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Preparatory School to the Winter College on Optics: Fundamentals of Photonics - Theory, Devices and Applications

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Introduction to Laser

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INTRODUCTION TO LASER

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Layout

- Fundamentals of Laser
    - Introduction
    - Properties of Laser Light
    - 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.

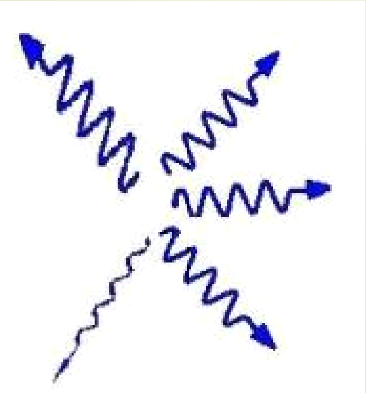
Properties of Laser Light

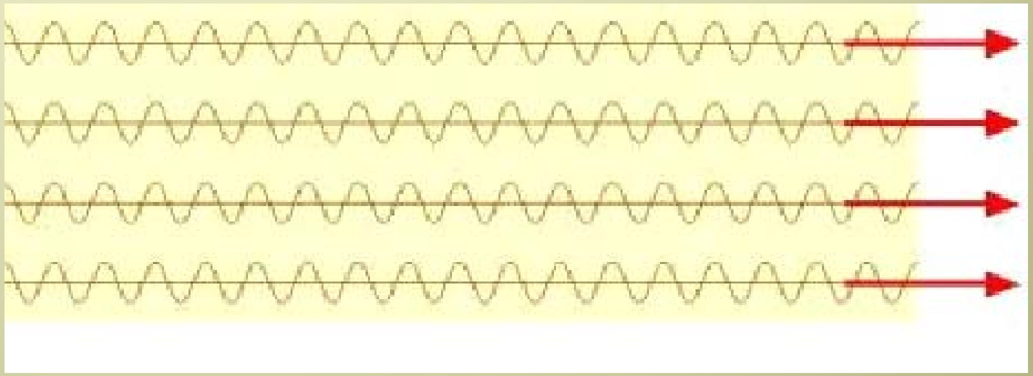
- The light emitted from a laser is ***monochromatic***, that is, it is of one color/wavelength. In contrast, ordinary white light is a combination of many colors (or wavelengths) of light.

- 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





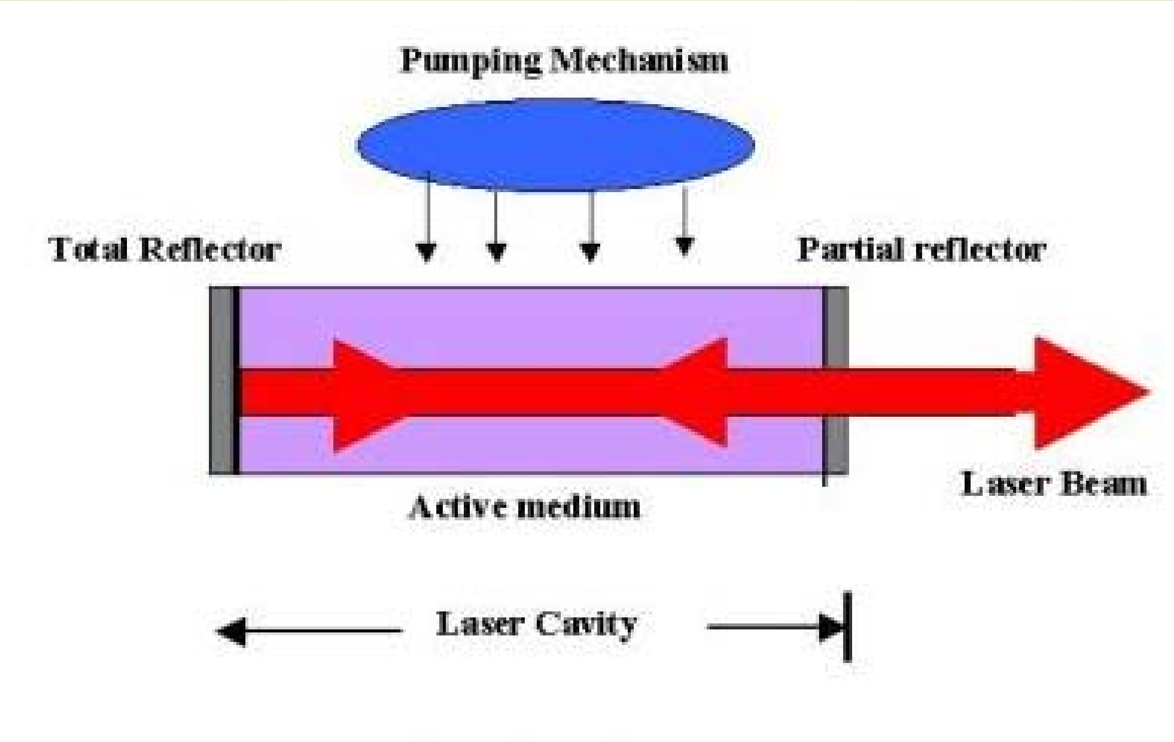
Laser Light

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 may 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.

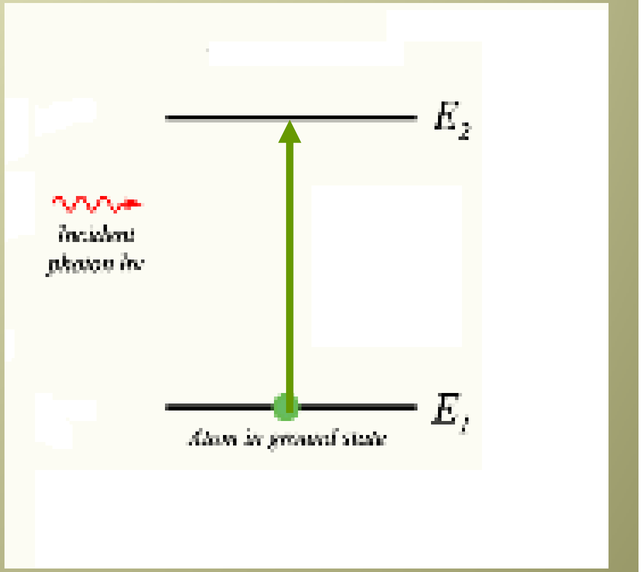
Basic Principles of Light Emission and Absorption

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

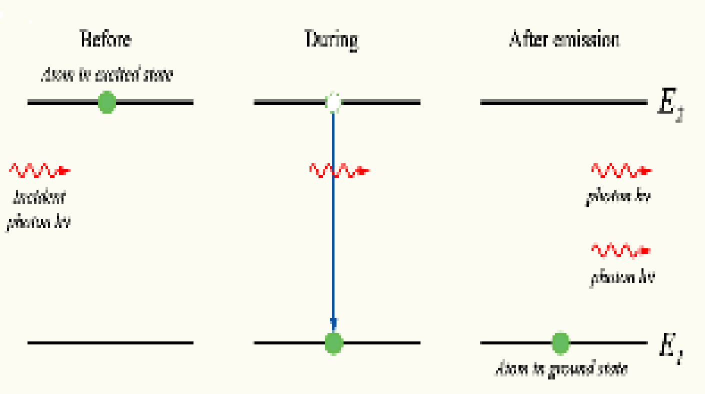
- **Stimulated Emission:**

  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

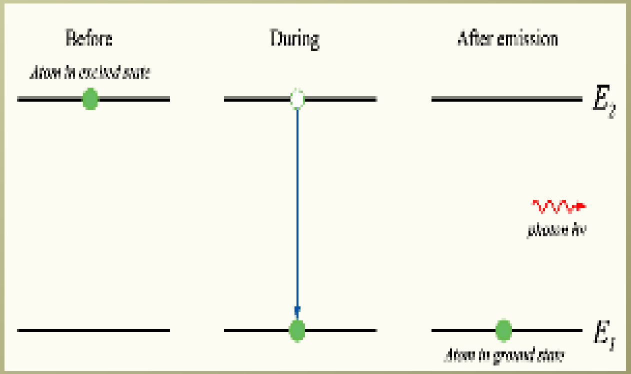


- **Spontaneous Emission:**

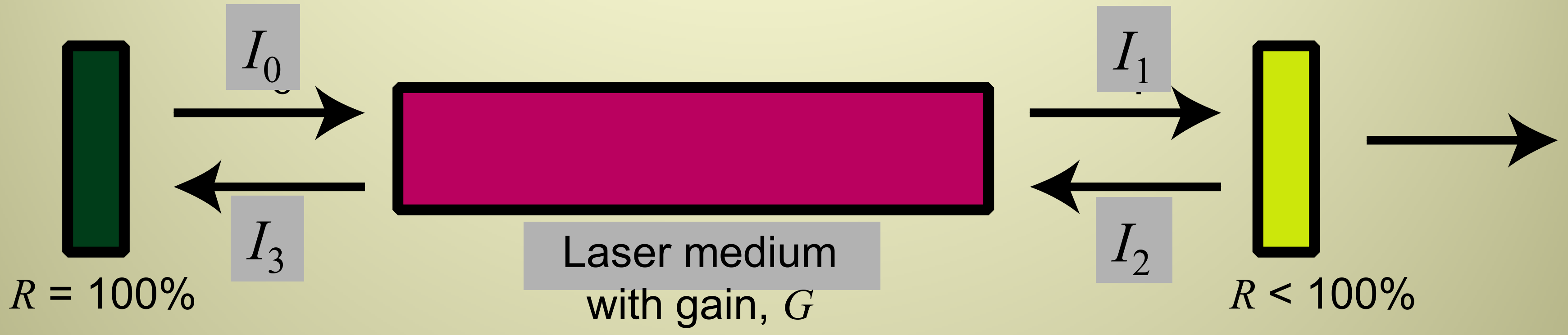
  A process by which an atom, molecule in an excited state drops to a lower energy level.

  Rate of spontaneous emission = $A N_2$

  A Einstein's Coefficient for Spontaneous Emission



Threshold Condition



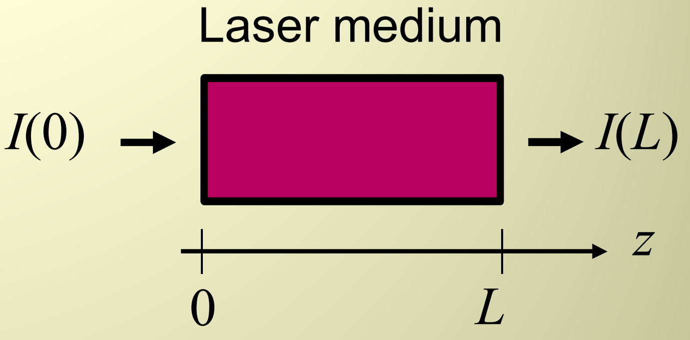
A laser action will be achieved if the beam increases in intensity during a round trip: that is, if $I_3 \geq I_0$

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:

$$\frac{dI}{dt} = c\frac{dI}{dz} \propto BN_2 I - BN_1 I$$ [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*:

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

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,

$$\boxed{N_2 > N_1}$$

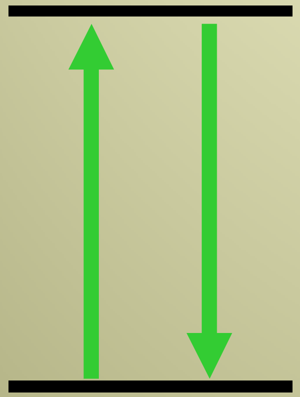
This condition is called ***population inversion***. It does not occur naturally. It is inherently a non-equilibrium state.

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.

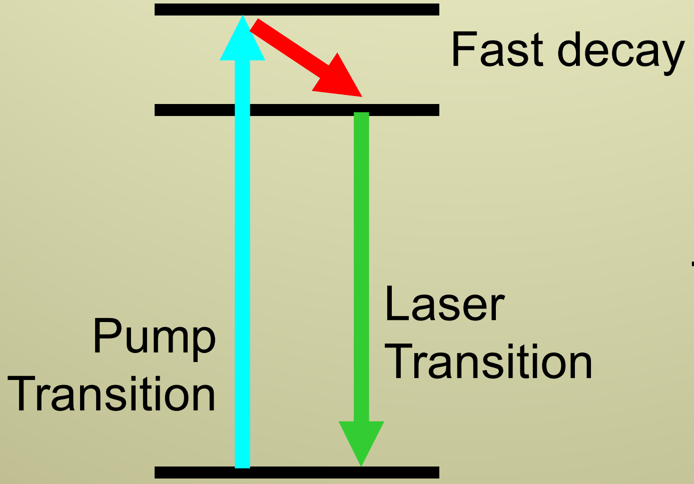
Two-, Three-, and Four-Level Systems

Two-level
system



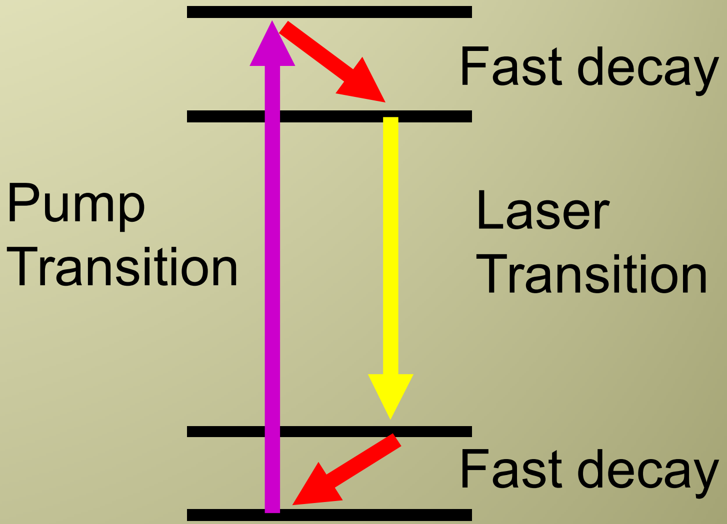
At best, you get
equal populations.
No lasing.

Three-level
system



If you hit it hard,
you get lasing.

Four-level
system



Lasing is easy!

Optical Resonators

- Cavities are essential components of the lasers. They provide the required feedback for laser oscillation.
- Cavities also act as resonators and frequency filters.
- Drastically reduce the number of modes that can oscillate with low loss.
- Consider passive optical resonators- which do not include an active medium within.
- Practical resonator sizes range from micrometers to meters.

Closed vs. Open Cavities

- In closed cavities the cavity modes correspond to stationary electric field configurations.
- In lasers we use open cavities- to have much smaller number of modes.
- The electric field of a mode can be written as:

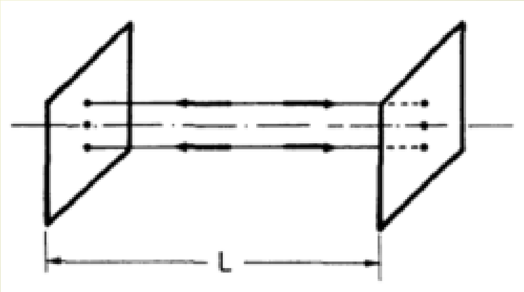
$$\mathbf{E}(\mathbf{r}, t) = E_0 \mathbf{u}(\mathbf{r}) \exp[(-t/2\tau_c) + j\omega t]$$

- Where τ_c is called the -cavity photon decay time.
- Need to find stable solutions for u(r).

Plane-Parallel (Fabry-Perot) Resonator

- The resonant frequencies -the longitudinal modes of the cavity are

$$\nu = n\left(\frac{c}{2L}\right) \qquad L = n(\lambda/2)$$



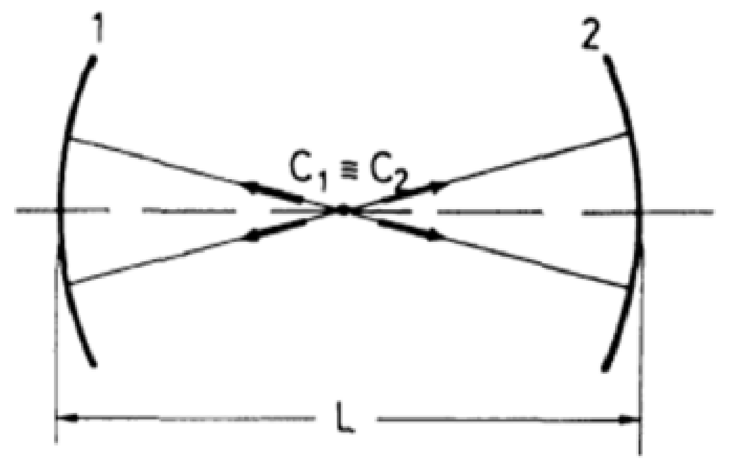
- This shows that the cavity modes form standing waves- the amplitude is zero at the mirrors.
- The frequency difference between two consecutive longitudinal modes :

$$\Delta\nu = \frac{c}{2L}$$

These frequencies are called the -longitudinal modes. Where n determines the number of half wavelengths of the mode along the cavity.

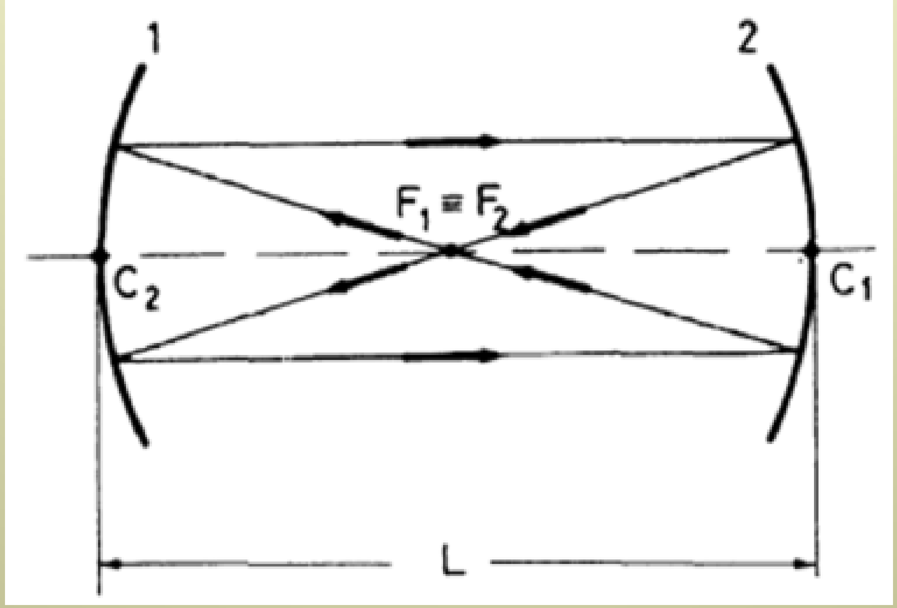
Concentric Resonator

This resonator is made of two spherical mirrors of coincident centers.



All rays have the same path length. Resonant frequencies are the same as the plane parallel resonator of separation L.

Confocal Resonator



the resonant frequencies cannot be obtained from geometrical optics, hence they are different from plane parallel resonator.

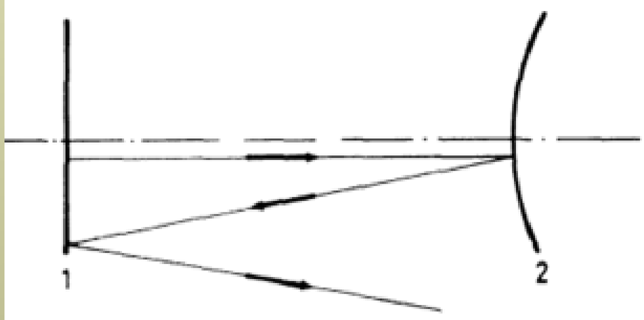
Generalized Spherical Resonator

- Resonators can also have cavity separation between concentric and confocal resonators.

$$R < L < 2R$$

- The mirrors can also be convex.
- For this case, we cannot find a complete loop with ray tracing.

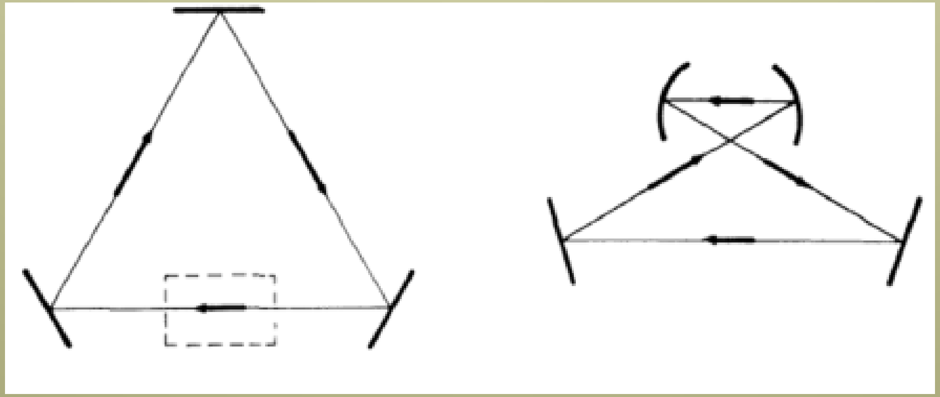
A resonator is called **stable** if the rays tend to stay within the cavity. A resonator is **unstable** if the rays diverge after some bounces.



An unstable resonator.

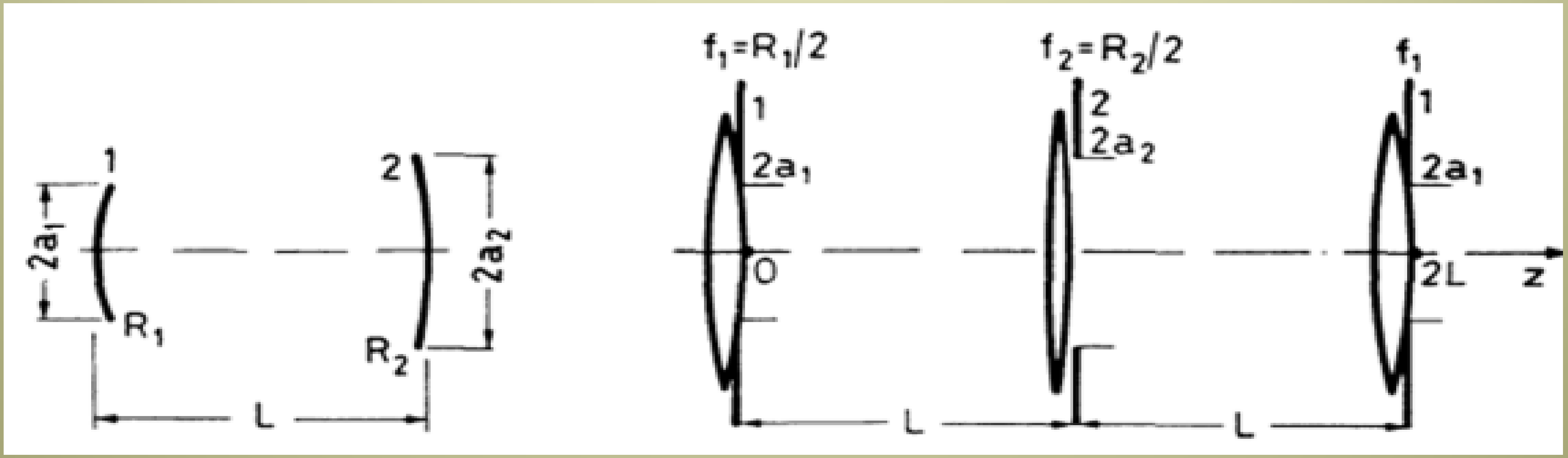
Ring Resonator

- The optical path is arranged in a ring configuration. For resonant frequencies- the total phase shift after one round trip should be an integer multiple of 2π.
- Ring resonators can also be stable or unstable.
- Resonance frequencies are given by: $\nu = \frac{nc}{L_p}$
- Where Lp is the length of the perimeter of the ring.



Stable Resonators

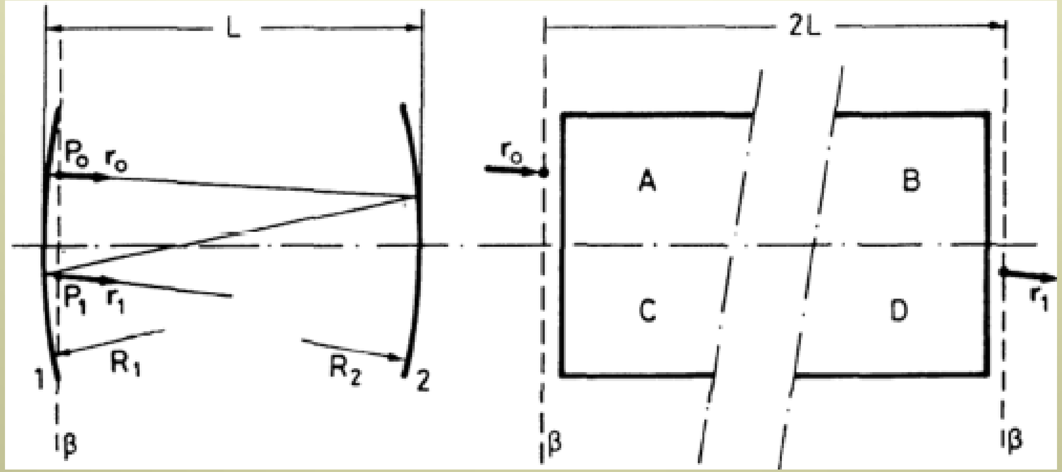
- Multiple bounces between the cavity mirrors can also be considered as continuous propagation through periodic lenses.
- For stable propagation, the field should **reproduce itself after one round trip.**



- We will use wave optics to find the longitudinal modes, and ABCD matrix method to find the stability condition.

Stability Condition

- To find the condition for stable oscillation within the cavity, we will use the ABCD matrices.



For one round-trip: $\begin{vmatrix} r_1 \\ r_1' \end{vmatrix} = \begin{vmatrix} A & B \\ C & D \end{vmatrix} \begin{vmatrix} r_0 \\ r_0' \end{vmatrix}$

For *n roundtrips:* $\begin{vmatrix} r_n \\ r_n' \end{vmatrix} = \begin{vmatrix} A & B \\ C & D \end{vmatrix}^n \begin{vmatrix} r_0 \\ r_0' \end{vmatrix}$

Stability Condition

This condition holds even if the cavity contains other elements. If the resonator is to be stable, we require that, for any initial point (r_0, r'_0), output point (r_n, r'_n), *does not diverge as n increases. This means that the* matrix

$$\begin{vmatrix} A & B \\ C & D \end{vmatrix}^n$$

Must not diverge as n increases.

Sylvester’s Theorem

Defining: $\cos\theta = (A + D)/2$

$$\begin{vmatrix} A & B \\ C & D \end{vmatrix}^n = \frac{1}{\sin\theta}\begin{vmatrix} A\sin n\theta - \sin(n-1)\theta & B\sin n\theta \\ C\sin n\theta & D\sin n\theta - \sin(n-1)\theta \end{vmatrix}$$

$$\sin n\theta = [\exp(jn\theta) + \exp(-jn\theta)]/2j$$

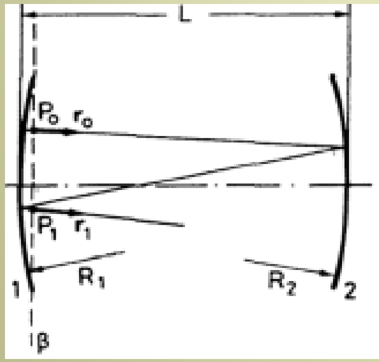
If θ *has an imaginary part- jnθ term becomes real and diverges with n.*

Therefore, n’th power of the matrix does not diverge if θ *is real.*

The stability condition:

$$-1 < \left(\frac{A+D}{2}\right) < 1$$

Generalized Spherical Resonator



$$\begin{vmatrix} A & B \\ C & D \end{vmatrix} = \begin{vmatrix} 1 & 0 \\ -2/R_1 & 1 \end{vmatrix} \begin{vmatrix} 1 & L \\ 0 & 1 \end{vmatrix} \begin{vmatrix} 1 & 0 \\ -2/R_2 & 1 \end{vmatrix} \begin{vmatrix} 1 & L \\ 0 & 1 \end{vmatrix}$$

$$\frac{A+D}{2} = 1 - \frac{2L}{R_1} - \frac{2L}{R_2} + \frac{2L^2}{R_1 R_2} \quad = 2\left[1 - \left(\frac{L}{R_1}\right)\right]\left[1 - \left(\frac{L}{R_2}\right)\right] - 1$$

by defining dimensionless g parameters:

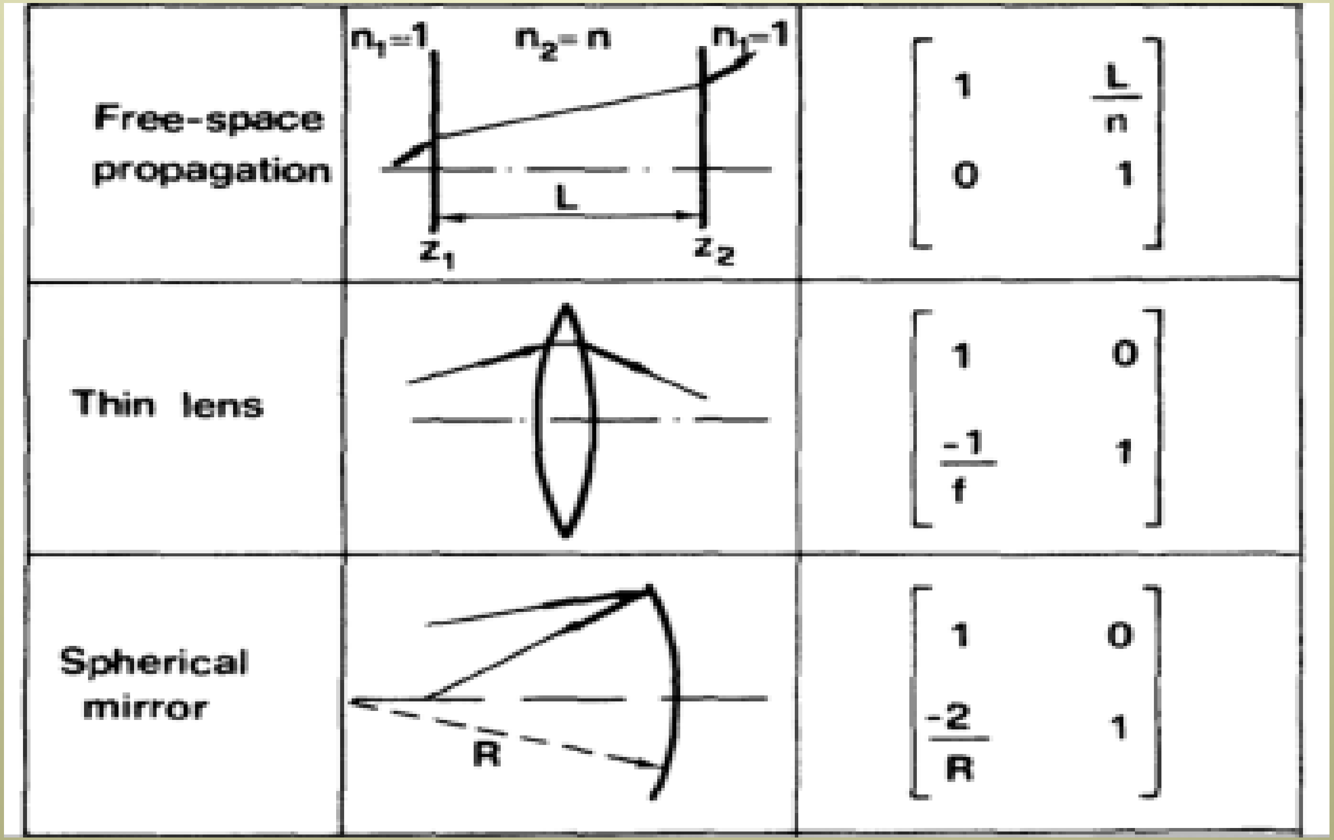
$$g_1 = 1 - \left(\frac{L}{R_1}\right)$$

$$g_2 = 1 - \left(\frac{L}{R_2}\right)$$

The stability condition becomes:

$$0 < g_1 g_2 < 1$$

ABCD matrices for different optical elements



Free-space propagation	$\begin{bmatrix} 1 & \frac{L}{n} \\ 0 & 1 \end{bmatrix}$
Thin lens	$\begin{bmatrix} 1 & 0 \\ \frac{-1}{f} & 1 \end{bmatrix}$
Spherical mirror	$\begin{bmatrix} 1 & 0 \\ \frac{-2}{R} & 1 \end{bmatrix}$

$$AD - BC = 1$$

Eigenmodes and Eigenvalues

- Using the Fresnel-Kirschoff integral we can write the reproduction condition as:

$$\tilde{E}(x, y, 2L) = [\exp(-2jkL)] \int\int_1 K(x, y; x_1, y_1)\tilde{E}(x_1, y_1, 0)dx_1\, dy_1$$

The reproduction condition requires

$$\tilde{E}(x, y, 2L) = \tilde{\sigma} \exp(-2jkL)\tilde{E}(x, y, 0)$$

Where σ is a complex numb $\tilde{\sigma} = |\tilde{\sigma}| \exp j\phi$

Real part of σ *describes the change in intensity and its* imaginary part describes the change in round trip phase (hence affects longitudinal modes).

Eigenmodes and Eigenvalues

- Self-reproducing field distributions are called eigenmodes and corresponding are called eigenvalues.
- eigenmodes: $\tilde{E}_{lm}(x, y, 0)$
- eigenvalues: $\tilde{\sigma}_{lm}$
- *l and m are pair of* integers.

Eigenvalues describe the losses and resonances

- Remember the relationship between the intensity and electric field: $I = \frac{1}{2} c \varepsilon \left| \vec{\underset{\sim}{E}}_0 \right|^2$

- Using this, we can define a round trip fractional power loss (also called diffraction loss):

$$\gamma_{lm} = 1 - |\tilde{\sigma}_{lm}|^2$$

- In wave optics, the total round trip phase includes imaginary part of *σ :*

$$\Delta\phi_{lm} = -2kL + \phi_{lm}$$

- Hence- the resonant frequencies become:

$$\nu_{lmn} = \frac{c}{2L}\left[n + \frac{\phi_{lm}}{2\pi}\right]$$

Modes of Laser Resonator

The mathematical function that describes the Gaussian beam is a solution to the paraxial form of the Helmholtz equation. The solution, in the form of a Gaussian function, represents the complex amplitude of the beam's electric field.

The behavior of the field of a Gaussian beam as it propagates is described by a few parameters such as the spot size, the radius of curvature, and the Gouy phase.

Gaussian Mode

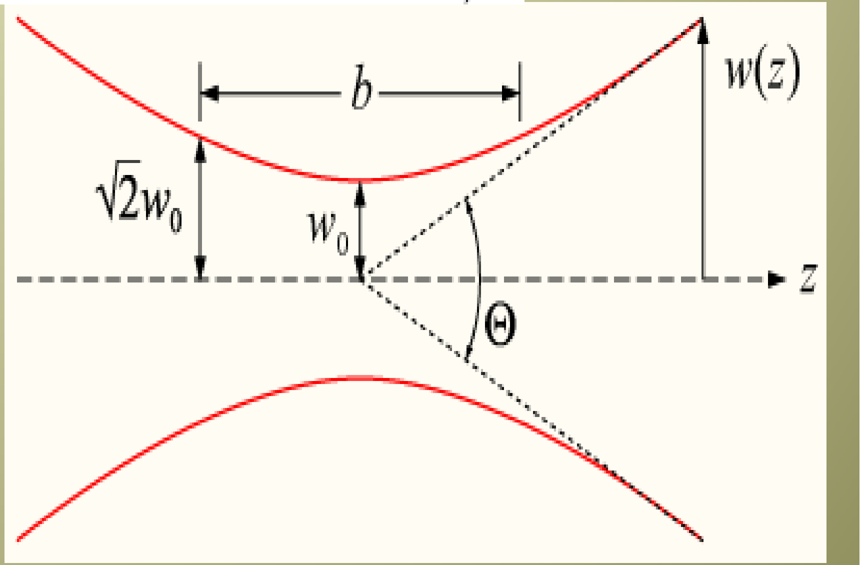
- Many lasers operating on fundamental Transverse mode, or TEM_{00} mode of the laser resonator, emit beams with a Gaussian profile.
- For a Gaussian beam, the complex electric field amplitude, measured in volts per meter, at a distance *r* from its centre, and a distance *z* from its waist, is given by

$$E(r,z) = E_0 \frac{w_0}{w(z)} \exp\left(\frac{-r^2}{w^2(z)}\right) \exp\left(-ikz - ik\frac{r^2}{2R(z)} + i\zeta(z)\right) ,$$

where *w(z)* Beam width or spot size

R(z) Radius of Curvature

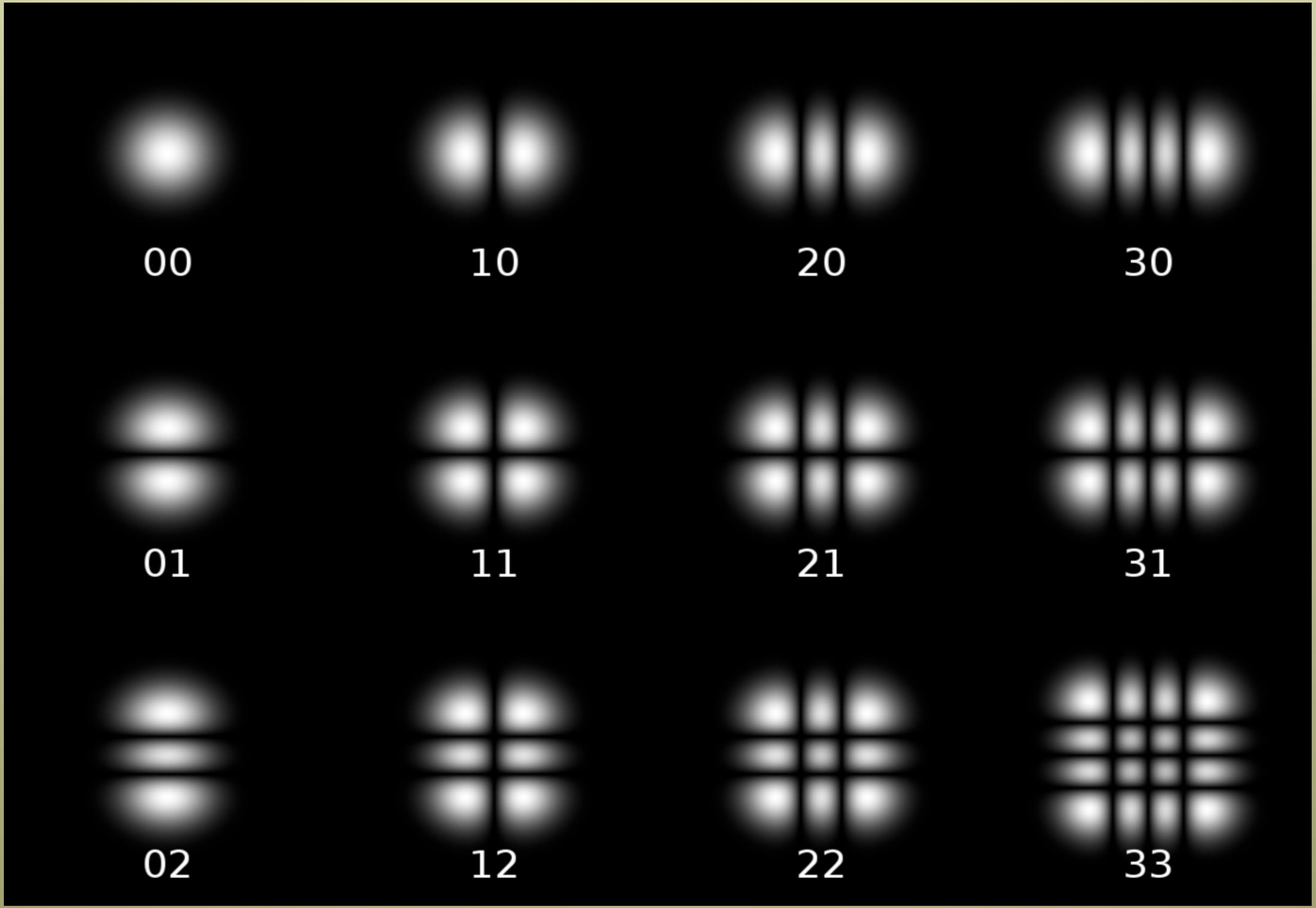
ζ(z) Longitudinal Phase delay



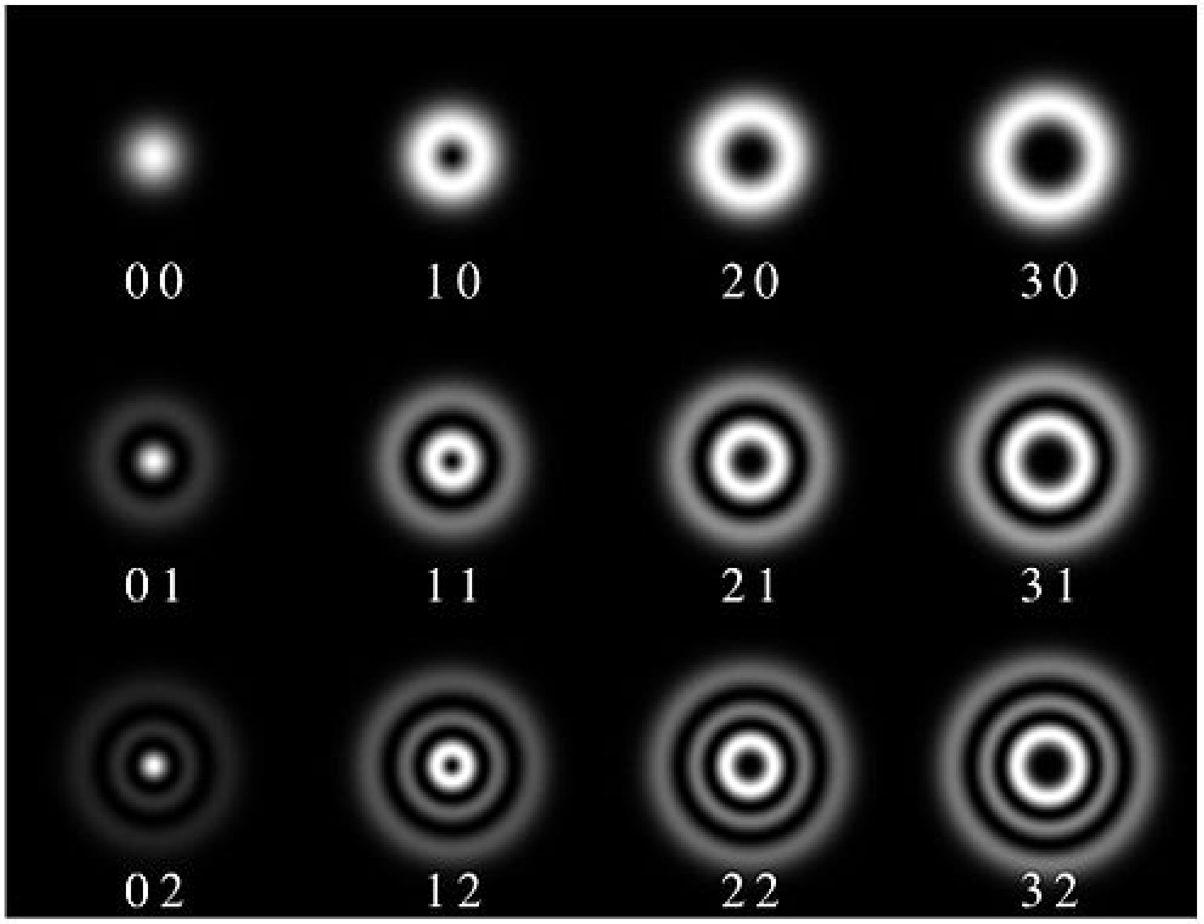
Higher-order Modes

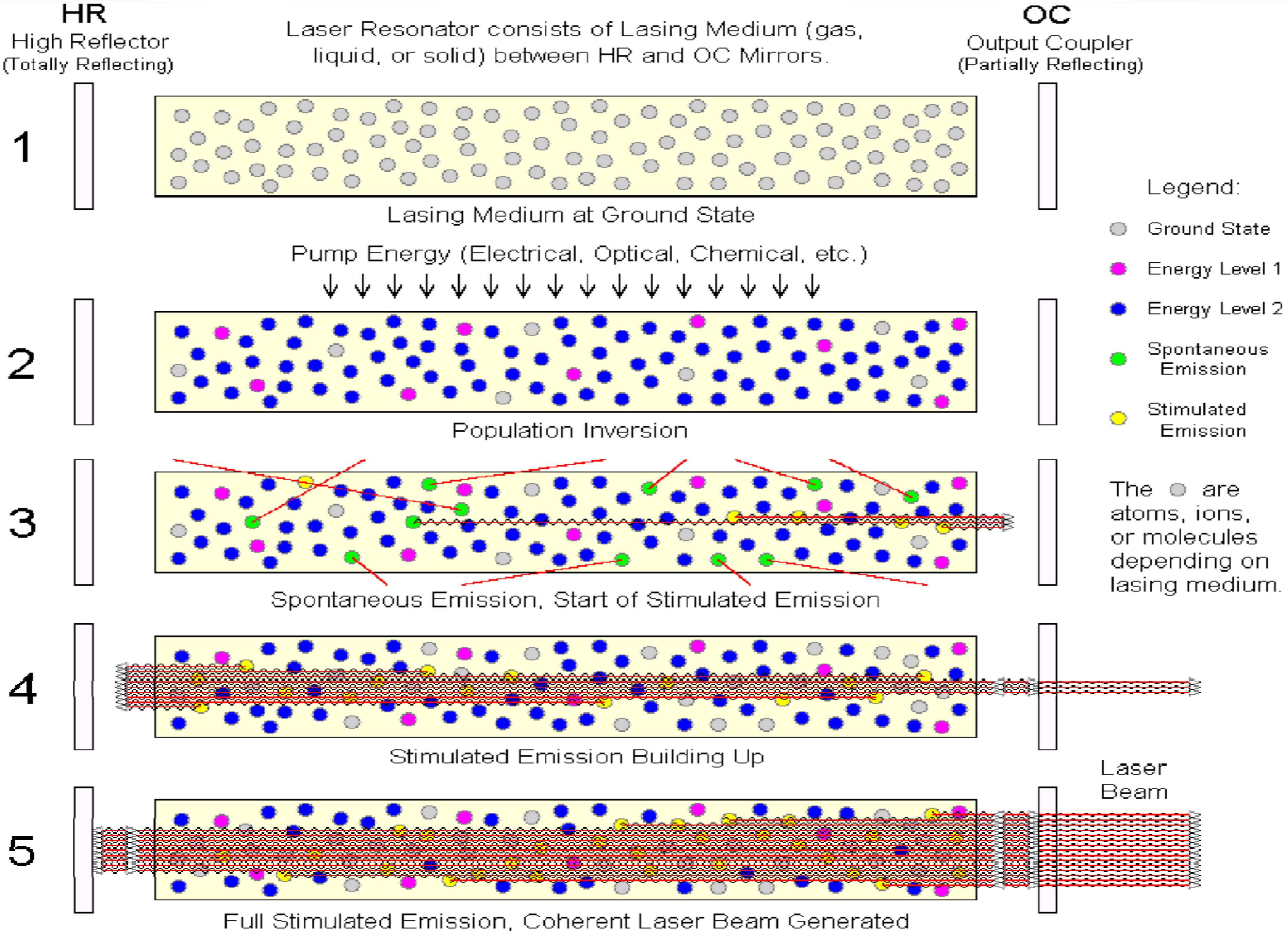
- If beam is not a pure Gaussian shape, the transveres modes of the beam may be analyzed as a superposition of Hermite-Gaussian or Laguerre-Gaussian beams.
- Other solutions to the paraxial form of the Helmholtz equation exist. Solving the equation in Cartesian coordinates leads to a family of solutions known as the Hermite–Gaussian modes, while solving the equation in cylindrical coordinates leads to the Laguerre–Gaussian modes.

Hermite-Gaussian Modes



Laguerre- Gaussian modes





Laser Resonator consists of Lasing Medium (gas, liquid, or solid) between HR and OC Mirrors.

The ● are atoms, ions, or molecules depending on lasing medium.

Basic Laser Operation

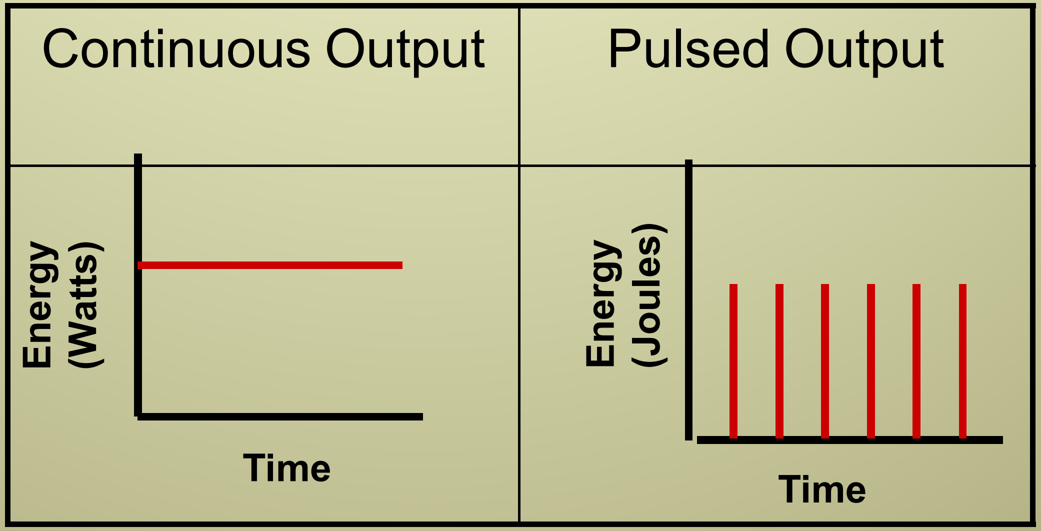
Laser Beam Output 1

- 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



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: Mode-Locking

- **Mode-locking** - technique that allowed the generation of ultra- short optical pulse in the range of femtosecond.

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

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

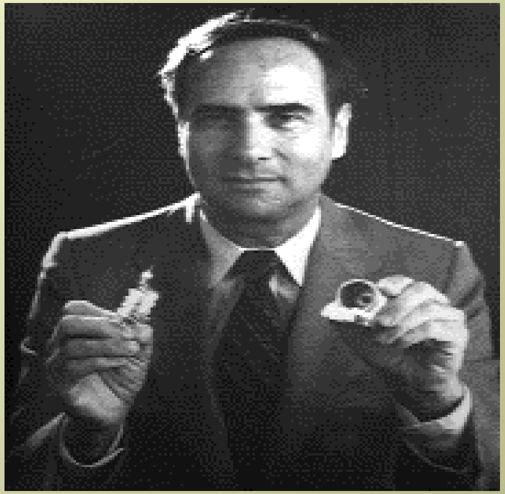
Physical Properties of Laser

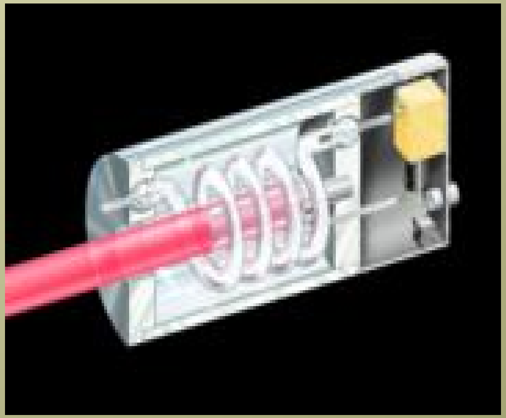
1. Energy- the amount of work accomplished – measured in joules
2. Power- Rate of energy expenditure – measured in joules per second or Watts (1J/s =1 W)
3. Irradiance- power density- the power of the laser per unit area.
4. Fluence - energy density- amount of energy delivered per unit area - irradiance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

- LASERS: Peter W, Milonni and Joseph H. Eberly
- LASERS : Anthony E. Siegman
- LASER FUNDAMENTALS: William T. Silfvast

THANK YOU