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Preparatory School to the Winter College on Optics

28 January - 1 February, 2013

Lasers, Q-switching and mode-locking

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LASER SYSTEMS AND THEIR APPLICATIONS

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- Basic Components of Laser
- Laser operation
- Types of Lasers
- Laser Applications

Introduction

LASER

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

- An optical source that emits photons in a coherent beam.
- In analogy with optical lasers, a device which produces any particles or electromagnetic radiations in a coherent state is called “Laser”, e.g., Atom Laser.
- In most cases “laser” refers to a source of coherent photons i.e., light or other electromagnetic radiations. It is not limited to photons in the visible spectrum. There are x-rays, infrared, UV lasers etc.

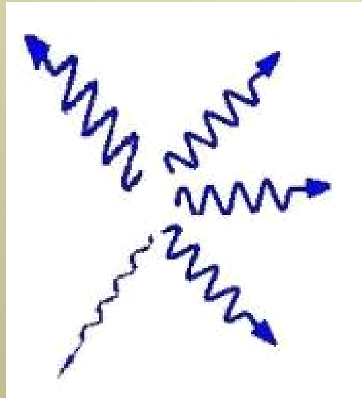
Properties of Laser Light

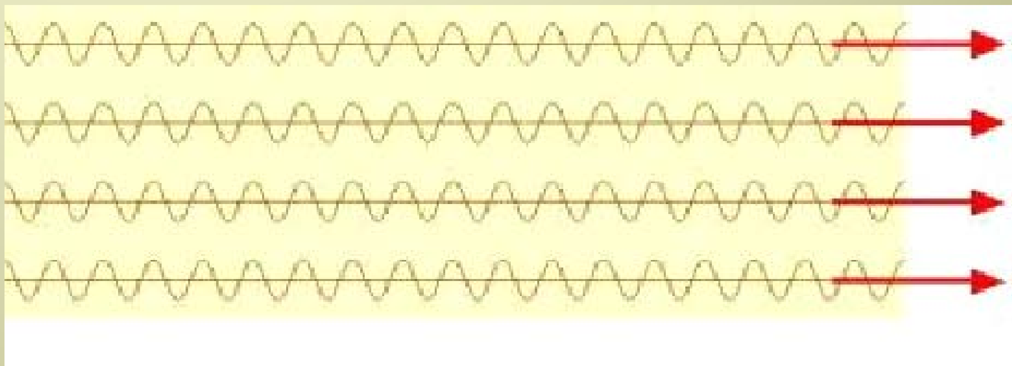
- The light emitted from a laser is ***monochromatic***, that is, it is of one color/wavelength. In contrast, ordinary white light is a combination of many colors (or wavelengths) of light.

- Lasers emit light that is highly ***directional***, that is, laser light is emitted as a relatively narrow beam in a specific direction. Ordinary light, such as from a light bulb, is emitted in many directions away from the source.

- The light from a laser is said to be ***coherent***, which means that the wavelengths of the laser light are in phase in space and time. Ordinary light can be a mixture of many wavelengths.

Ordinary Light vs. Laser Light





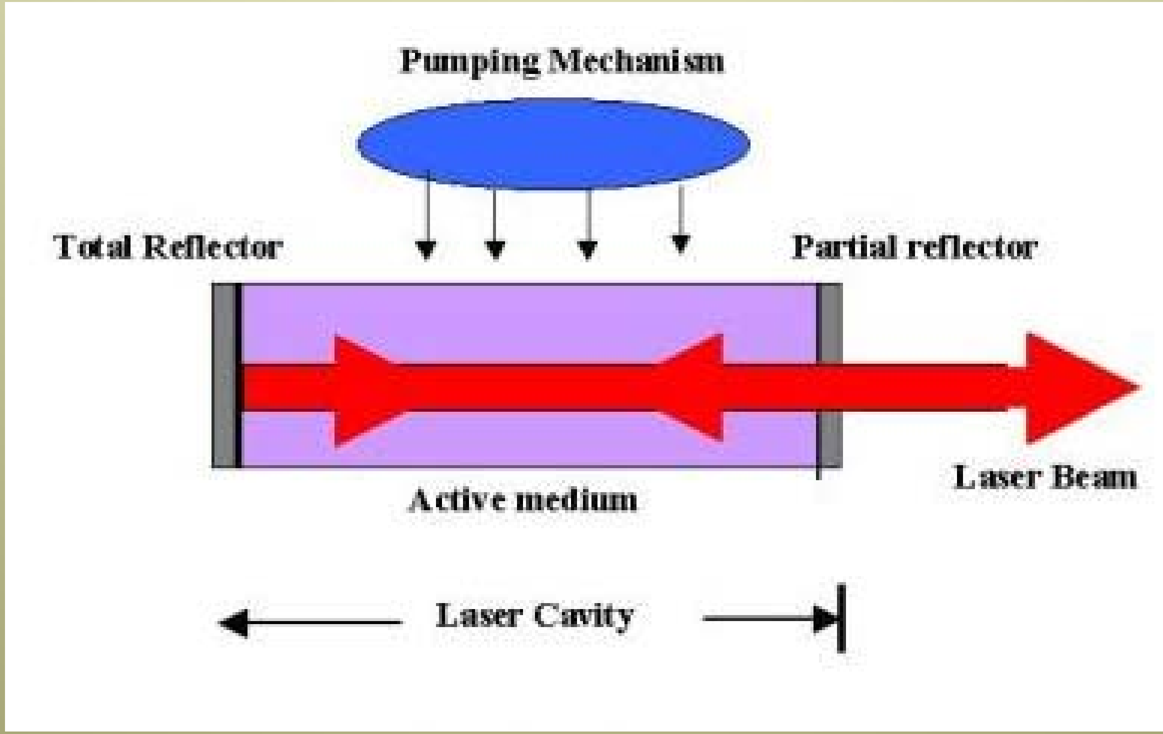
Laser Light

Ordinary Light

Basic Components of Laser 1

Laser system consists of three important parts.

1. Active medium or laser medium
2. An energy source (referred to as the pump or pump source)
3. An optical resonator consisting of a mirror or system of mirrors



Basic Components of Laser 2

Active Medium

Major determining factor of the wavelength of operation and other properties of laser.

- **Hundreds of different gain media in which laser operation has been achieved.**
- **The gain medium could be solid crystals such as ruby or Nd:YAG, liquid dyes, gases like CO_2 or Helium-Neon, and semiconductors such as GaAs.**

Pumping Mechanism

- **The pump source is the part that provides energy to produce a population inversion.**
- **Pump sources include electrical discharges, flash lamps, light from another laser, chemical reactions.**
- **The type of pump source used principally depends on the gain medium.**

Optical Resonator

Its simplest form is two parallel mirrors placed around the gain medium.

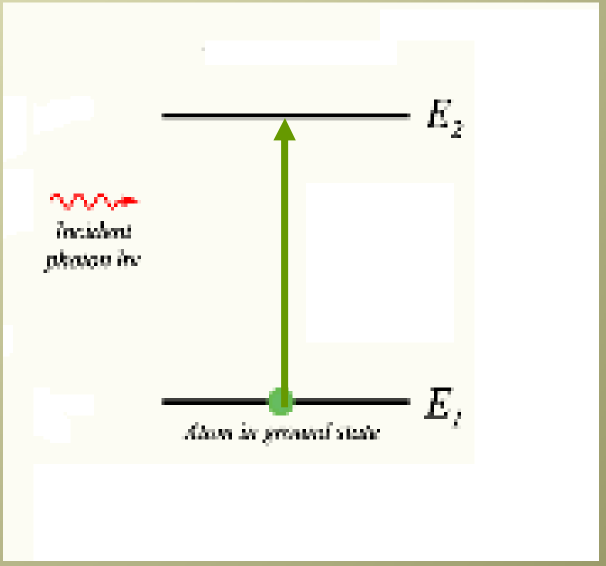
- **Light from the medium produced by the spontaneous emission is reflected by the mirrors back into the medium where it may be amplified by stimulated emission.**
- **One of the mirrors reflects essentially 100% of the laser light while the other reflects less than 100% of the laser light and transmits the remainder.**

Basic Principles of Light Emission and Absorption 1

In 1916, Einstein considered various transition rates between atomic states (say, 1 and 2) involving light of intensity, *I*.

- **Absorption:**

  Absorption is the process by which the energy of the photon is taken up by another entity, e.g., by an atom whose valence electrons make transition between two electronic energy levels. The photon is destroyed in the process.



Rate of Stimulated Absorption $= B\, N_1\, I$

B Einstein's Coefficient for Stimulated Absorption

N_1 Population in the Ground State

Basic Principles of Light Emission and Absorption 2

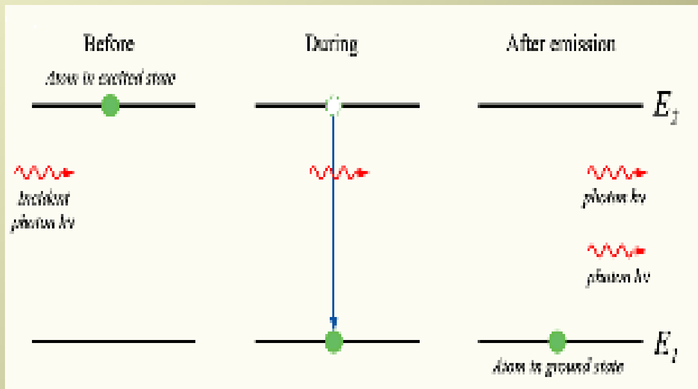
- **<u>Stimulated Emission:</u>**

  A process by which, when perturbed by a photon, matter may lose energy resulting in the creation of another identical photon.

  Rate of stimulated emission = $B\,N_2\,I$

  B Einstein's Coefficient for Stimulated Emission

  N_2 Population in the Excited State

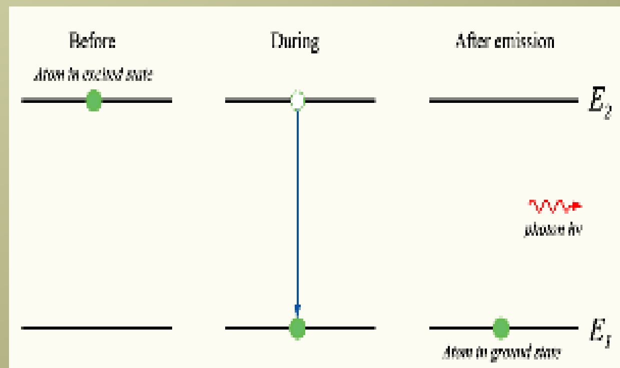


- **<u>Spontaneous Emission:</u>**

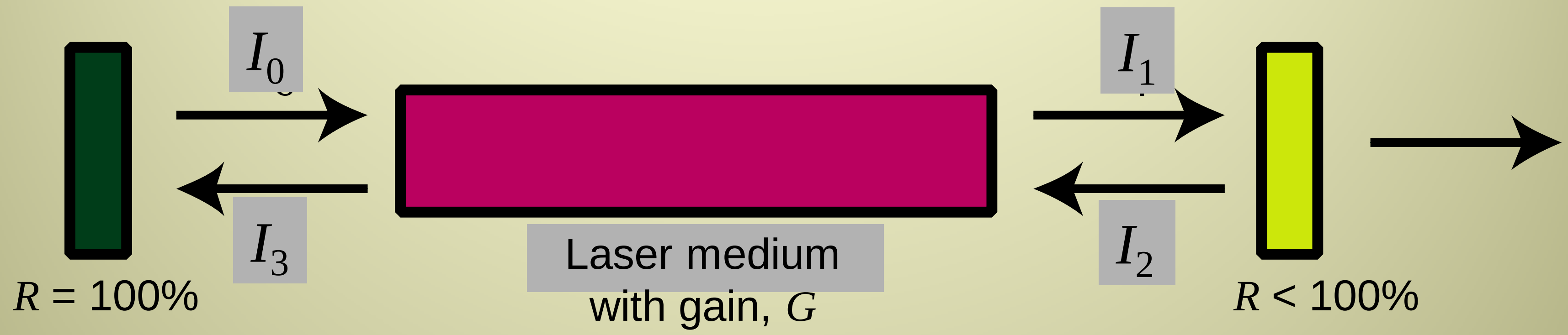
  A process by which an atom, molecule in an excited state drops to a lower energy level.

  Rate of spontaneous emission = $A\,N_2$

  A Einstein’s Coefficient for Spontaneous Emission



Threshold Condition



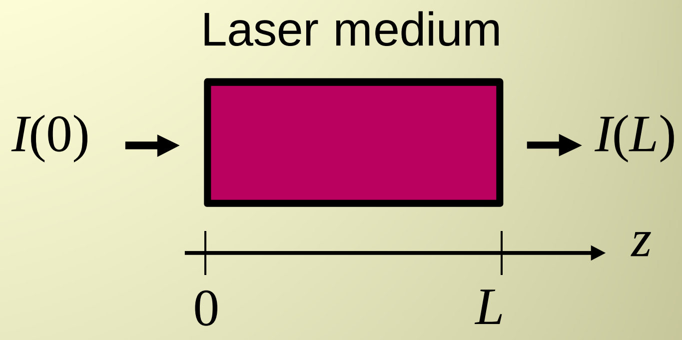
A laser action will be achieved if the beam increases in intensity during a round trip: that is, if $I_3 \geq I_0$

Usually, additional **losses** in intensity occur, such as absorption, scattering, and reflections. In general, the laser will lase if, in a round trip:

Gain > Loss

This is called achieving **Threshold**.

Laser Gain



Neglecting spontaneous emission:

$$\frac{dI}{dz} \propto BN_2 I - BN_1 I$$

[Stimulated emission minus absorption]

$$\propto B\left[N_2 - N_1\right] I$$

$$I(z) = I(0)\exp\left\{\sigma\left[N_2 - N_1\right]z\right\}$$

Proportionality constant is the **absorption/gain cross-section, σ**

There can be exponential gain or loss in intensity. Normally, $N_2 < N_1$, and there is loss (absorption). But if $N_2 > N_1$, there's gain, and we define the gain, G:

$$\boxed{G \equiv \exp\left\{\sigma\left[N_2 - N_1\right]L\right\}}$$

If $N_2 > N_1$: $\quad g \equiv \left[N_2 - N_1\right]\sigma$

If $N_2 < N_1$: $\quad \alpha \equiv \left[N_1 - N_2\right]\sigma$

Population Inversion

In order to achieve $G > 1$, that is, stimulated emission must exceed absorption:

$$B\,N_2\,I > B\,N_1\,I$$

Equivalently,

$$\boxed{N_2 > N_1}$$

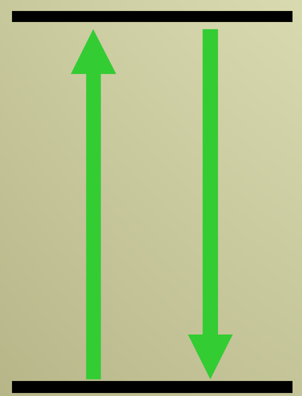
This condition is called ***population inversion***. It does not occur naturally. It is inherently a non-equilibrium state.

In order to achieve inversion, we must pump the laser medium in some way and choose our medium correctly.

Population inversion is the necessary condition for laser action.

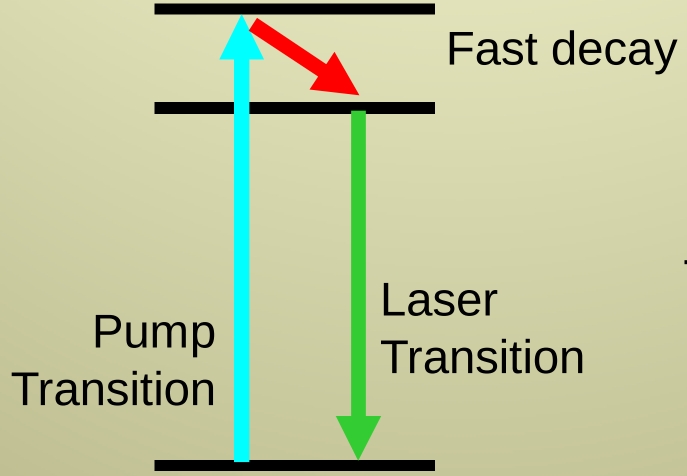
Two-, Three-, and Four-Level Systems

Two-level system



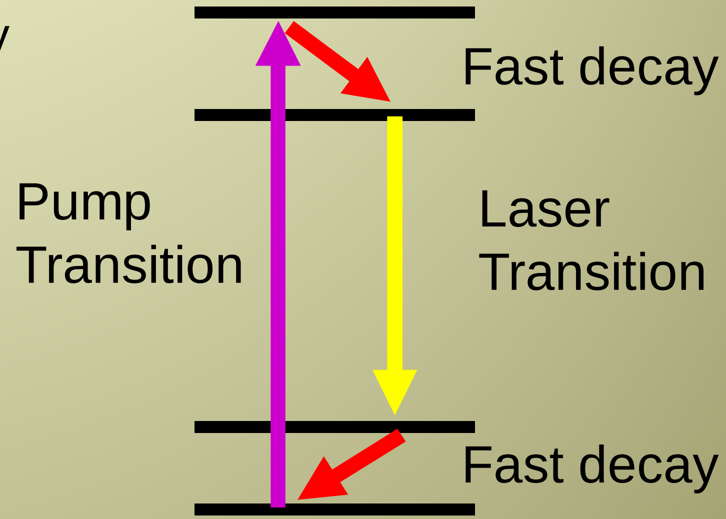
At best, you get equal populations. No lasing.

Three-level system

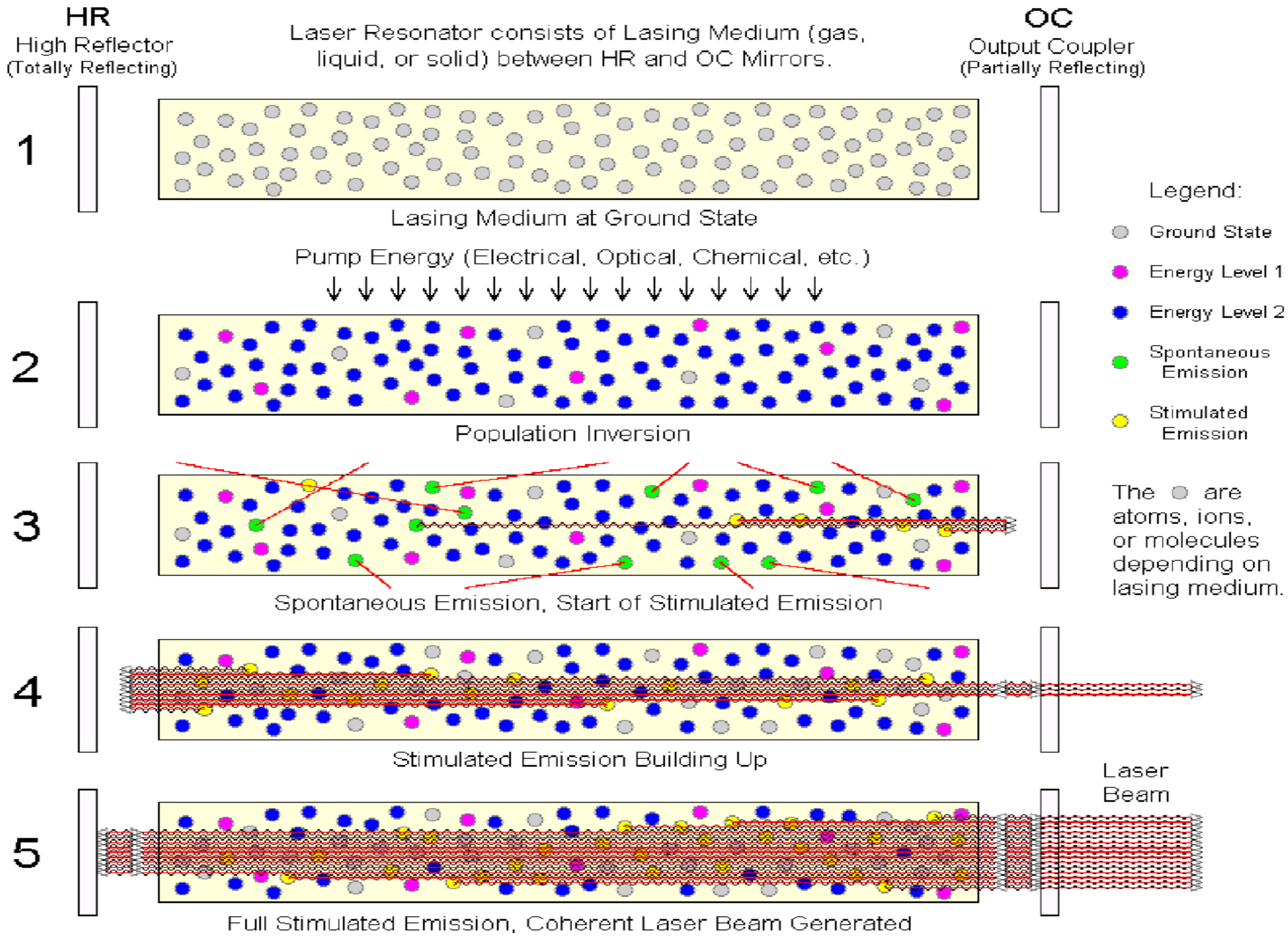


If you hit it hard, you get lasing.

Four-level system



Lasing is easy!



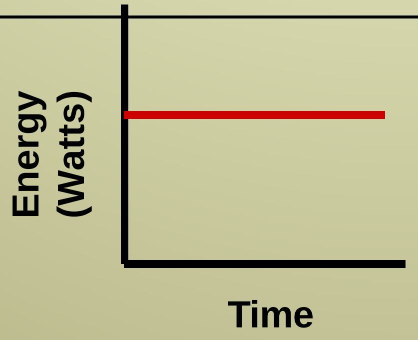
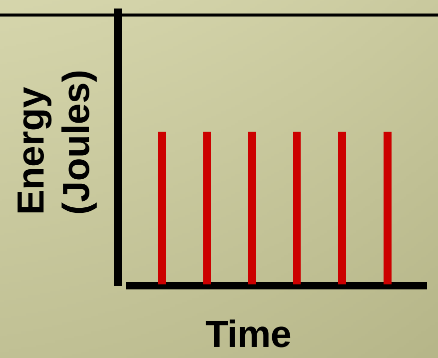
Basic Laser Operation

Laser Beam Output 1

- Characteristics that affect laser performance are the **power output** and **mode of emission** - continuous wave, pulsed, Q-switched or Mode –locked lasers.
- **CW laser**- emits a continuous beam of light as long as medium is excited.
- **Pulsed laser**- emit light only in pulses- from femtoseconds to second
- **Q-switched laser**-pulses from micro to nanosecond are produced
- **Mode-Locked laser** –pulses from pico (10^{-12}s) - to femtoseconds (10^{-15}s) are produced

Laser Beam Output 2

Lasers operated in ***Continuous Wave* (CW)** or ***Pulsed*** modes.
CW lasers-energy is continuously ***pumped*** - producing a continuous laser output. ***Pulsed lasers* -** the pump energy is applied in pulses- usually with a flash lamp

Continuous Output	Pulsed Output
	

Laser: Q-switching

- Q-switching is a way of obtaining ***short*** - from a few nano -seconds to few tens of nano -seconds – ***powerful -*** from a few megawatts to few tens of megawatts- pulses of laser.
- Q – quality factor of laser resonator.
- High Q – Low losses
- Low Q - High losses
- The term Q-switching refers to an abrupt switching of the cavity Q from low value to a high value.

Laser: Q-switching

- Methods of Q-switching: There are many ways to Q-switch a laser
- **Active Q-switching**

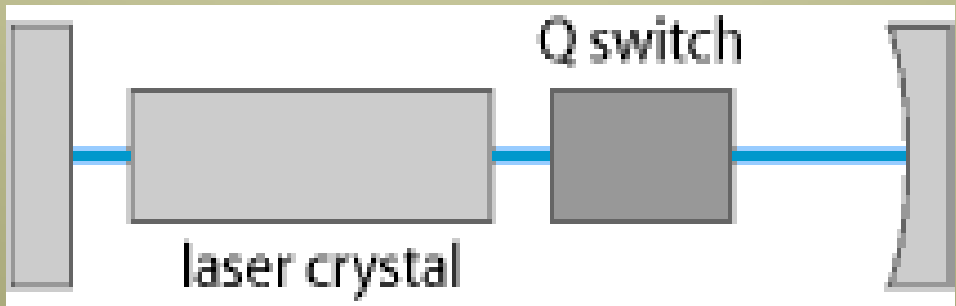
1. Mechanical devices- shutters, chopper wheel or spinning mirror.
2. Electro-optic device: Pockel cells and kerr cells.
3. Acousto-optic device

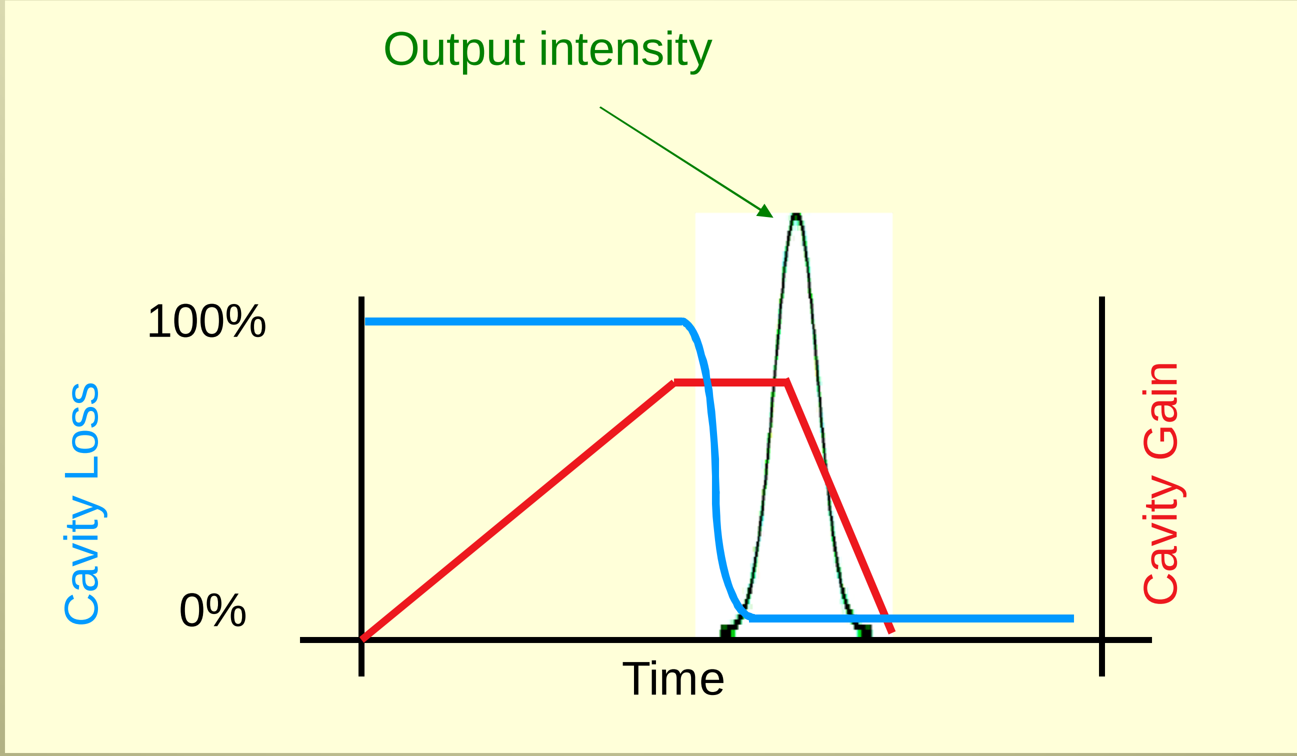
- **Passive Q-switching**

1. Q-switch is a saturable absorber.

Laser: Q-switching

- **The active medium is excited without feedback -by blocking the reflection from one of the end mirrors of the cavity**
- **The end mirror is then suddenly allowed to reflect**
- **Suddenly applied feedback causes a rapid population inversion of the lasing levels**
- **Results in a very high peak power output pulse of short duration**




Output intensity
100%
0%
Cavity Loss
Cavity Gain
Time

Techniques for Q switching

Using a mechanically driven device

- **A rotating prism or mirror**
- **Rotate one of the mirrors about an axis perpendicular to the laser**
- **Rotating speed cannot be made very large**
- **Q switching does not take place instantaneously**

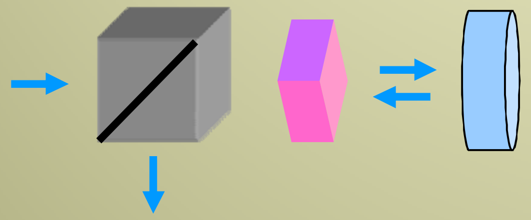
Electro-optical Switches

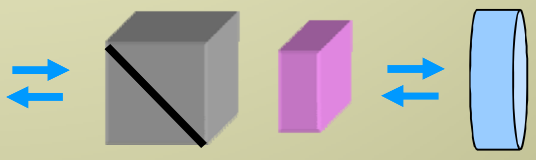
- Light passes through a polarizer and an Electro-optic cell (controlling the phase or polarization of the laser beam)
- When appropriate voltage is applied- the material inside the cell becomes birefringent
- By varying the voltage – cell blocks or transmits beam.
- Two kinds of electro-optics switches are used-namely Kerr and Pockels' cell.

Pockels' Cell

- A Pockels' cell switches (in a few nanoseconds) from a quarter-wave plate to nothing.

Before switching | **After switching**





Light becomes circular on the first pass and then horizontal on the next and is then rejected by the polarizer.

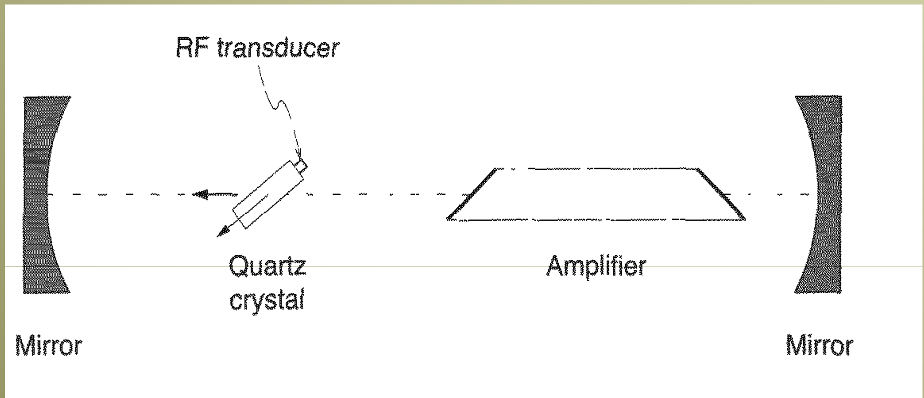
Light is unaffected by the Pockels' cell and hence is passed by the polarizer.

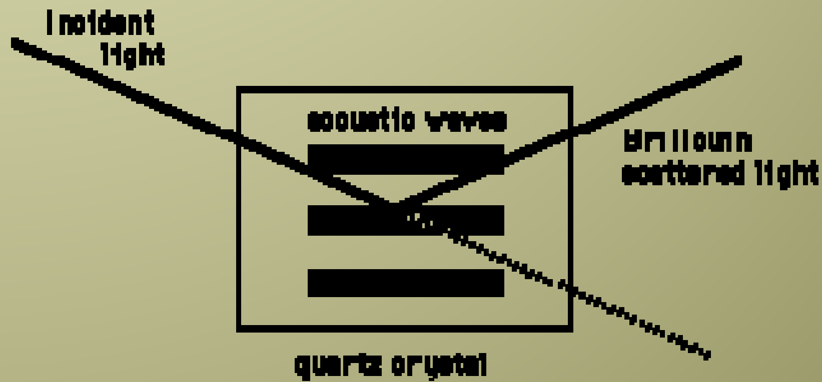
Acousto-optic Shutter

•Uses a quartz crystal

•RF on- beam deflect out of the cavity yielding high loss

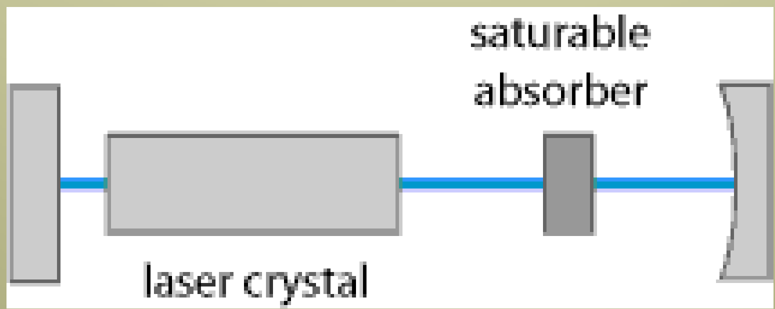
•RF off-beam transits the cavity with low loss





Passive Q- switching

- **Initially** **light output absorbed** **by dye-preventing reflection**
- **After a particular intensity is reached- dye is bleached(allows light)**
- **Now reflection from mirror is possible**
- **Results in rapid increase in cavity gain**



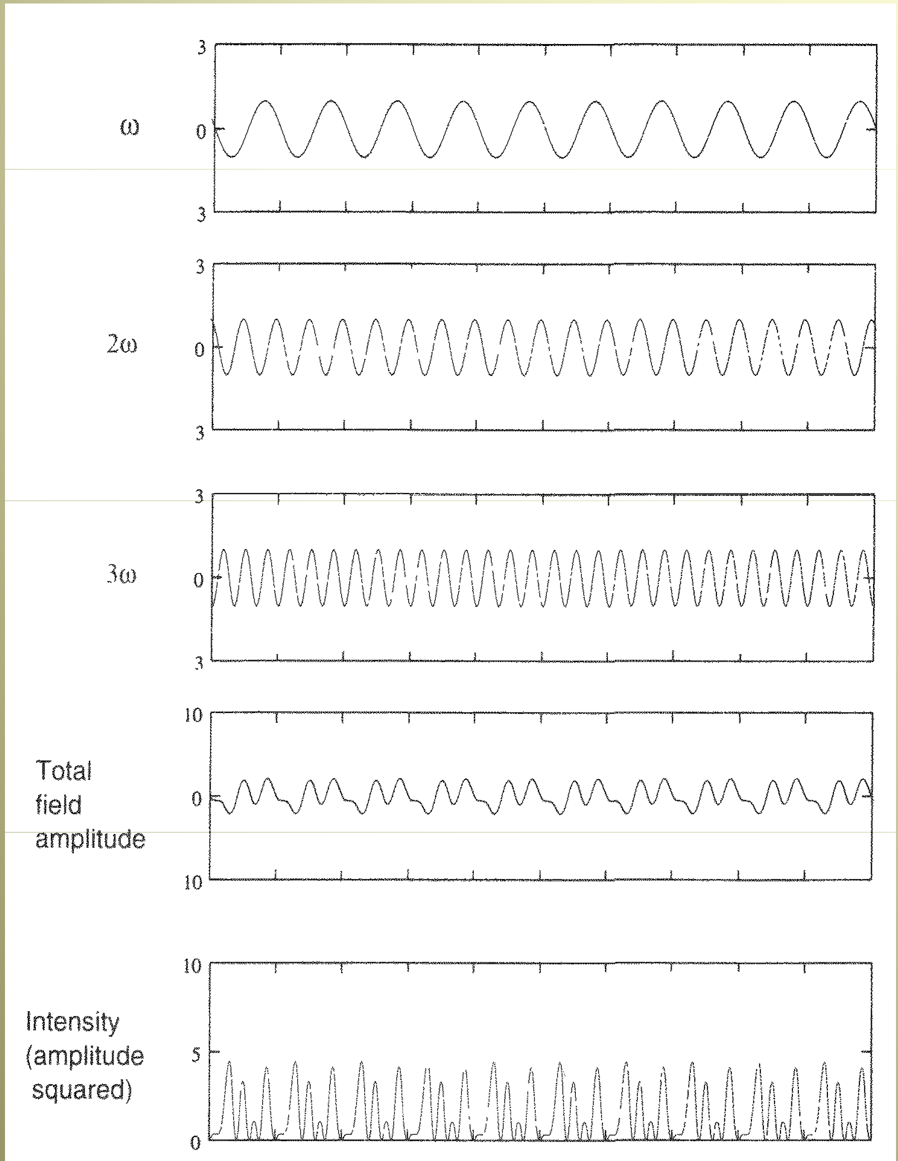
Laser: Mode-Locking

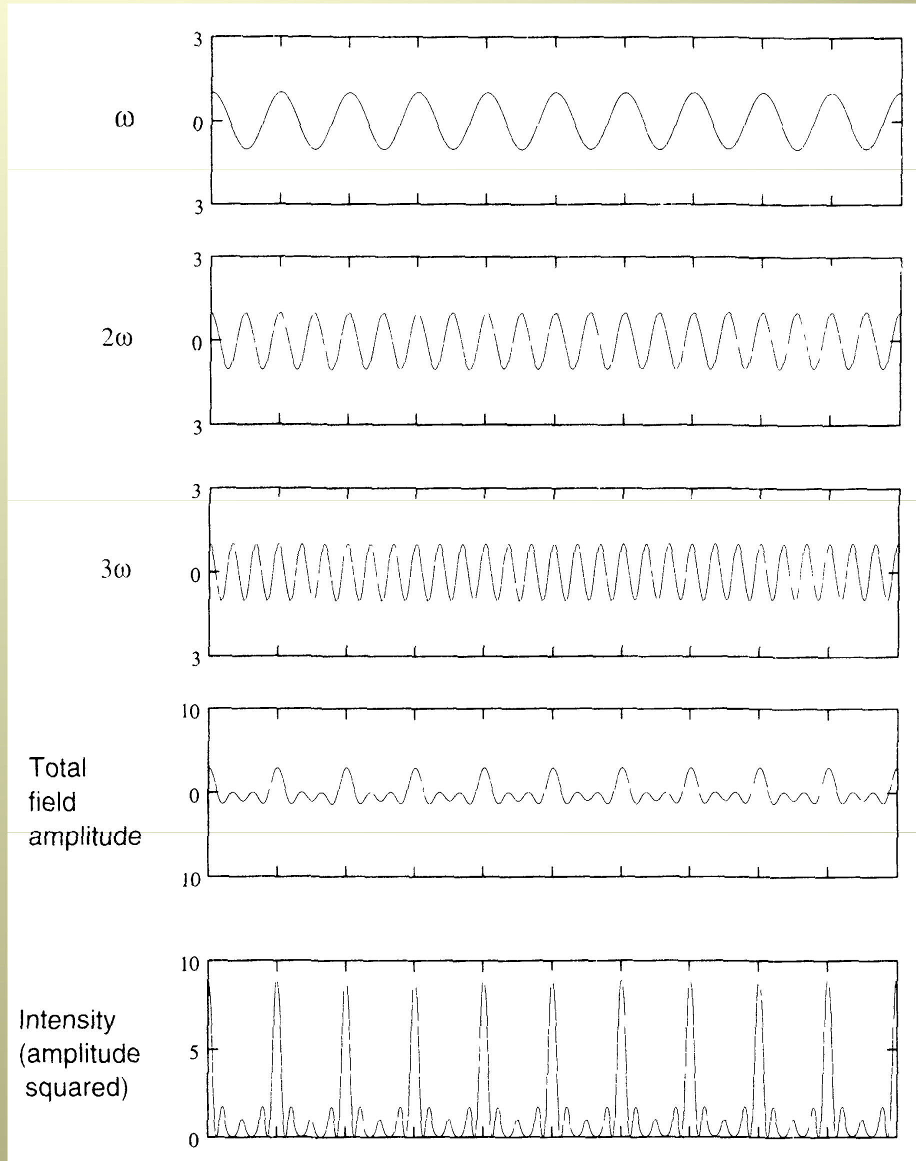
- **Mode-locking** - technique that generate ultra-short optical pulse in the range of femto-second.

Principle of Mode-Locking

- Mode-locking- achieved by locking together the phases of all oscillating axial laser modes - having slightly different frequencies.
- Interference between these modes causes the laser light to be produced as a train of pulses.

Laser: Mode-Locking





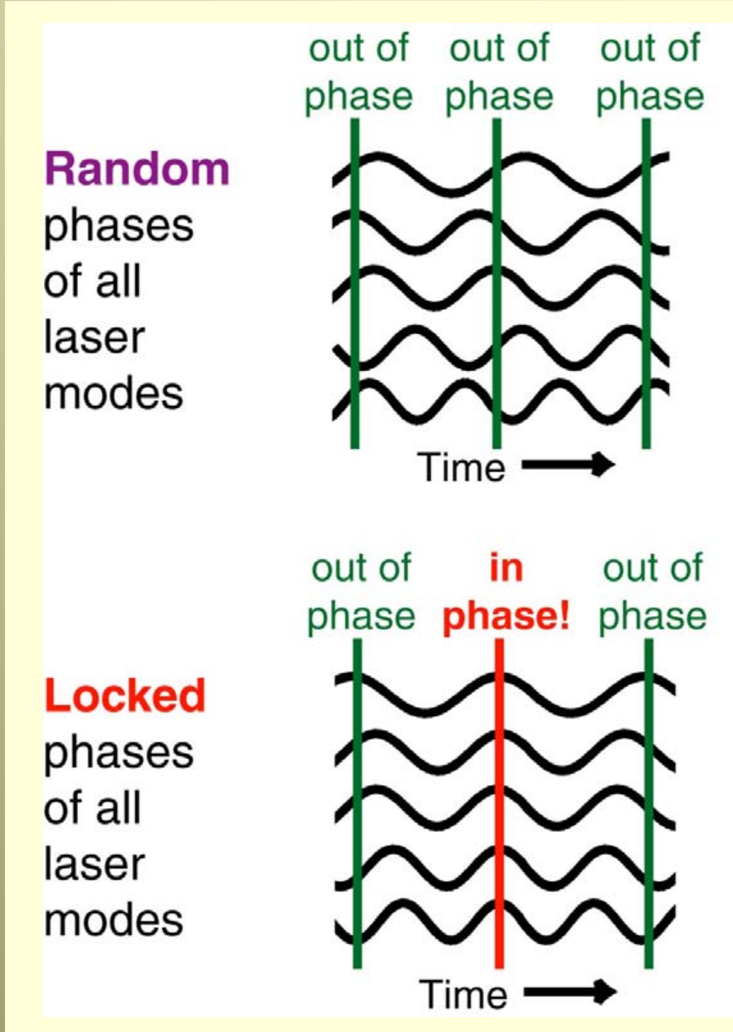
Laser: Mode-Locking

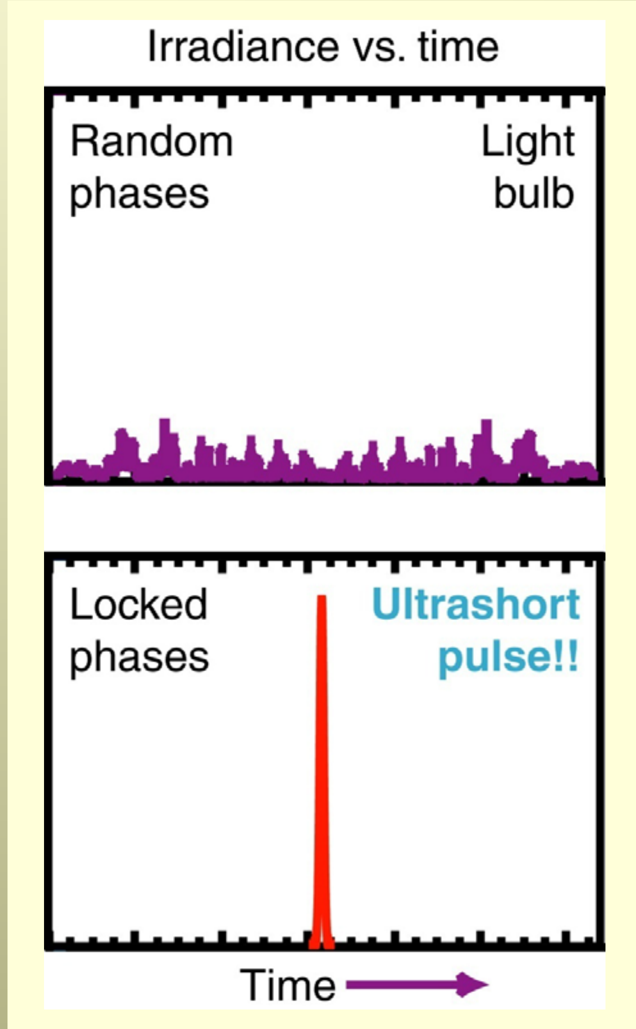
When laser is oscillating with various modes and if modes are uncorrelated The output intensity

$$I(t) = NE_0^2$$

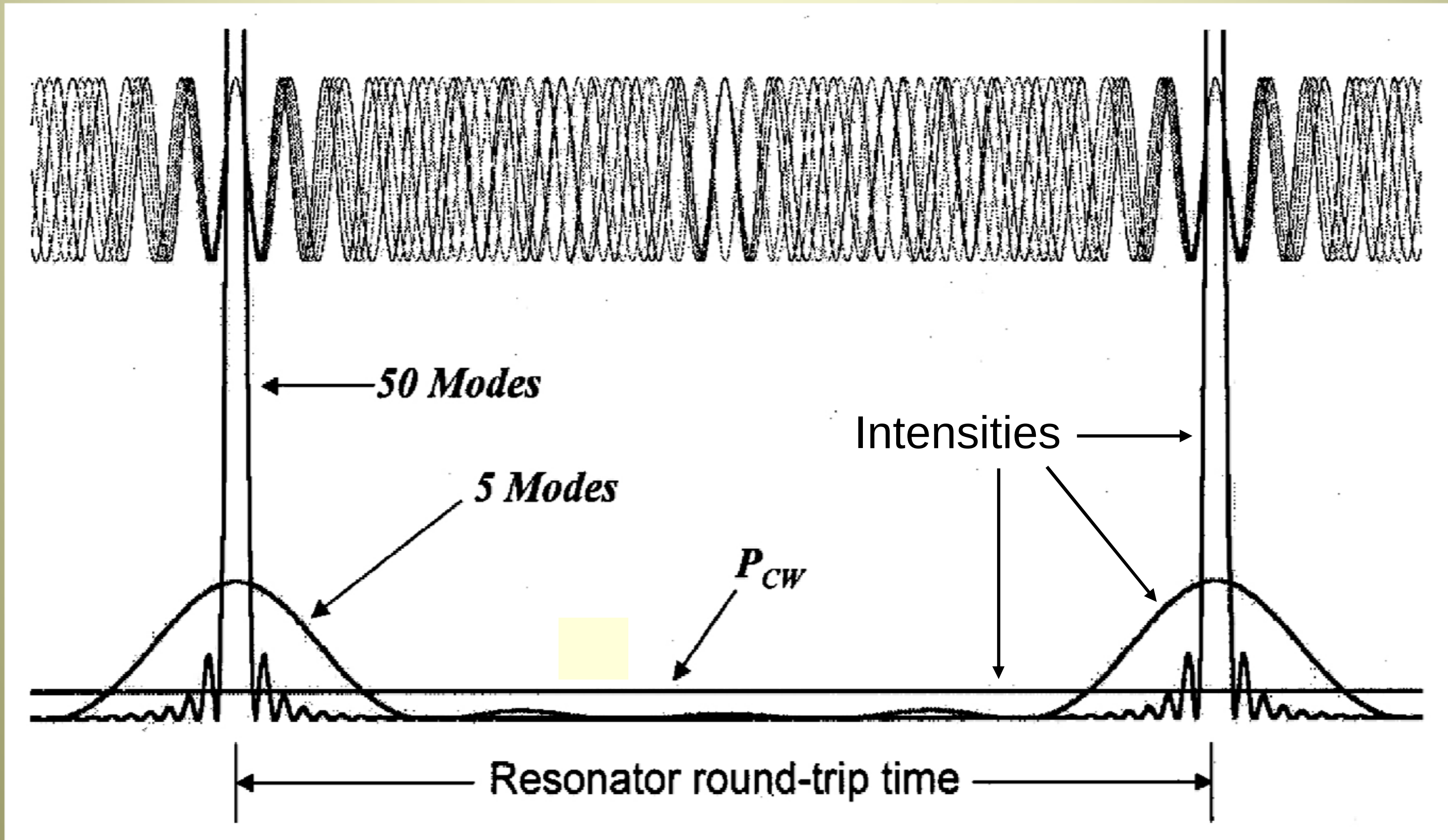
When modes are locked in phase the output intensity is given as

$$I(t) = N^2 E_0^2$$

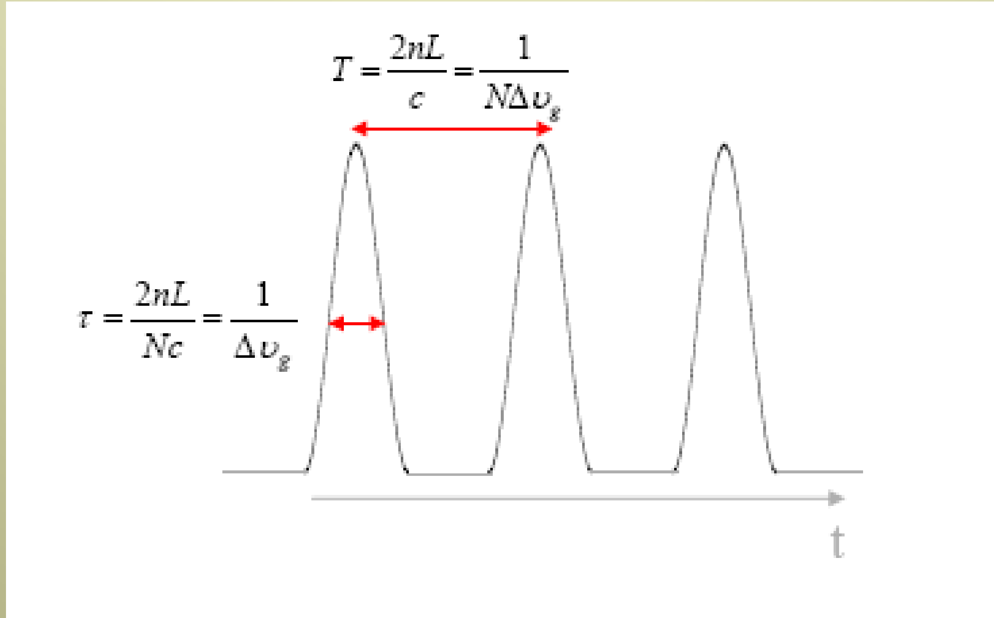

out of phase
out of phase
out of phase
Random phases of all laser modes
Time
out of phase
in phase!
out of phase
Locked phases of all laser modes
Time


Irradiance vs. time
Random phases
Light bulb
Locked phases
Ultrashort pulse!!
Time

Locked Mode



Locked Mode



$T = \frac{2nL}{c} = \frac{1}{N\Delta\upsilon_g}$
$\tau = \frac{2nL}{Nc} = \frac{1}{\Delta\upsilon_g}$
t

Laser: Mode-Locking

Methods of Mode-Locking

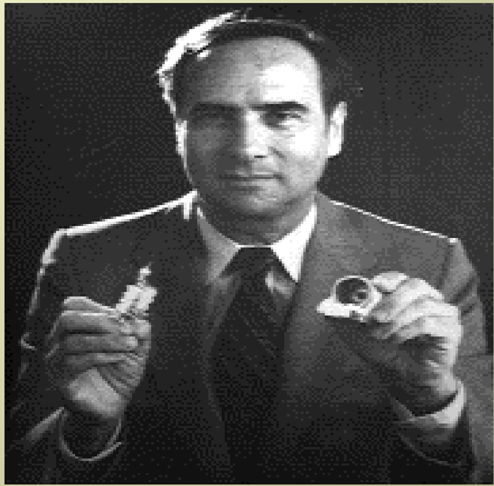
- A modulation of the electromagnetic field is induced by-fast modulating crystals-Active Mode-locking or saturable absorbers-Passive Mode-Locking.
- Mode-Locking- fundamentally multimode phenomenon

Physical Properties of Laser

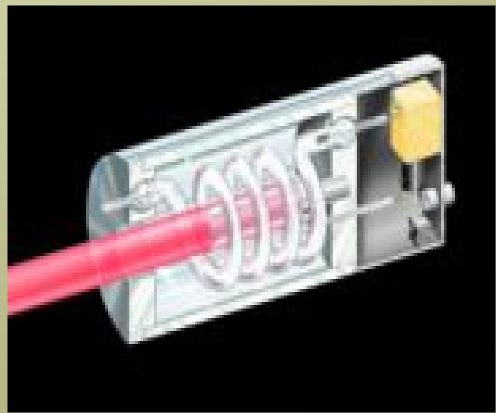
1. Energy- the amount of work accomplished – measured in joules
2. Power- Rate of energy expenditure – measured in joules per second or Watts (1J/s =1 W)
3. Irradiance- power density- the power of the laser per unit area.
4. Fluence - energy density- amount of energy delivered per unit area - irradiance multiplied by the exposure time (j/cm^2).

Types of Laser

Lasers are usually classified in terms of their active (lasing) medium. Major types are:



- **Solid-state lasers**
- **Semiconductor Lasers**
- **Dye Lasers**
- **Gas Lasers**
- **Excimer Lasers**



Types of Lasers 2

- **Solid-state lasers** have lasing material distributed in a solid material (such as ruby or neodymium: yttrium-aluminum garnet "YAG"). Flash lamps are the most common power source. The Nd:YAG laser emits infrared light at 1.064 micrometers.
- **Semiconductor lasers** sometimes called diode lasers- are pn junctions. Current is the pump source. Applications: laser printers or CD players.
- **Dye lasers** use complex organic dyes, such as rhodamine 6G, in liquid solution or suspension as lasing media. They are tunable over a broad range of wavelengths.

Types of Lasers 3

- **Gas lasers** are pumped by current. Helium-Neon lases in the visible and IR. Argon lases in the visible and UV. CO_2 lasers emit light in the far-infrared (10.6 micro m), and are used for cutting hard materials.
- **Excimer Lasers** **d**ifferent reactive gases (e.g chlorine, fluorine) are used with inert gases (e.g argon, xenon, and krypton). Mixture of these gases is excited- resulting in the release of a simulated molecule- called dimer. Upon lasing - this dimer produces ultraviolet lasers. The term Excimer comes from excited dimer

Applications of Laser

- Laser considered to be "a solution in search of a problem“ in 1958. Now Laser has many applications

- **Scientific Applications.**
- **Commercial Applications.**
- **Medical Applications**.

- The properties like Coherence, mono-chromaticity, and ability to reach extremely high powers, allow for these specialized applications.

Scientific Applications

- Laser Spectroscopy: atmospheric physics - pollution monitoring-cancer detection
- Optical metrology: optical distance measurement- optical temperature measurements etc.,
- Optical frequency metrology: for precise position measurements
- Laser induced breakdown spectroscopy: Solid materials can be analyzed
- Laser cooling: makes it possible to bring clouds of atoms or ions to extremely low temperatures
- Optical tweezers: used for trapping and manipulating small particles- such as bacteria or parts of living cells.
- Laser microscopes: provide images of, e.g., biological samples with very high resolution - often in three dimensions

Scientific Applications

Communications:

- Optical fiber communication: extensively used for long-distance optical data transmission-relies on laser light in optical glass fibers.
- Free-space optical communications: for inter-satellite communications- is based on higher-power lasers- generating collimated laser beams which propagate over large distances with small beam divergence.

Commercial Applications

- Cutting, welding, marking,
- Rangefinder / surveying,
- LIDAR / pollution monitoring,
- CD/DVD player,
- Laser printing,
- Laser engraving of printing plates,
- Laser pointers, holography, laser light displays
- Optical communications.

Medical Applications

- Cosmetic surgery:
- Dentistry:
- Dermatology:
- Eye surgery:
- Cardiology:
- Neurology:
- Urology:
- Optical Imaging:

Laser :Medical Applications

- **Cosmetic surgery:** removing tattoos, scars, stretch marks, wrinkles, birthmarks, and hairs.
- **Dentistry:** caries removal, tooth whitening, and oral surgery.
- **Dermatology:** Treatment of acne and skin cancer by PDT
- **Eye surgery:** Cataract and Glaucoma surgery

Laser :Medical Applications 2

- **Cardiology:** Angioplasty, vessel recanalization
- **Neurology:** To cut, ,vaporize and coagulate tissue with out mechanical contacts
- **Urology:** lithotripsy (removal of kidney stones)
- **Laser scalpel:** gynecology, urology, laparoscopy
- **Optical Imaging:** field of online monitoring and diagnostics

References

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- LASERS : Anthony E. Siegman
- LASER FUNDAMENTALS: William T. Silfvast

THANK YOU