTION OF WHICH ARE CONTAINED IN THE SPECIFICATION OF WHICH A COPY IS HEREUNTO ANNEXED AND MADE A PART HEREOF, AND COMPLIED WITH THE VARIOUS REQUIREMENTS OF LAW IN SUCH CASES MADE AND PROVIDED, AND

Whereas UPON DUE EXAMINATION MADE THE SAID CLAIMANTS are ADJUDGED TO BE JUSTLY ENTITLED TO A PATENT UNDER THE LAW.

Now therefore these Letters Patent are to grant unto the said Bell Telephone Laboratories, Incorporated, its successors or assigns for the term of SEVENTEEN years from the date of this grant

...e right to exclude others from making, using or selling the said Inven-...n throughout the United States.

In testimony whereof I have hereunto set my hand and caused the seal of the Patent Office to be affixed at the City of Washington this twenty-second day of March, in the year of our Lord one thousand nine hundred and sixty, and of the Independence of the United States of America the one hundred and eighty-fourth.

Attest:

Attesting Officer.

Robert C. Watson

Commissioner of Patents.

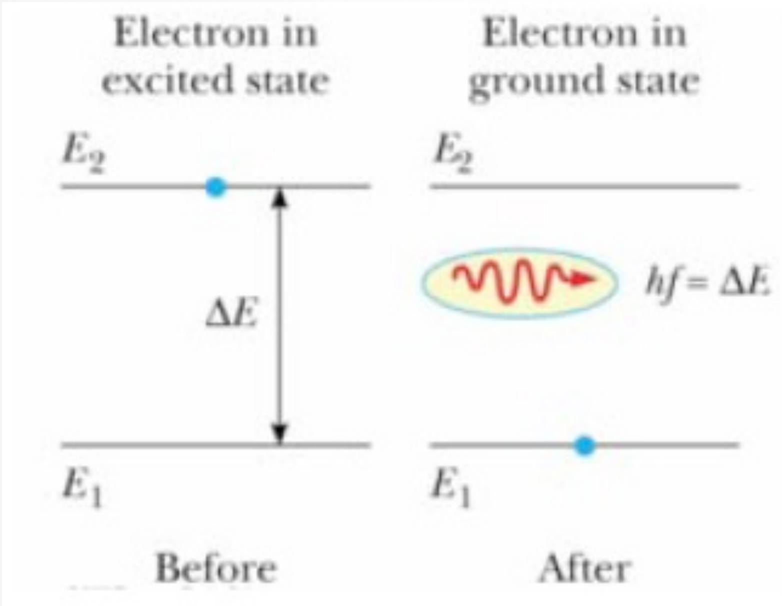
US patent number 2,929,922

Interaction of Radiation with Atoms

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

1. Spontaneous emission

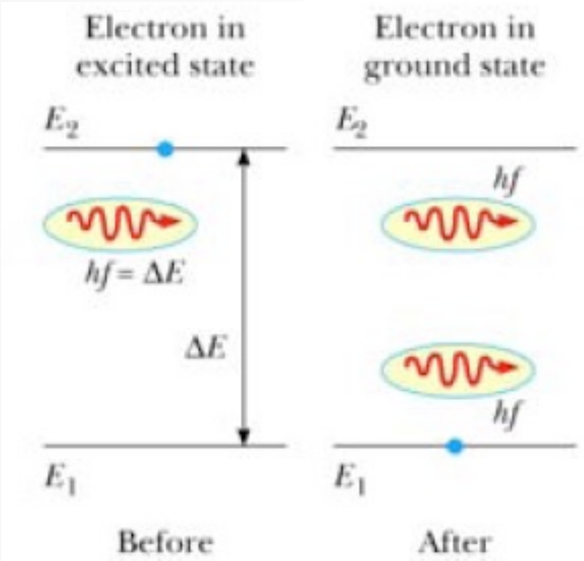
Energy of the emitted photon $= hf = \Delta E$



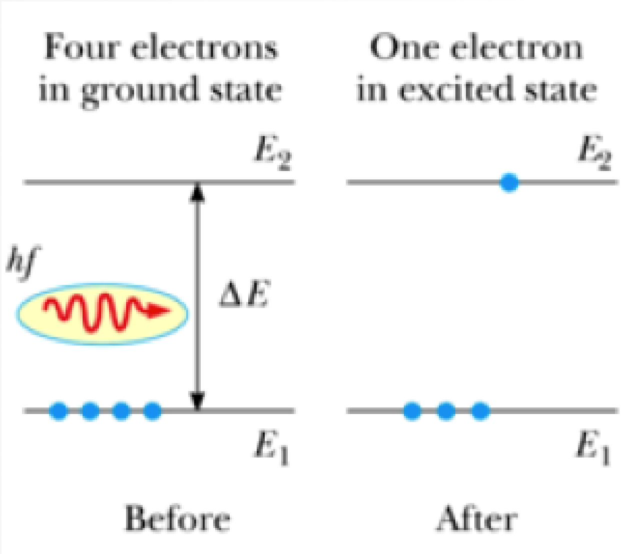
Atomic transition

2. Stimulated emission

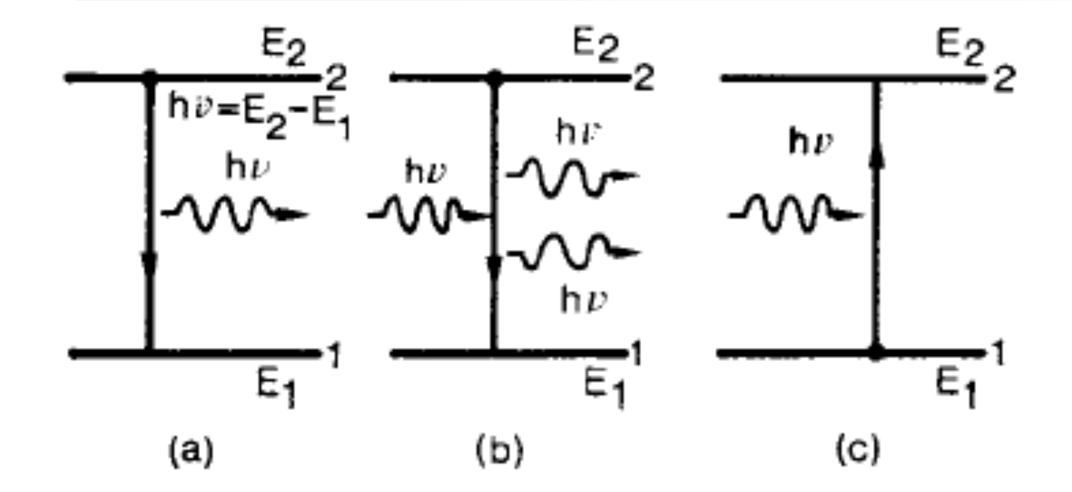
One photon produces two photons with the same properties



3. Absorption:



Spontaneous (a) and stimulated emission (b), absorption (c)



$$\nu_0 = (E_2 - E_1)/h$$

For a spontaneous emission, the probability for the process to occur

$$\left(\frac{dN_2}{dt}\right)_{sp} = -AN_2$$

A is the rate of spontaneous emission or the Einstein A coefficient

The quantity $\tau_{sp} = 1/A$ is called the spontaneous emission (or radiative) lifetime

For a stimulated emission, the rate of 2 ➔ 1 transitions

$$\left(\frac{dN_2}{dt}\right)_{st} = -W_{21}N_2 \qquad W_{21} = \sigma_{21}F$$

W_{21} is called the rate of stimulated emission, σ_{21} is the stimulated emission cross section. W_{21} depends not only on the particular transition but also on the intensity of the incident e.m. wave.

For absorption, the rate of the 1 ➔ 2 transitions due to absorption

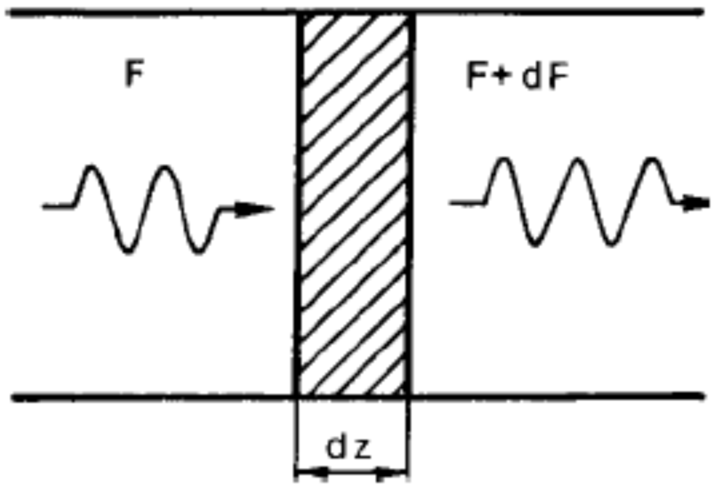
$$\left(\frac{dN_1}{dt}\right)_{a} = -W_{12}N_1 \qquad W_{12} = \sigma_{12}F$$

W_{12} is the rate of absorption, σ_{12} is the absorption cross section
If two levels are non-degenerate, then $W_{21} = W_{12}$ and $\sigma_{21} = \sigma_{12}$
If levels 1 and 2 are g_1 -fold and g_2 -fold degenerate

$$g_2W_{21} = g_1W_{12} \qquad g_2\sigma_{21} = g_1\sigma_{12}$$

The Idea of laser

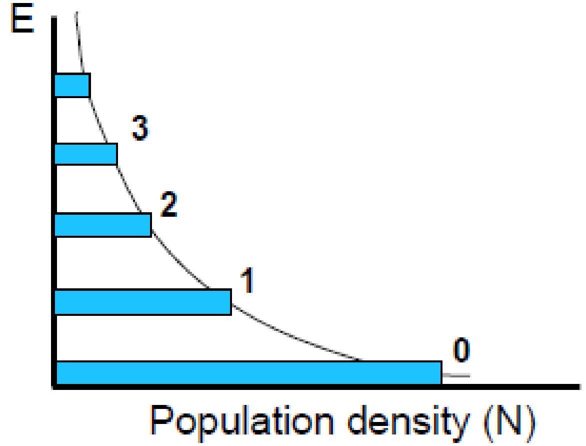
The change of incoming photon flux, F, is determined by both stimulated emission and absorption



$$dF = \sigma_{21} F \left[N_2 - (g_2 N_1 / g_1) \right] dz$$

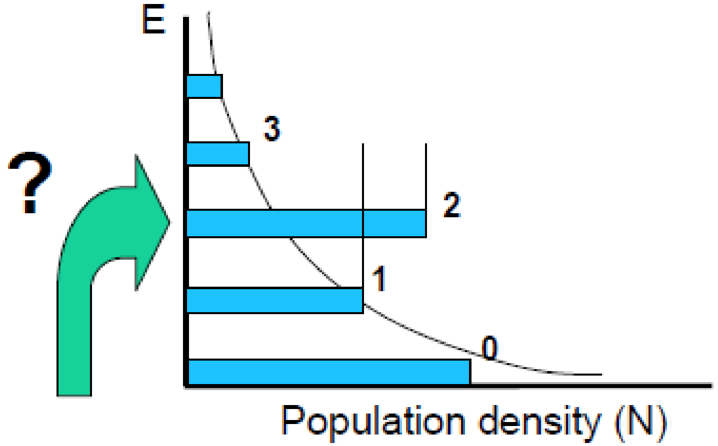
The material behaves as an amplifier (i.e., $dF/dz > 0$) if $N_2 > g_2 N_1 / g_1$, while it behaves as an absorber if $N_2 < g_2 N_1 / g_1$.

Inversion of energy level



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

$$N_2 - N_1 < 0$$



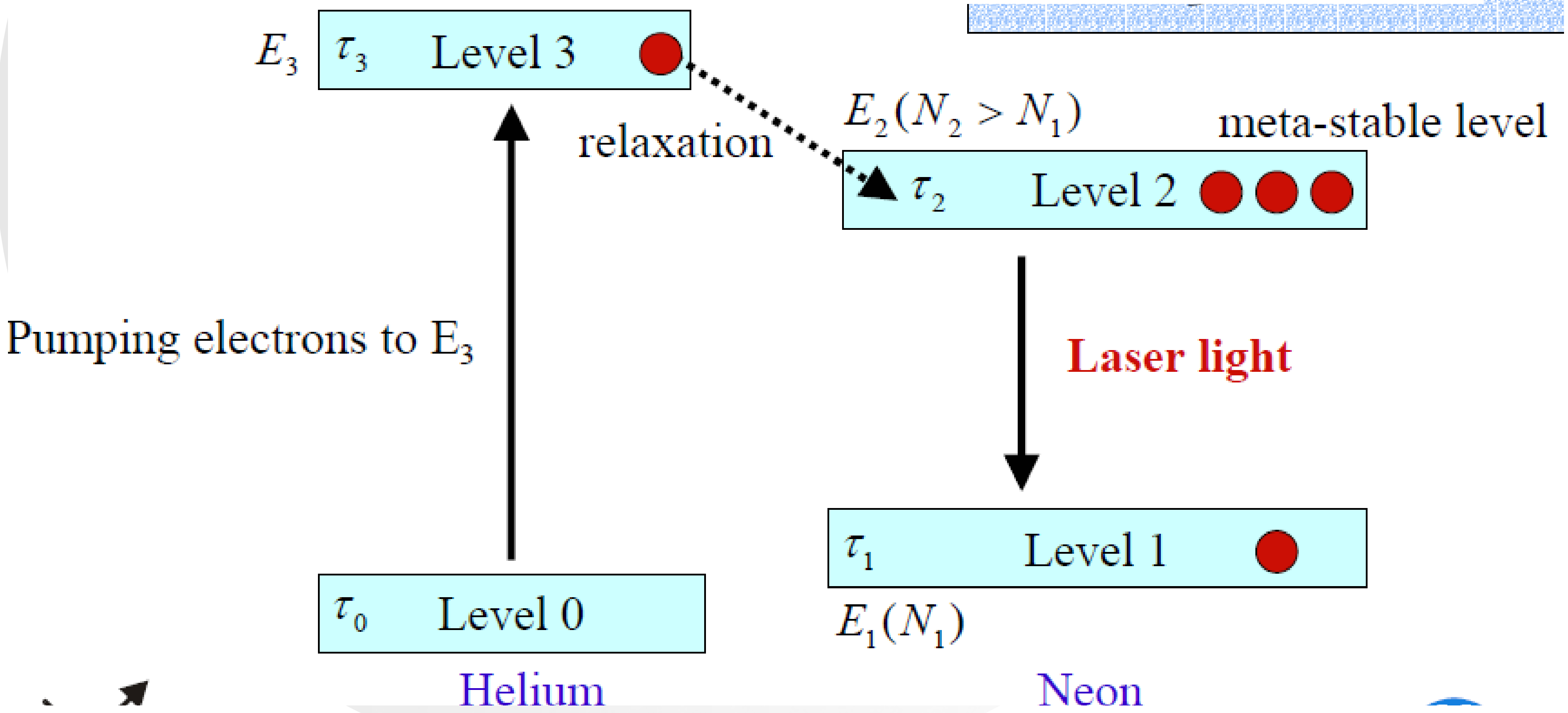
$$\Delta N = N_2 - N_1 > 0$$

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

Inversion of energy level

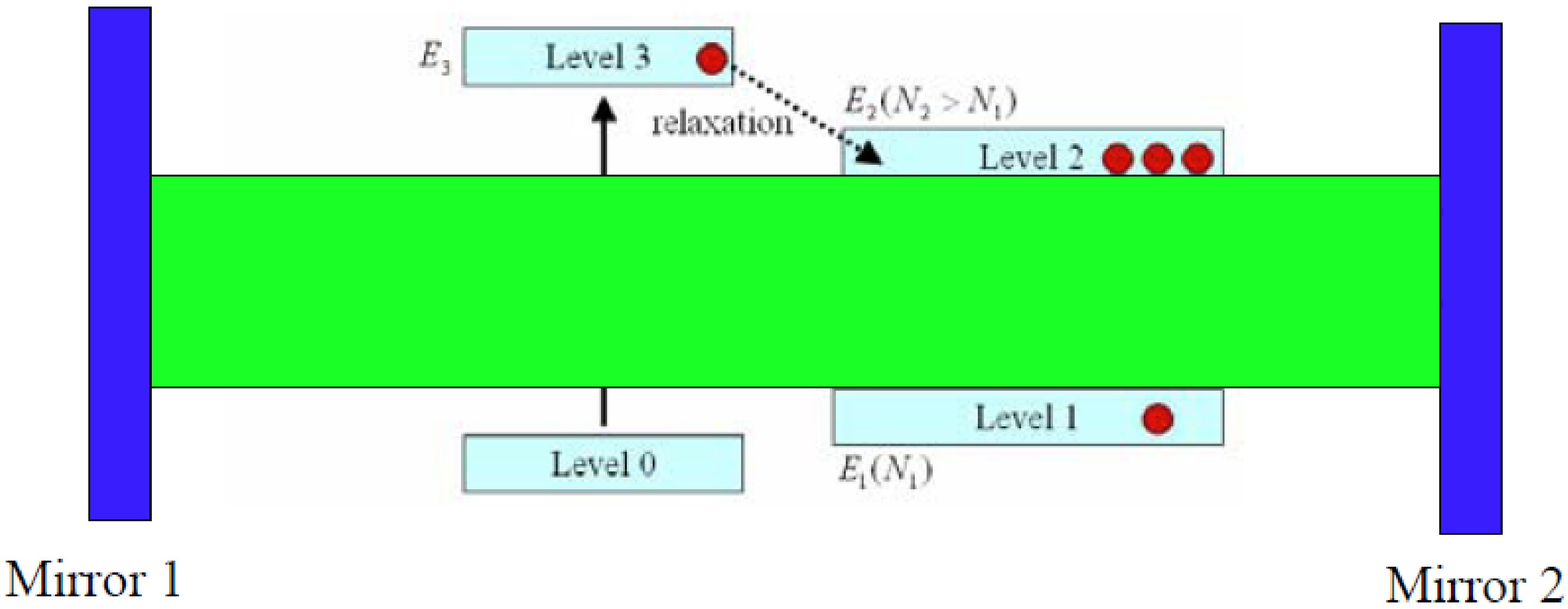
One solution to this problem is to use three energy levels (example He-Ne laser):

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



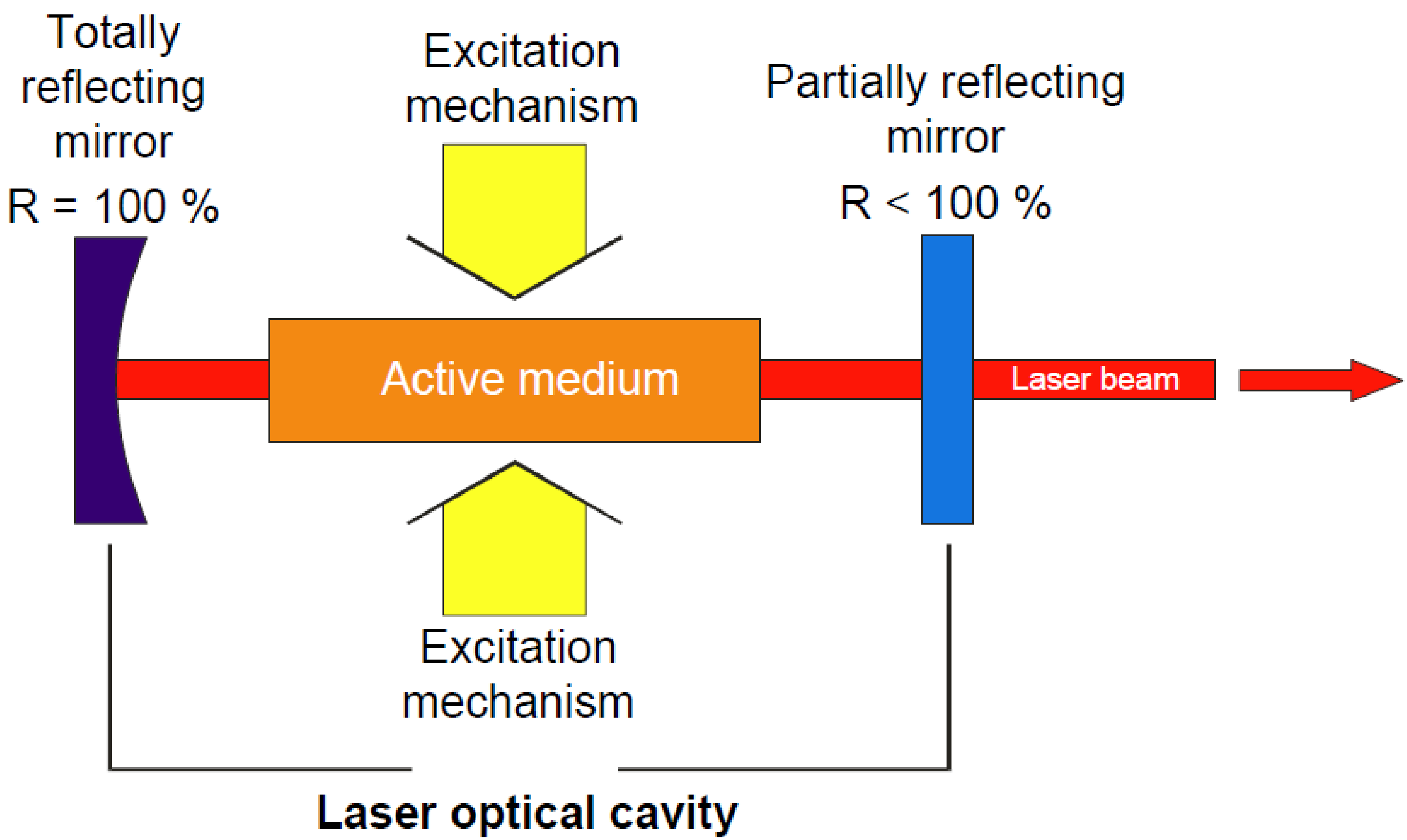
Stimulated emission

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



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



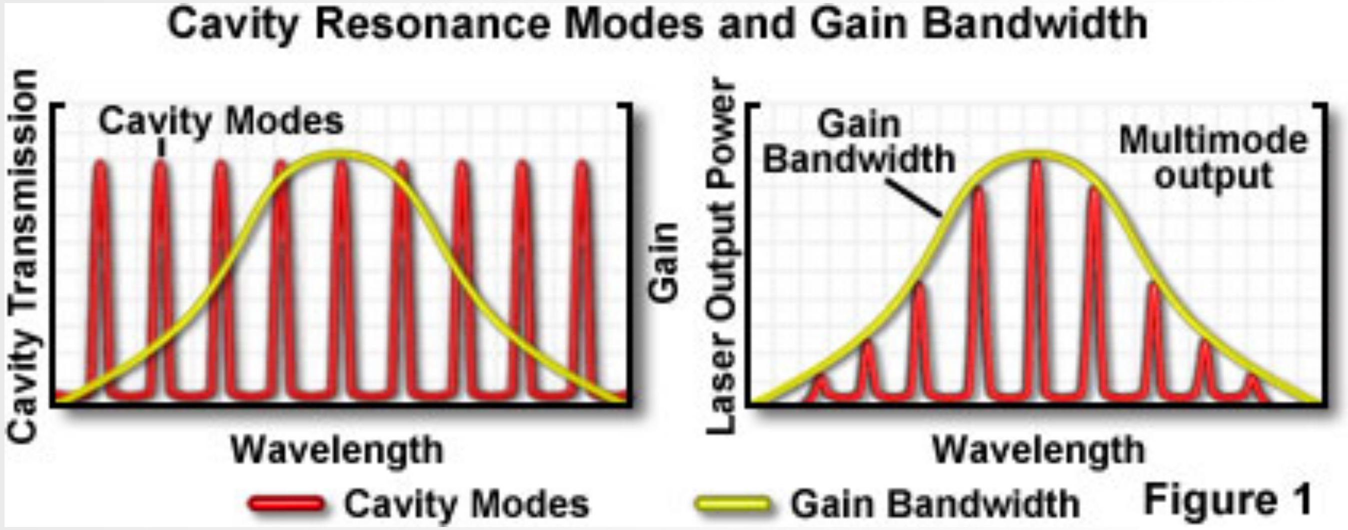
The cavity is of course a Fabry-Perot etalon.

Cavity mode

Longitudinal cavity modes:

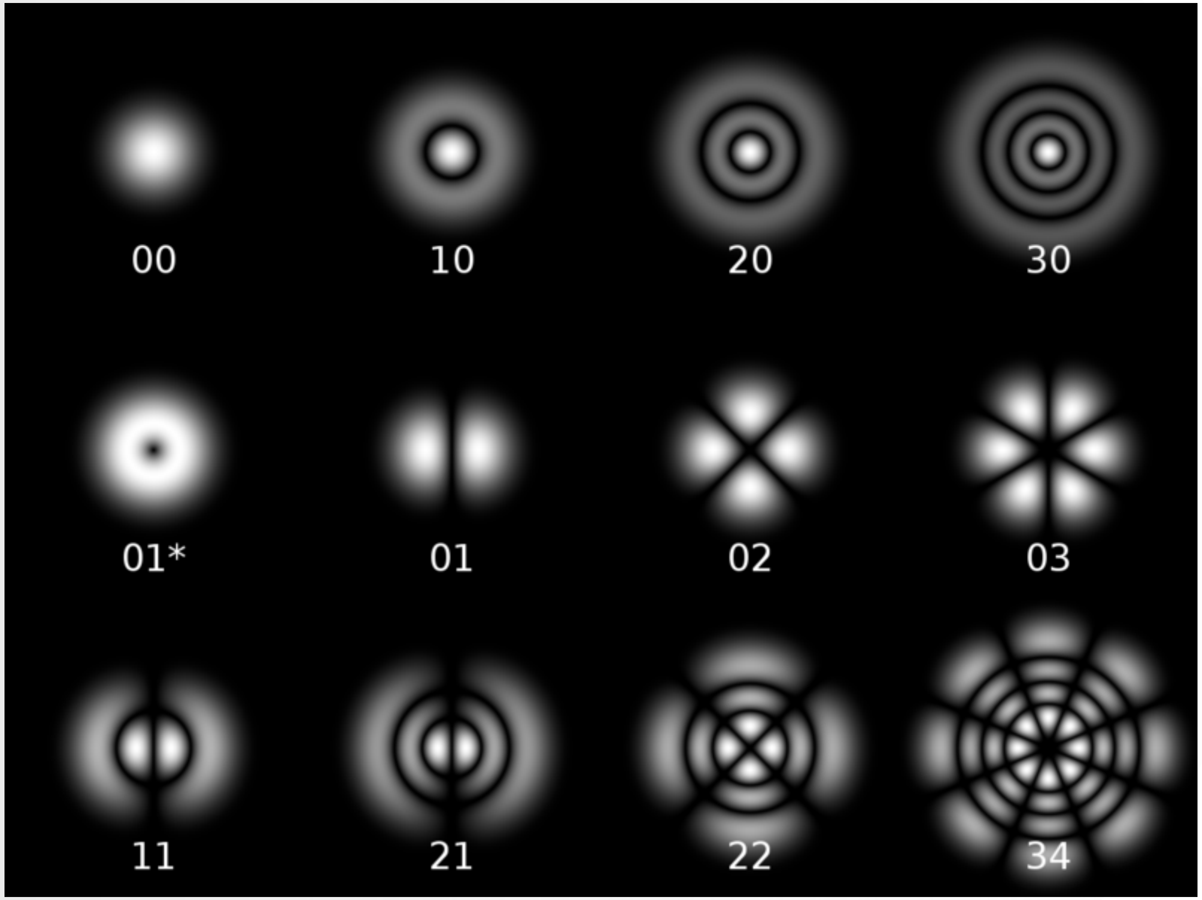
$$v_m = \frac{m\upsilon}{2L}, v_{m+1} - v_m = \Delta v = \frac{\upsilon}{2L}$$

For a gas laser L = 1m, Δν=~150MHz.



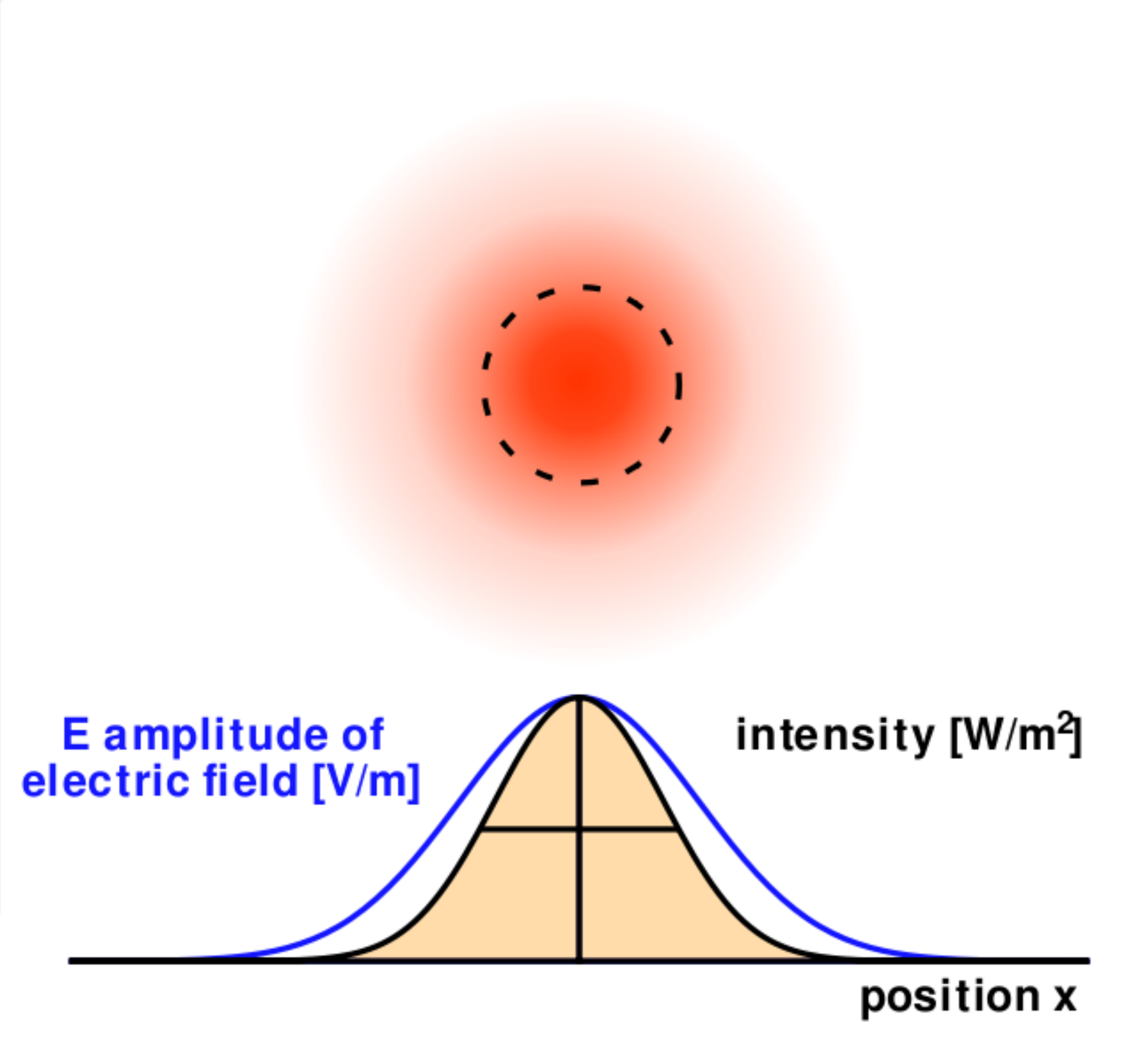
How to generate a single longitudinal mode in the cavity?
Need mode separation exceed the transition bandwidth

Transverse modes (TEM_{mn}): perpendicular to z direction



TEM_{00} is the mostly widely used.

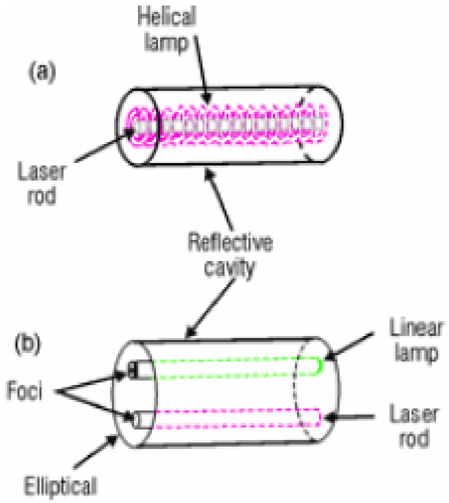
Gaussian beam profile:

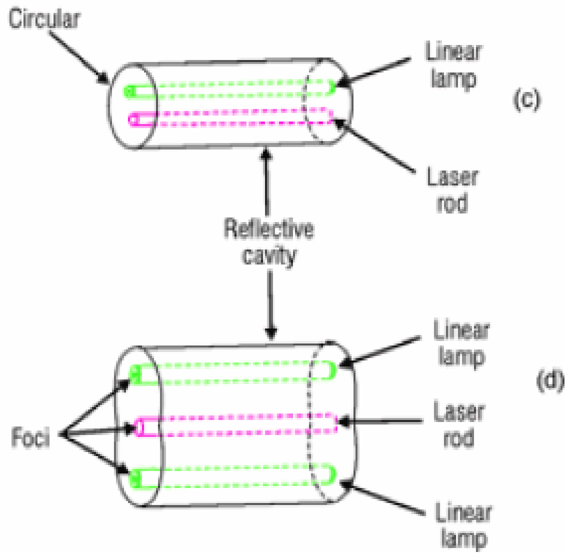


Excitation mechanism

Optical pumping

(flash lamps
or other lasers)





•Generally used with dye-lasers and solid-state lasers

•Cylindrical quartz tubes with metal electrodes mounted on the ends, filled with a gaseous species

•A voltage is applied across the electrodes of the flashlamp ➔ current flows through the gas produced populating excited levels of the atoms ➔ intense light emission.

•The process is similar to that of electron excitation of lasers except that a population inversion is not produced and the radiating material of the lamp radiates via spontaneous emission

Active medium

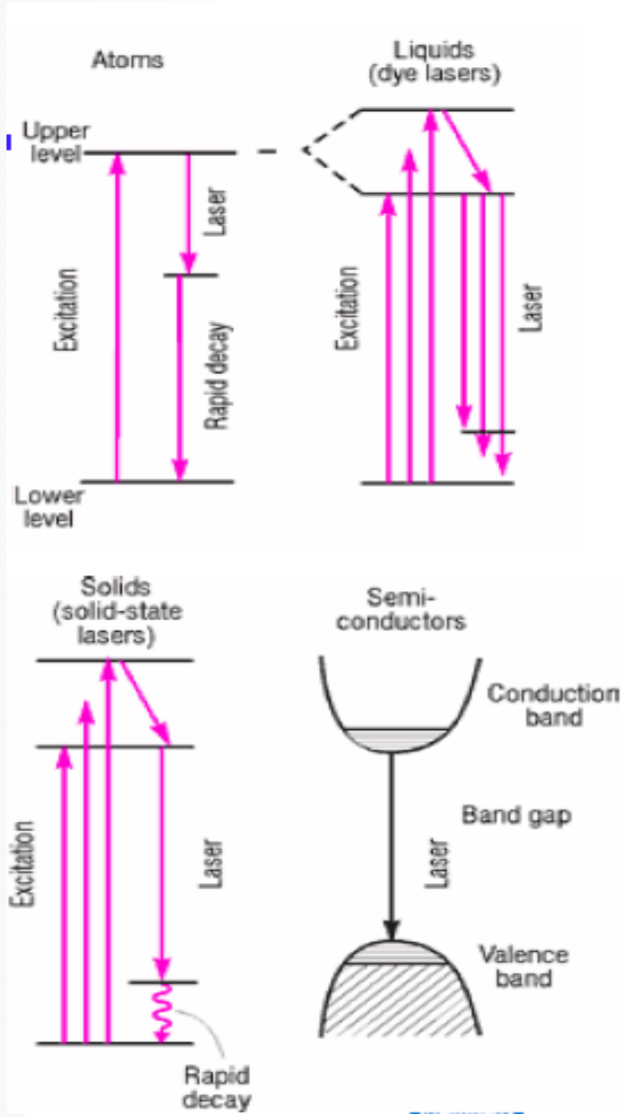
- **Atoms**: helium-neon (HeNe) laser; helium-cadmium (HeCd) laser, copper vapor lasers (CVL)

- **Molecules:** carbon dioxide (CO2) laser, ArF and KrF excimer lasers, N2 laser

- **Liquids:** organic dye molecules dilutely dissolved in various solvent solutions

- **Dielectric solids:** neodymium atoms doped in YAG or glass to make the crystalline Nd:YAG or Nd:glass lasers

- **Semiconductor materials:** gallium arsenide, indium phosphide crystals.



Gain medium :

gas, liquid, solid or plasma

Light generated by stimulated emission :

similar to the input signal wavelength, phase, and polarization

The optical cavity (cavity resonator):

a coherent beam of light between reflective surfaces

passes through the gain medium more than once

The minimum pump power needed to begin laser action (lasing threshold)

gain medium will amplify any photons passing through it, regardless of direction

only the photons aligned with the cavity manage to pass more than once through the medium and so have significant amplification

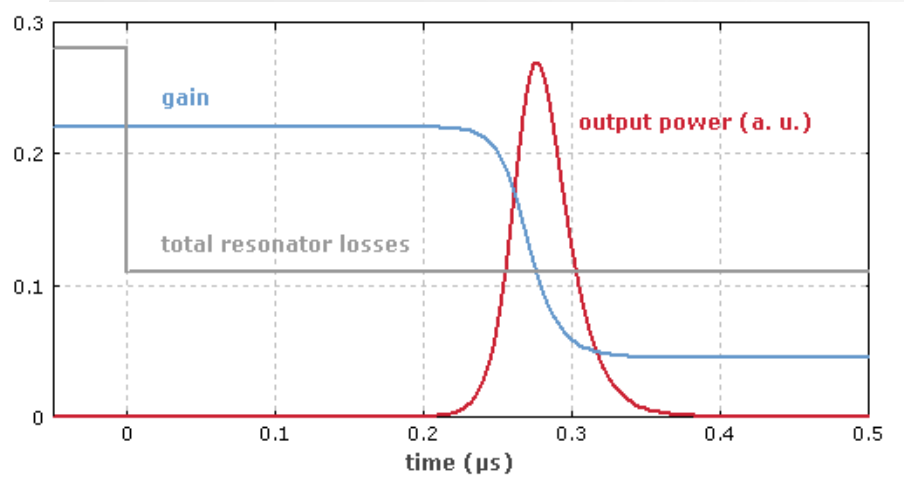
Modes of operation

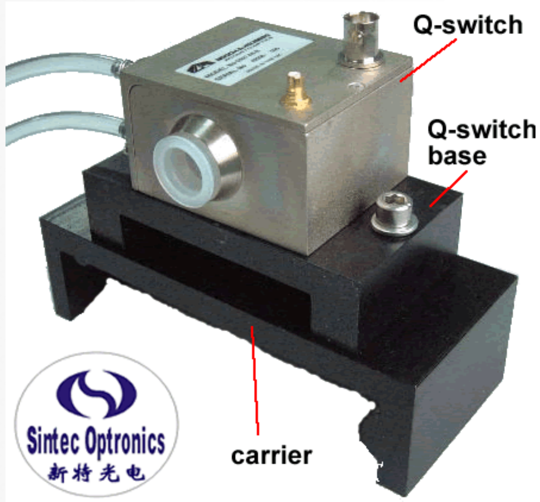
1. Continuous constant-amplitude output (known as *CW* or *continuous wave*)
   CW Dye laser (a broad range of wavelengths)

2. Pulsed, Q-switching (produce high peak power), Modelocking (extremely short duration pulse, picoseconds (10^{-12s}) femtoseconds (10^{-15s}))
   Gain-switching (picoseconds (10-12s))
   Produce high peak power at particular wavelength

Q-switch

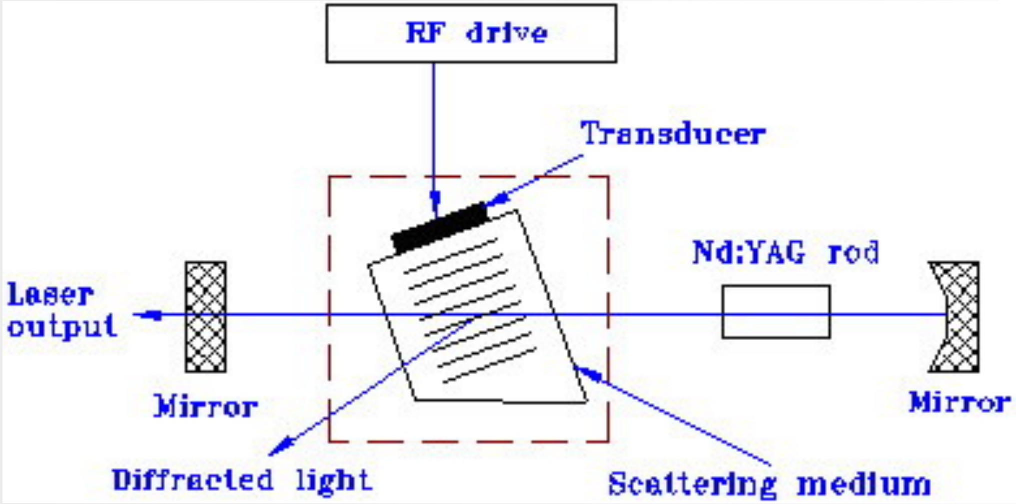
Q-switching, sometimes known as **giant pulse formation**, to produce a pulsed output beam (short pulse). Q-switch is some type of variable attenuator inside the cavity.

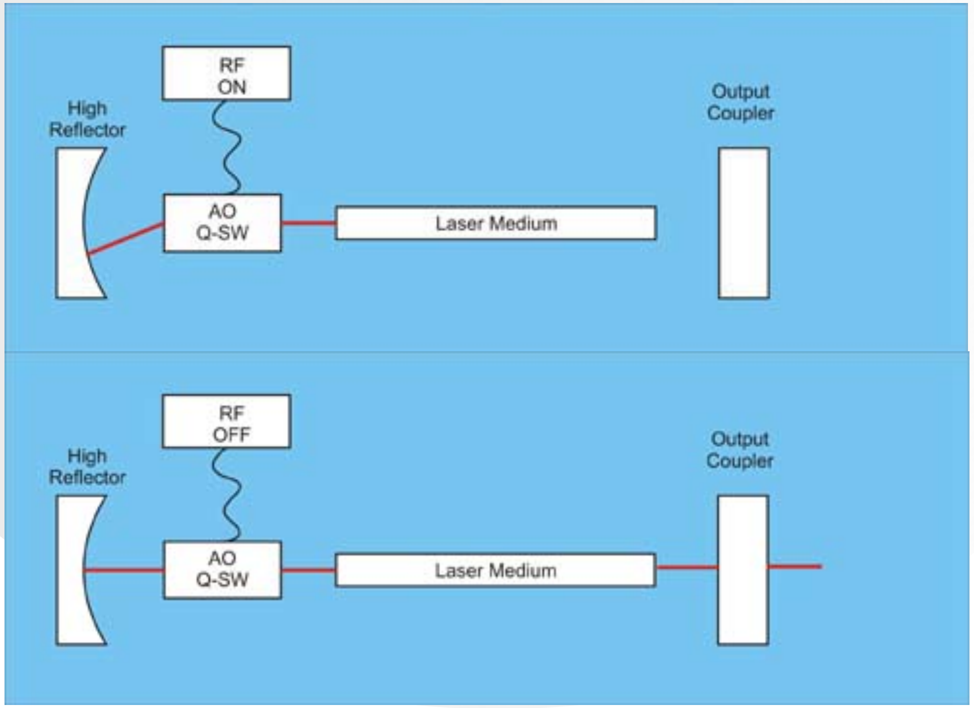




Initially, the laser medium is pumped while the Q-switch is set to prevent feedback light into gain medium (low Q), after a certain time the stored energy will reach some maximum level; the medium is said to be *gain saturated*. At this point, the Q-switch device is quickly changed from low to high Q, allowing feedback and the process of emission.

Acousto-Optic Q-switch

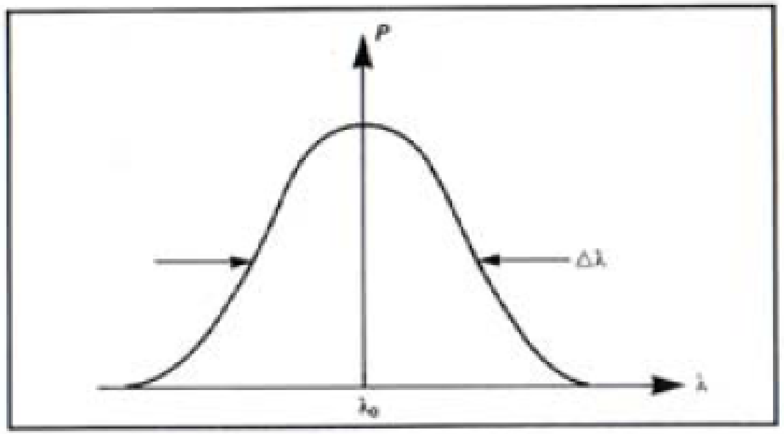




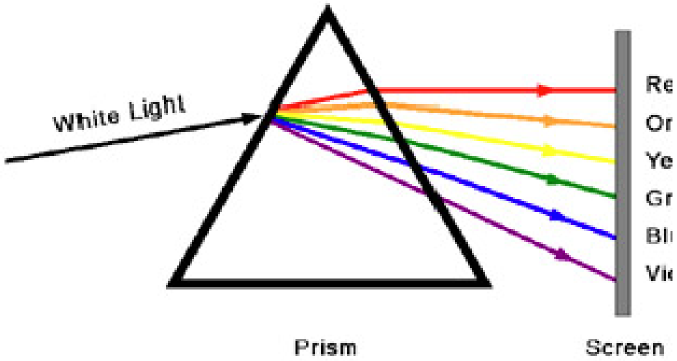
Repetition rate:
0.5 – 5kHz

Properties of Laser

Monochromaticity:

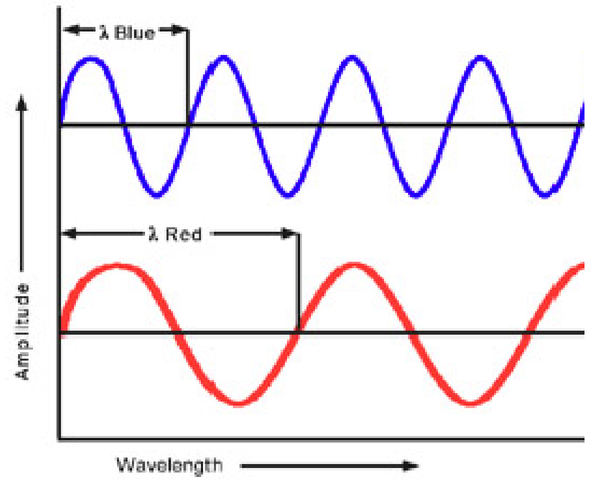


Nearly monochromatic light



Example:

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

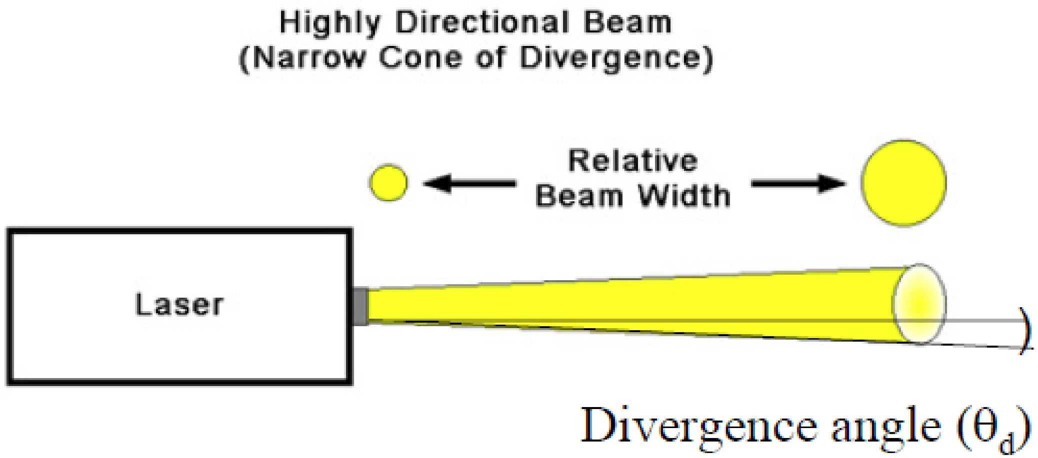


Comparison of the wavelengths of red

Properties of Laser

Directionality:

Conventional light source

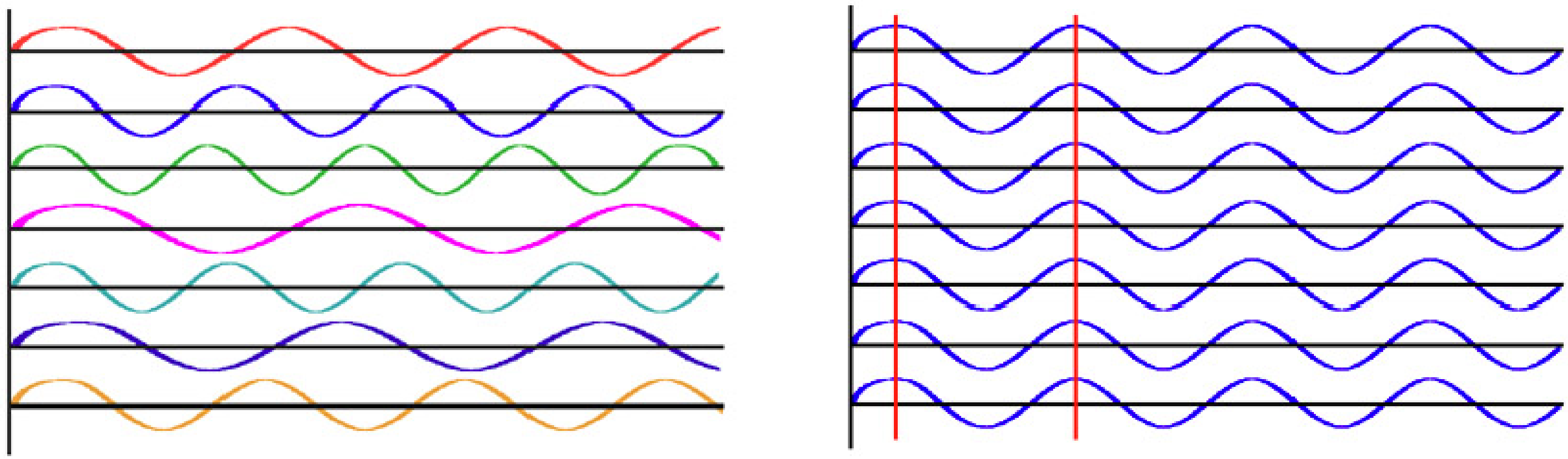


Beam divergence: $\theta_d = \beta \lambda / D$

$\beta \sim 1$ = f(type of light amplitude distribution, definition of beam diameter)
λ = wavelenght
D = beam diameter

Properties of Laser

Coherence:



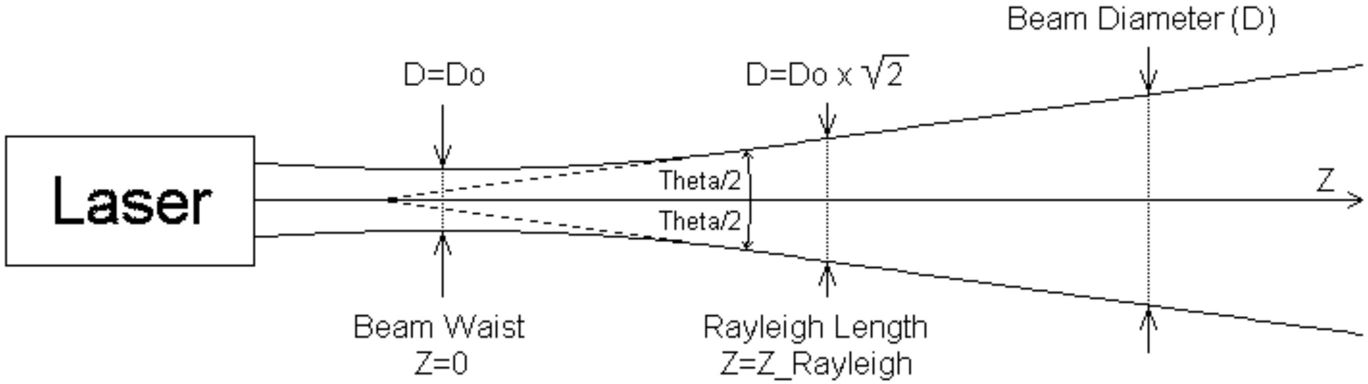
Incoherent light waves Coherent light waves

Laser light Cannot: be perfectly monochromatic
be perfectly directional
perfect coherent

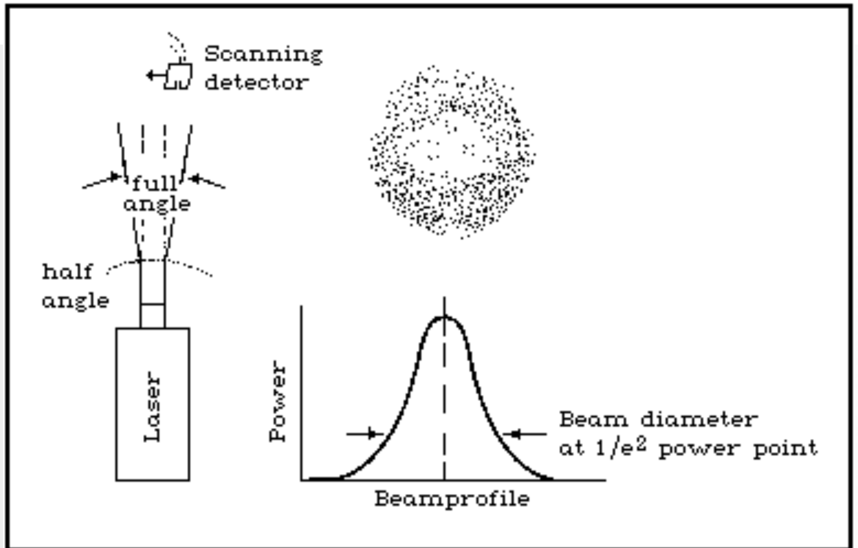
Properties of Laser

However, laser light is far more coherent than light from any other source.

Laser divergence



Divergence, Beam Waist, Rayleigh Length



Gaussian profile of a single-mode laser beam plotted by scanning across the centre of the beam pattern above. The beam divergence of a laser should be expressed at the full-angle and not at the half angle. (From: Sliney & Wolbarsht, 1980).

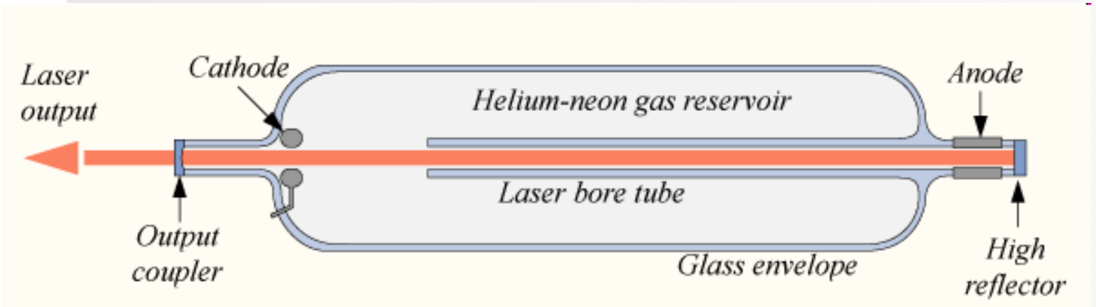
Types and operating principles

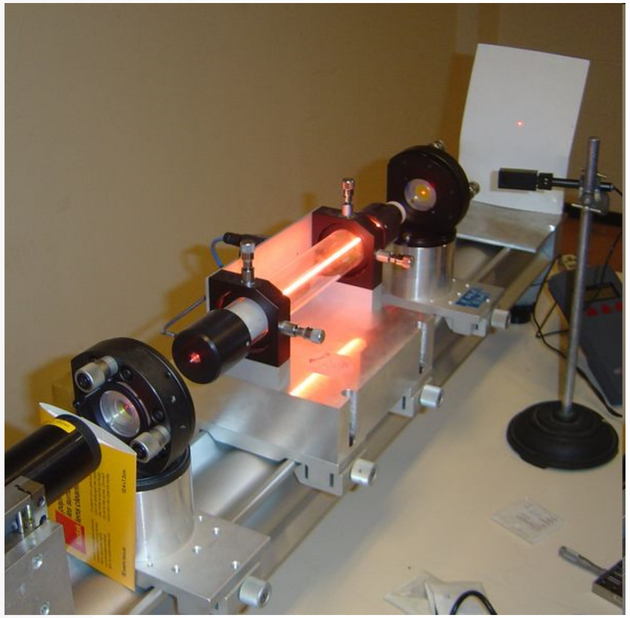
<u>Gas lasers</u>:

<u>Helium-neon laser</u> (operation wavelength is 632.8 nm, CW output)

Gain Medium: a mixture of helium and neon gases

Pump source: electrical discharge of around 1000 between anode and cathode

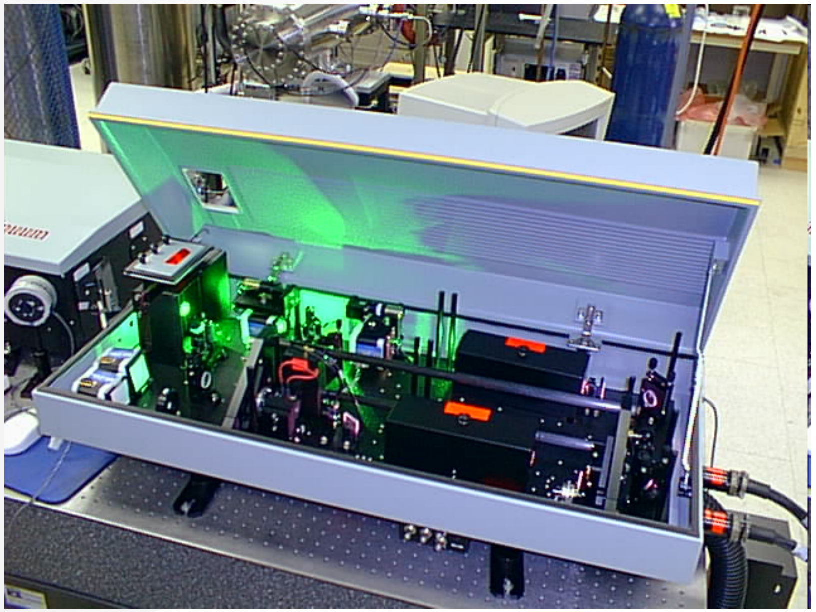




Solid state lasers

Commonly made by doping a crystalline solid host with ions that provide the required energy states

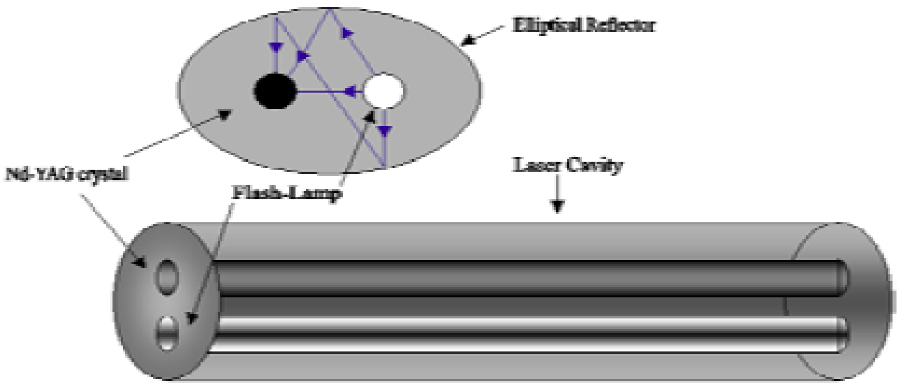
<u>**Yttrium Aluminium Garnet (Nd:YAG) laser**</u>**:**
produce high powers in the infrared spectrum at 1064 nm, frequency doubled, tripled or quadrupled to produce 532 nm (green, visible), 355 nm (UV) and 266 nm (UV) light



Solid state lasers

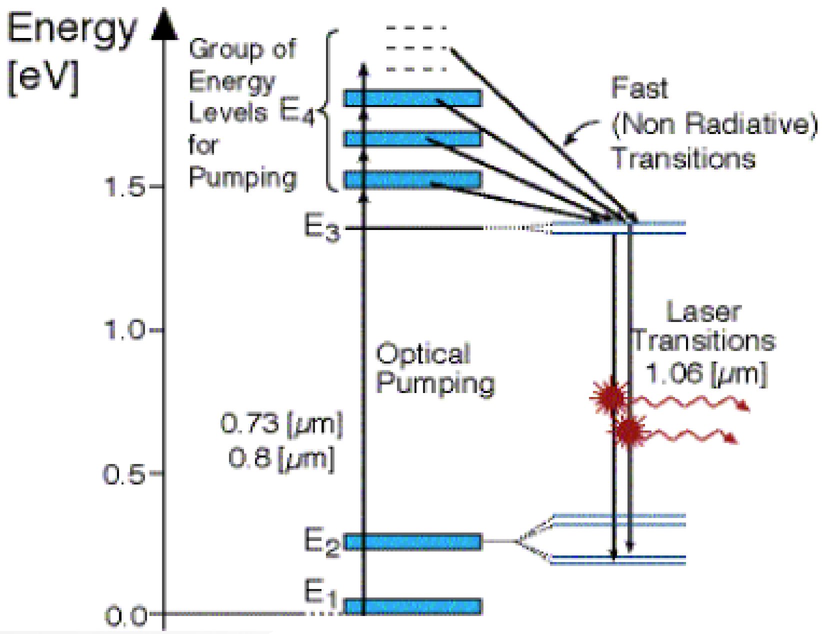
Nd:YAG Laser:

$\lambda = 1.064\ \mu m$



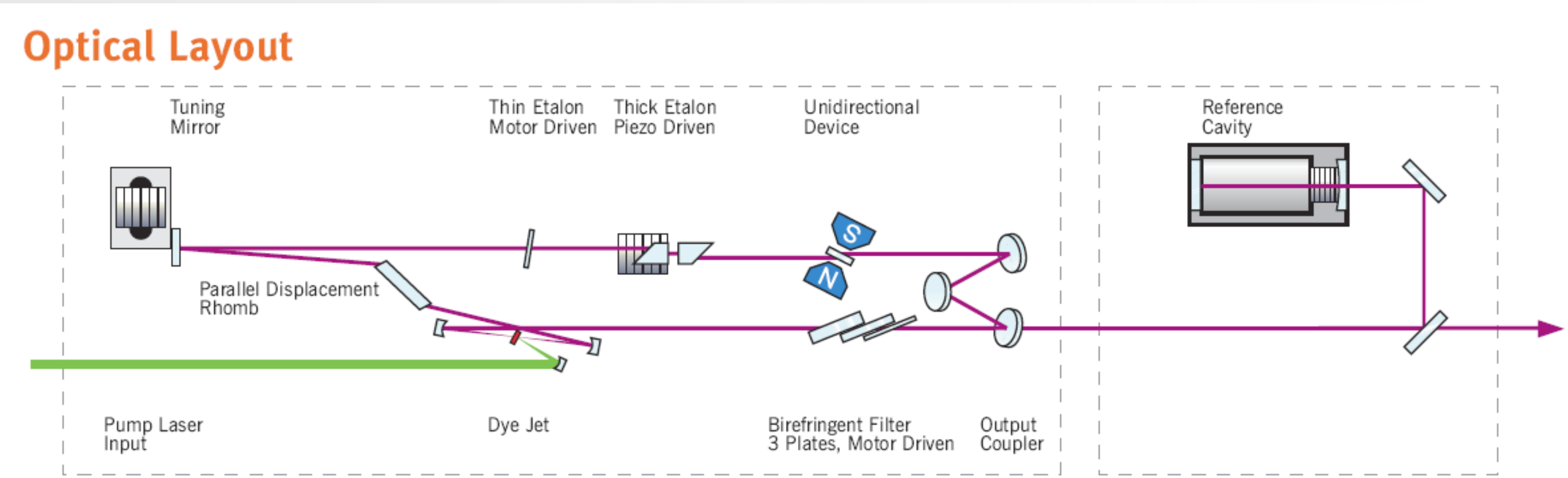
- YAG = Yttrium-Aluminium-Garnet ($Y_3Al_5O_{12}$), it is transparent and colourless.

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



Ring dye lasers

use an organic dye as the gain medium.
The wide gain spectrum of available dyes allows these lasers to be highly tunable, or to produce very short-duration pulses (on the order of a few femtoseconds)
Dyes:
Rhodamine 6G, fluorescein, coumarin, stilbene, umbelliferone, tetracene, malachite green



Semiconductor lasers

active medium is a semiconductor, emit at wavelengths from 375 nm to 1800 nm

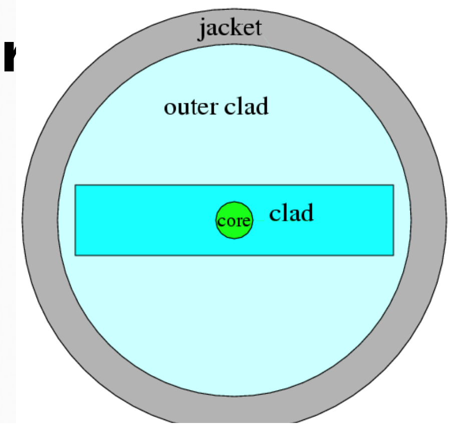
Low power laser diodes are used in laser printers and CD/DVD players

More powerful laser diodes frequently used to optically pump other lasers with high efficiency

Fiber lasers

guided due to the total internal reflection in an optical fiber

Double-clad fibers (high-power fiber laser



gain medium forms the core of the fiber
The lasing mode propagates in the core,
while a multimode pump beam propagates
in the inner cladding layer

Fiber disk lasers

the pump is not confined within
The cladding of the fiber but
pump light is delivered across
The core multiple times

Output power for fiber laser

Typically 100W – >1KW

Chemical lasers:

Involve chemical reaction

achieve high powers in continuous operation

hydrogen fluoride laser

(wavelength around 2.7-2.9 μm , infrared, output power in the megawatt range)

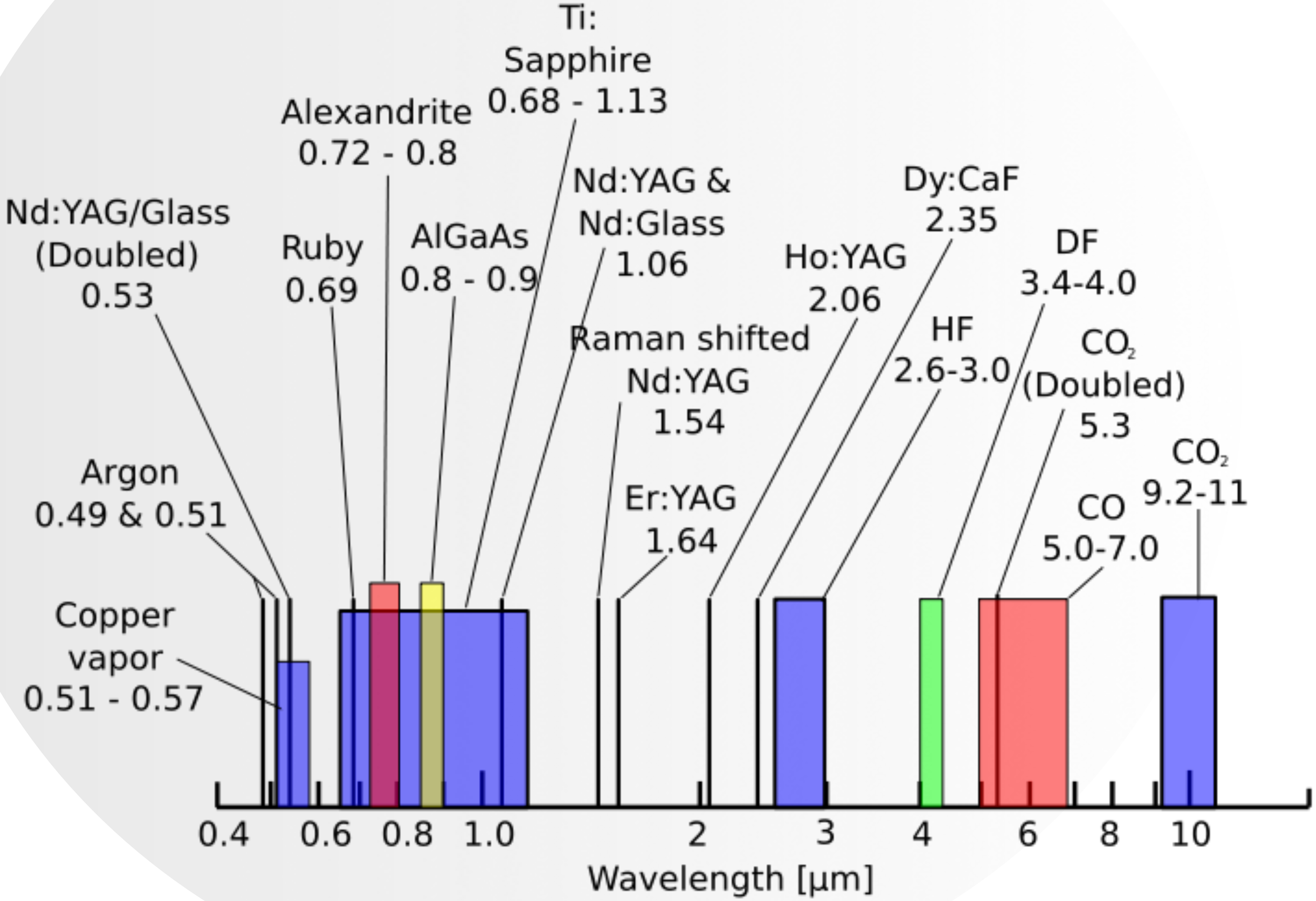
Excimer lasers (准分子激光器)

powered by a chemical reaction involving an *excimer*, (a short-lived dimeric or heterodimeric molecule formed from two species (atoms)) typically produce ultraviolet light

Commonly used excimer noble gas compounds (ArF [193 nm], KrCl [222 nm], KrF [248 nm], XeCl [308 nm], and XeF [351 nm]).

XeCl excimer laser, commonly used in DIAL ozone lidar system

Spectral output of several types of lasers



Laser safety

potentially dangerous

Class I/1 is inherently safe, light is contained in an enclosure, for example in cd players.

Class II/2 is safe during normal use; Usually up to 1 mW power (laser pointers).

Class IIIa/3A lasers are usually up to 5 mW and involve a small risk of eye damage. Staring into such a beam for several seconds is likely to cause (minor) eye damage.

Class IIIb/3B can cause immediate severe eye damage upon exposure. Usually lasers up to 500 mW

Class IV/4 lasers can burn skin, and in some cases, even scattered light can cause eye and/or skin damage. Many industrial and scientific lasers are in this class.