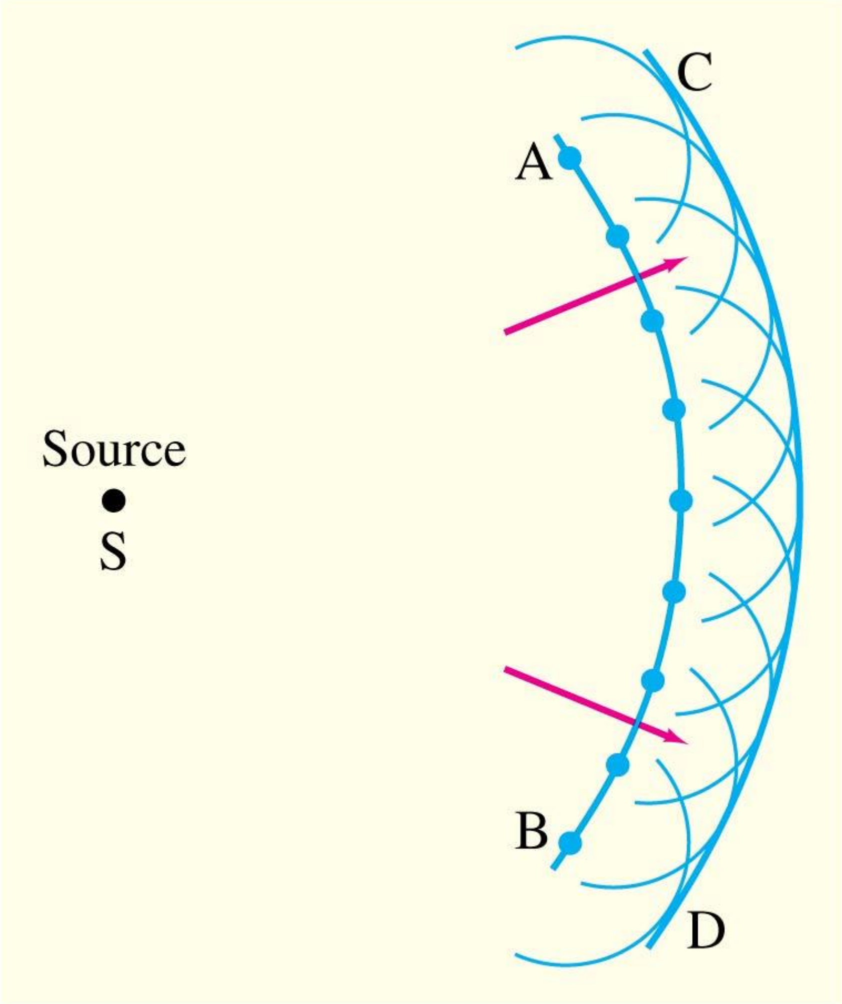
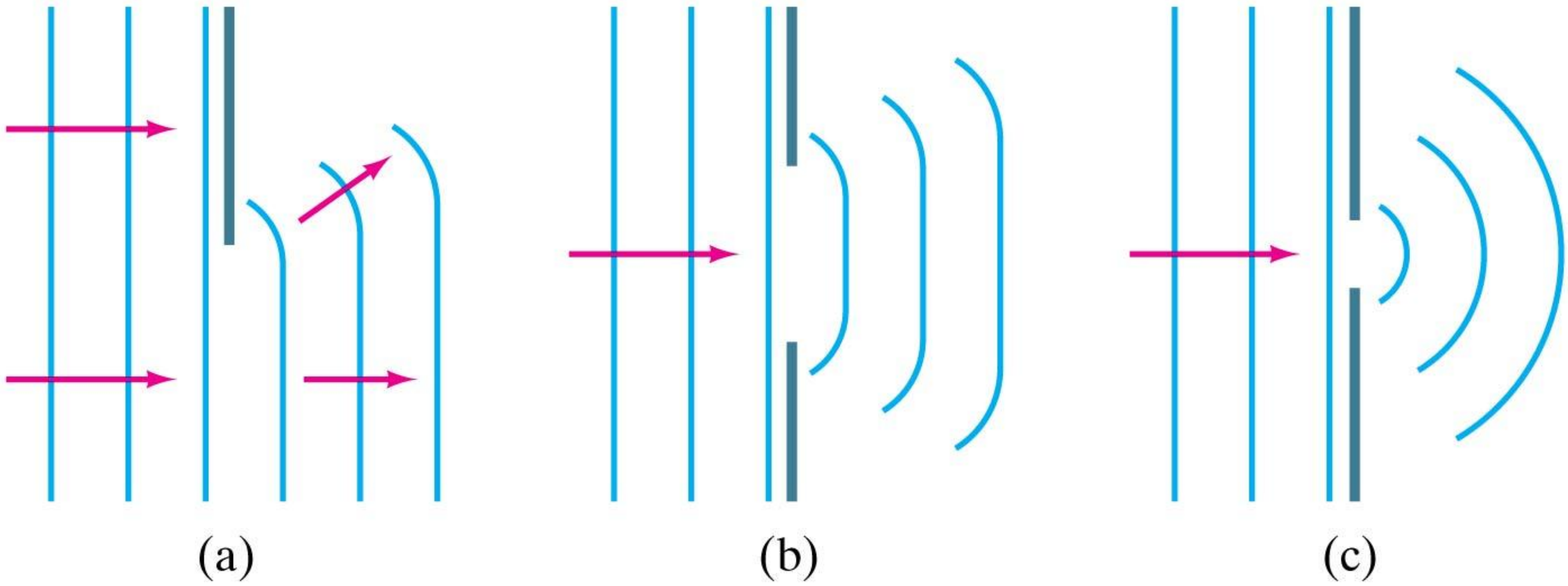
Unit II : Wave Optics and Lasers

Huygens' Principle

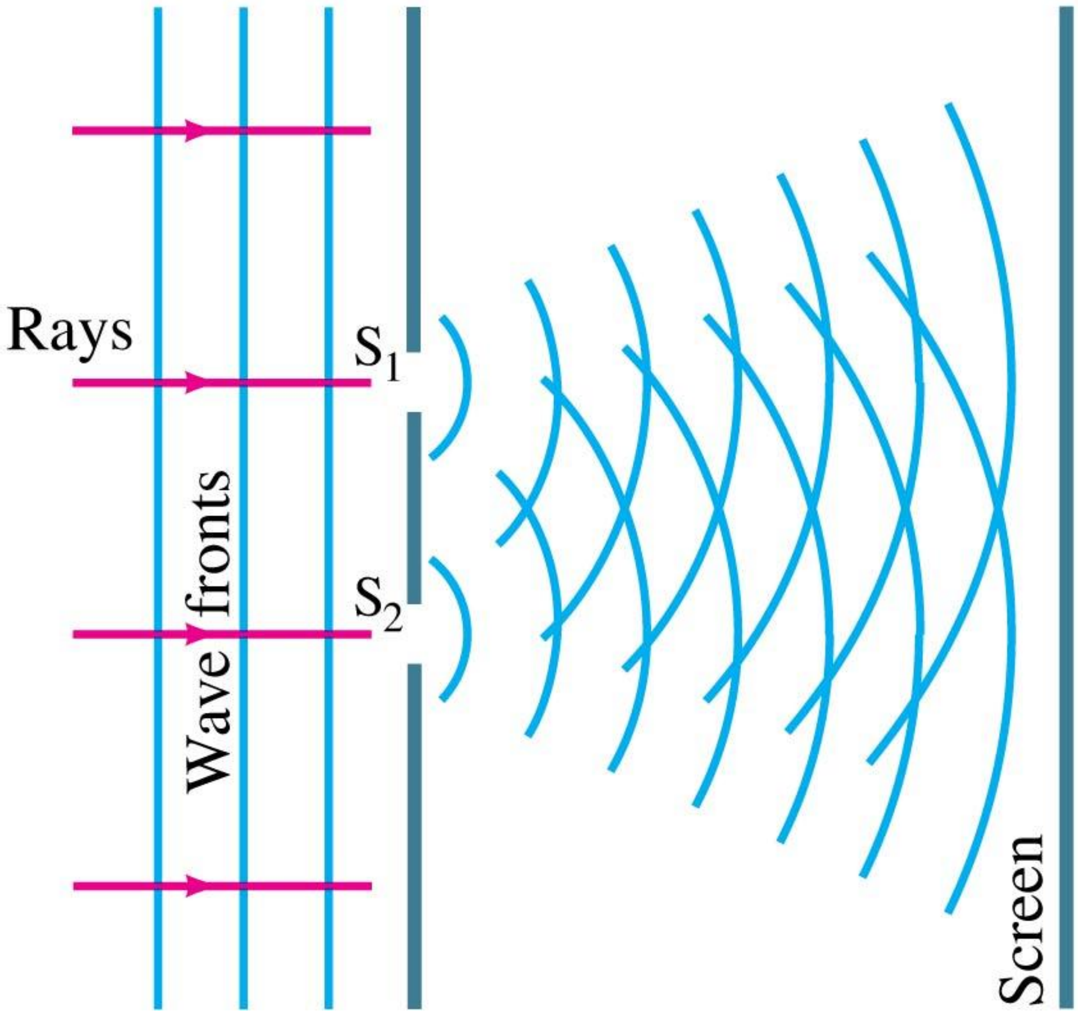
Huygens' principle: Every point on a wave front acts as a point source; the wavefront as it develops is tangent to their envelope



Huygens' principle is consistent with diffraction:



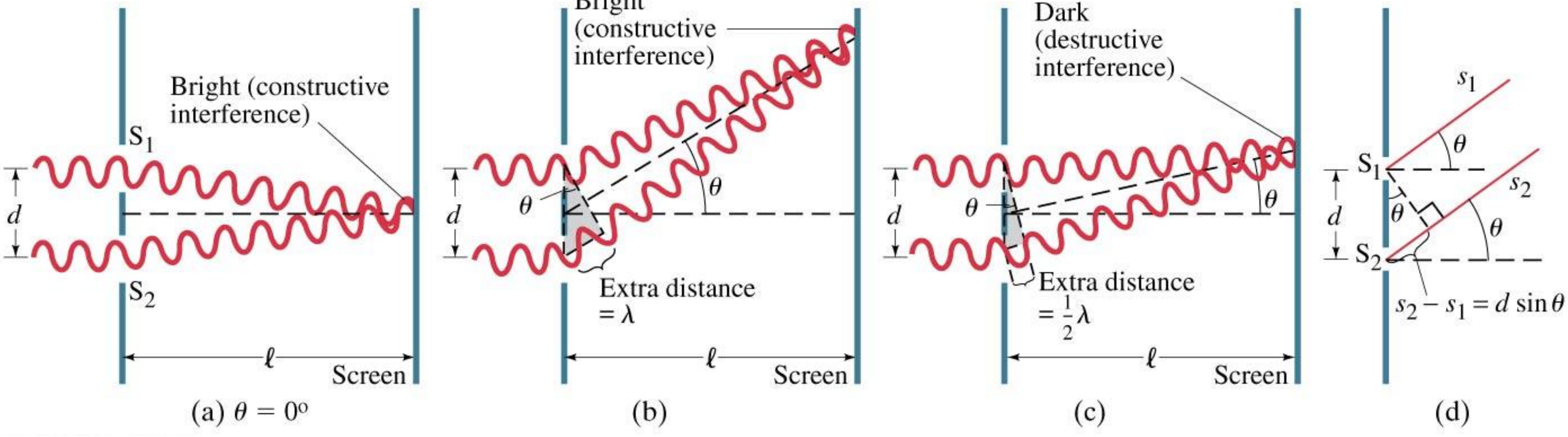
Young's Double-Slit Experiment



If light is a wave, there should be an interference pattern.

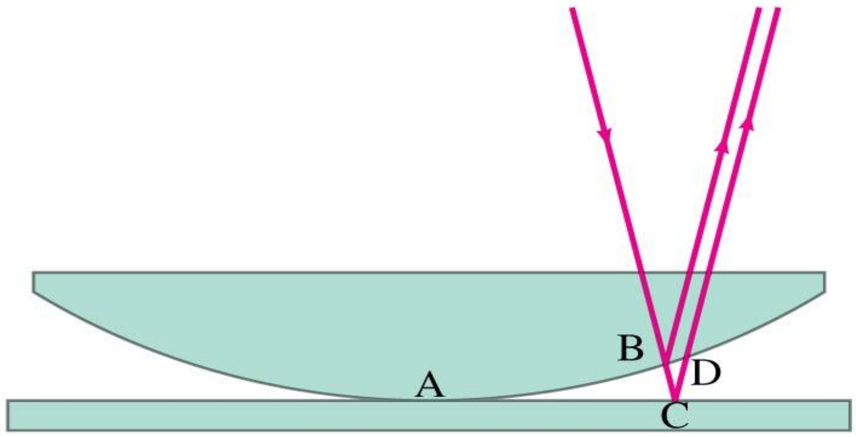
Young's Double-Slit Experiment

The interference occurs because each point on the screen is not the same distance from both slits. Depending on the path length difference, the wave can interfere constructively (bright spot) or destructively (dark spot).

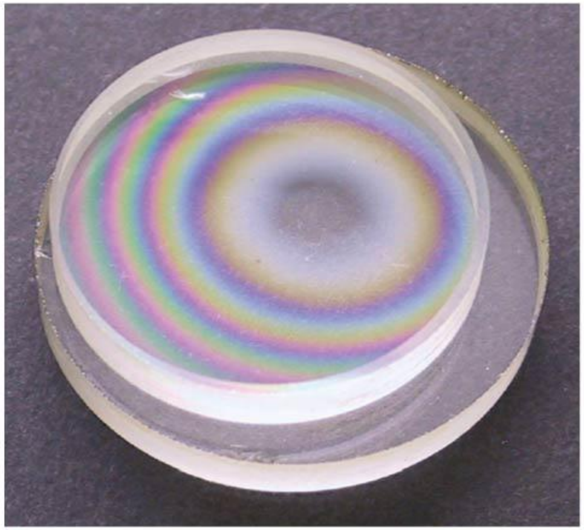


Interference in Thin Films

A similar effect takes place when a shallowly curved piece of glass is placed on a flat one. When viewed from above, concentric circles appear that are called Newton’s rings.



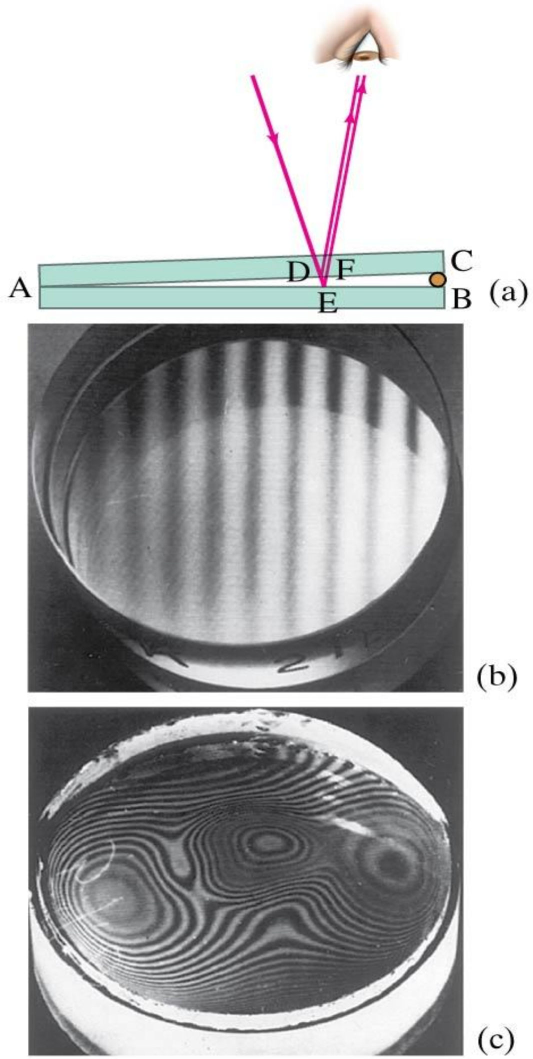
(a)



(b)

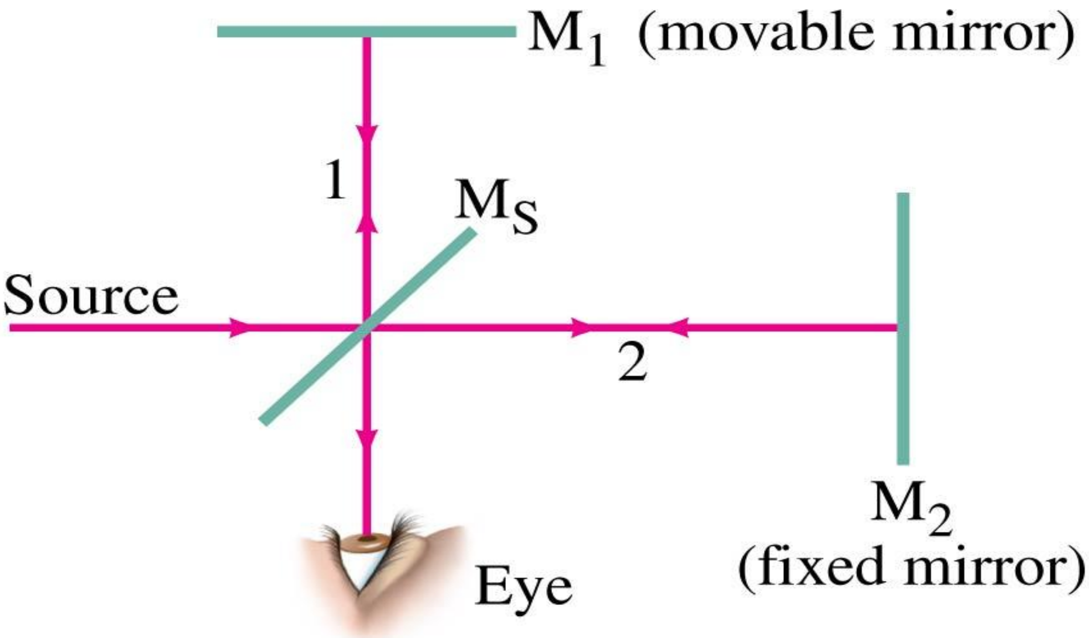
Interference in Thin Films

One can also create a thin film of air by creating a wedge-shaped gap between two pieces of glass.



Michelson Interferometer

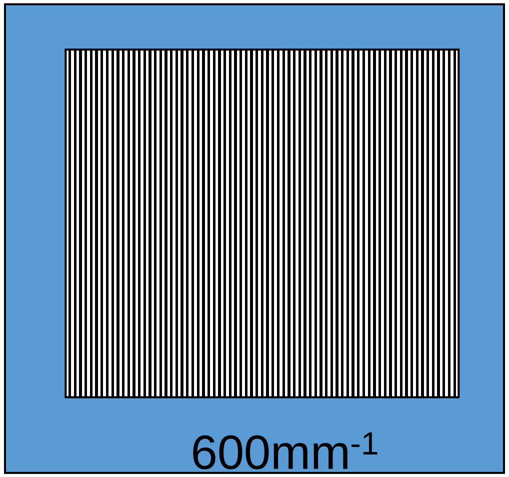
The Michelson interferometer is centered around a beam splitter, which transmits about half the light hitting it and reflects the rest. It can be a very sensitive measure of length.



The Diffraction Grating

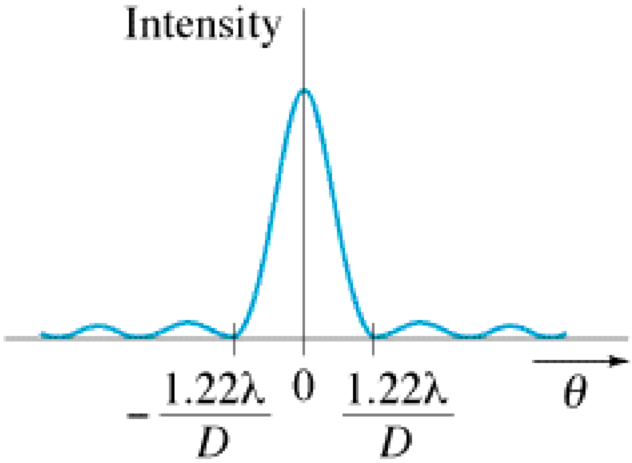
- A (transmission) diffraction grating is an arrangement of identical, equally spaced parallel lines ruled on glass.
- A typical diffraction grating will have something like.600 lines per millimetre

Diffraction gratings are used to produce optical spectra



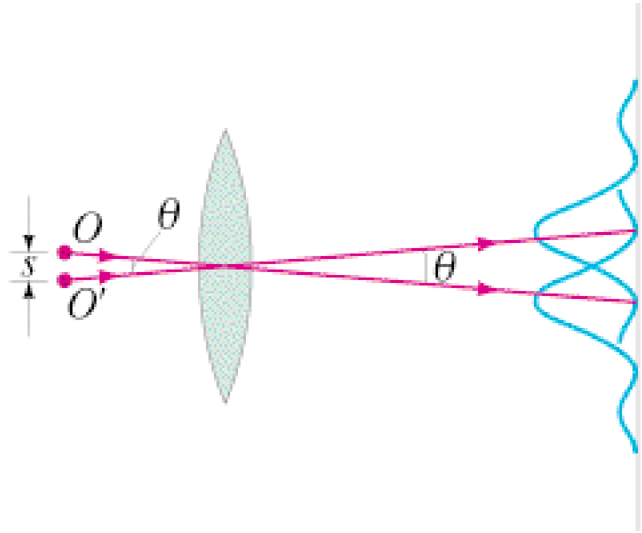
Rayleigh Criterion

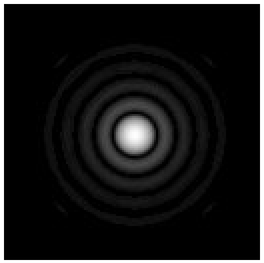
$$\theta = \frac{1.22\lambda}{b}$$

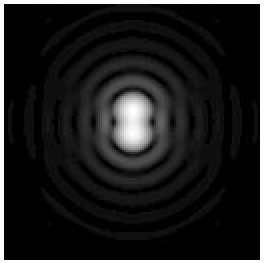


θ = Angle of resolution (Rad)
λ = Wavelength (m)
b = Diameter of circular opening (m)
(Telescope aperture)

the bigger the aperture, the smaller the angle you can resolve.







Central maximum of one is over minimum of the other

What is Laser?

Light Amplification by Stimulated Emission of Radiation

- A device produces a coherent beam of optical radiation by stimulating electronic, ionic, or molecular transitions to higher energy levels
- When they return to lower energy levels by stimulated emission, they emit energy.

Properties of Laser

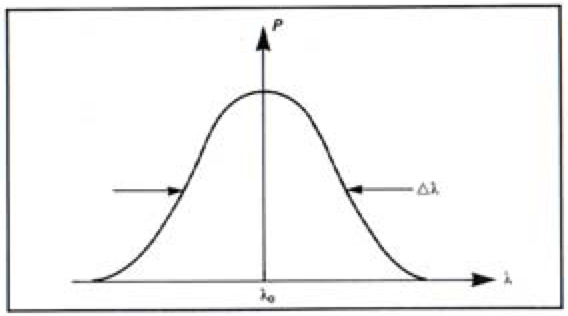
- The light emitted from a laser is **monochromatic**, that is, it is of one color/wavelength. In contrast, ordinary white light is a combination of many colors (or wavelengths) of light.

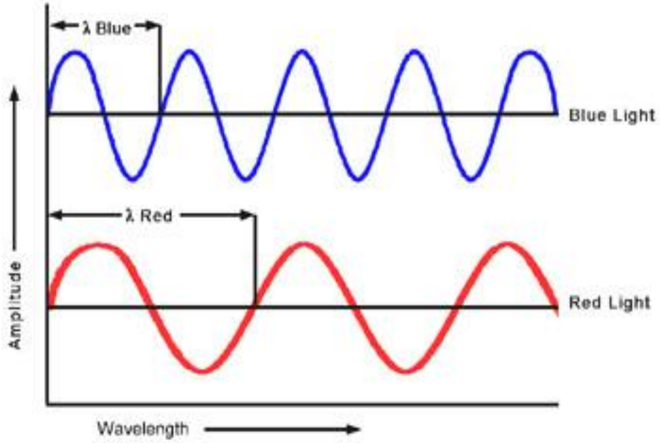
- Lasers emit light that is highly **directional**, that is, laser light is emitted as a relatively narrow beam in a specific direction. Ordinary light, such as from a light bulb, is emitted in many directions away from the source.

- 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.

These three properties of laser light are what can make it more hazardous than ordinary light. Laser light can deposit a lot of energy within a small area.

Monochromacity

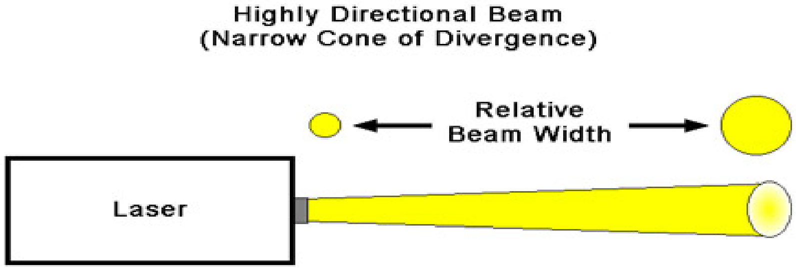




Nearly monochromatic light
Example:
He-Ne Laser
λ0 = 632.5 nm
Δλ = 0.2 nm
Diode Laser
λ0 = 900 nm
Δλ = 10 nm

Comparison of the wavelengths of red and blue light

Directionality



Conventional light source Divergence angle (θ_d)

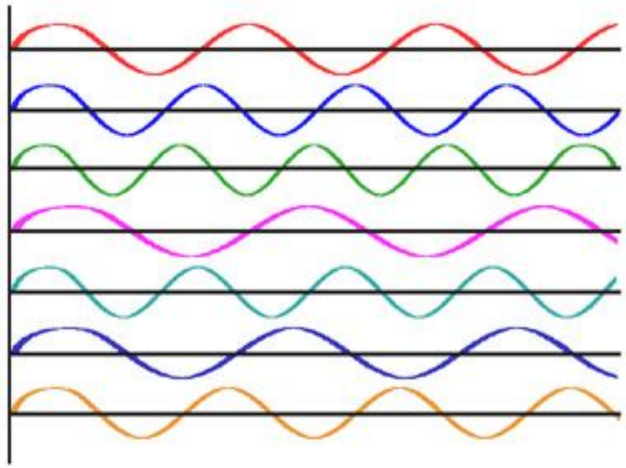
Beam divergence: $\boldsymbol{\theta_d = \beta \lambda / D}$

β ~ 1 = f(type of light amplitude distribution, definition of beam diameter)

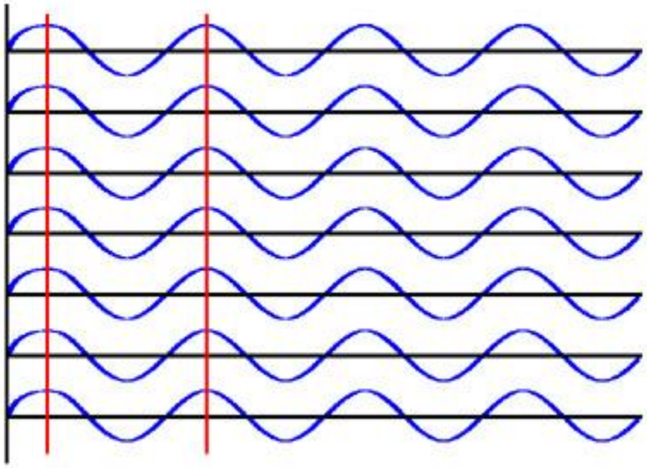
λ = wavelength

D = beam diameter

Coherence

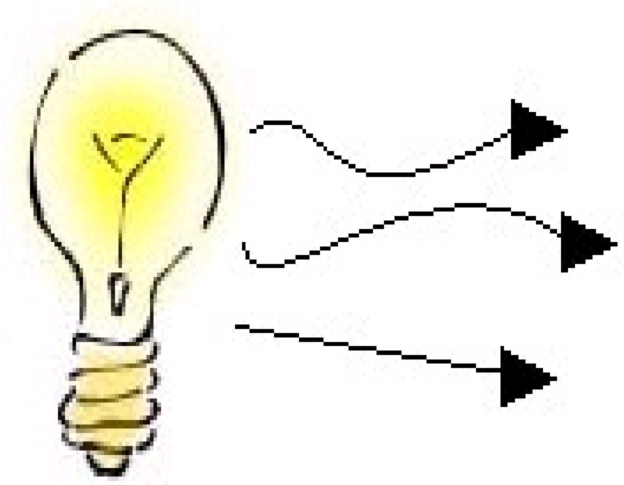


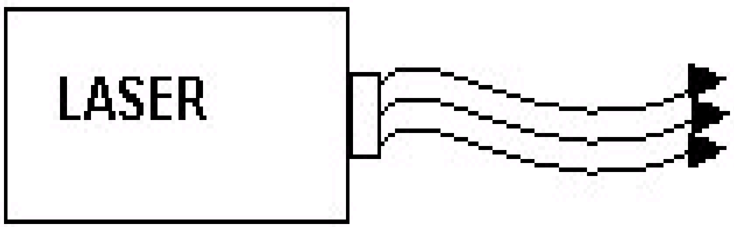
Incoherent light waves



Coherent light waves

Incandescent vs. Laser Light





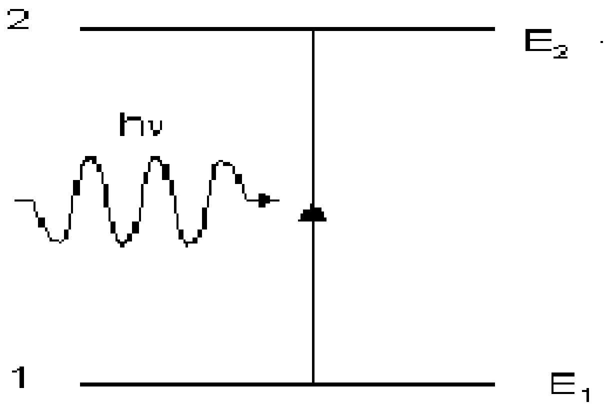
1. **Many wavelengths**
2. **Multidirectional**
3. **Incoherent**

1. **Monochromatic**
2. **Directional**
3. **Coherent**

Basic concepts for a laser

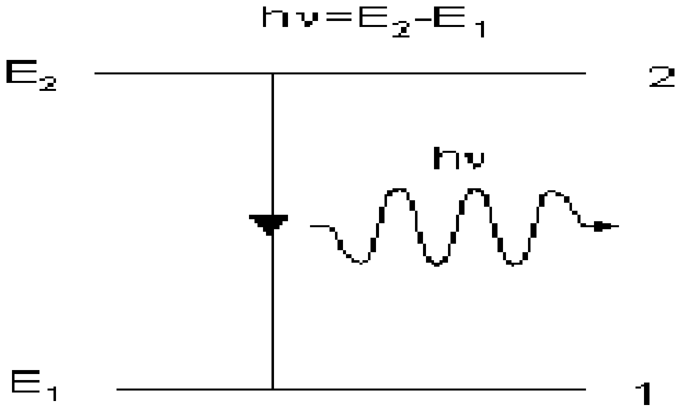
- Absorption
- Spontaneous Emission
- Stimulated Emission
- Population inversion

Absorption



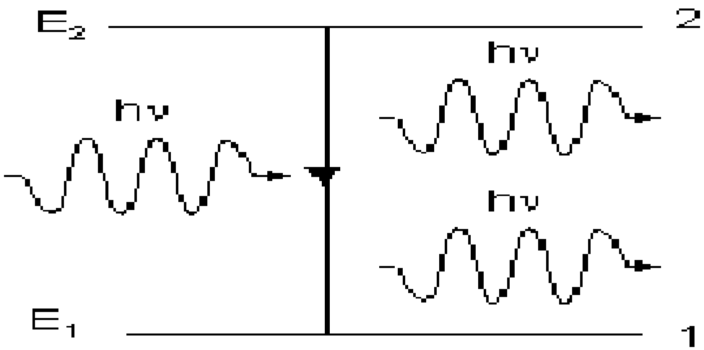
- Energy is absorbed by an atom, the electrons are excited into vacant energy shells.

Spontaneous Emission



- The atom decays from level 2 to level 1 through the emission of a photon with the energy *hv*. It is a completely random process.

Stimulated Emission



atoms in an upper energy level can be triggered or stimulated in phase by an incoming photon of a specific energy.

Stimulated Emission

The stimulated photons have unique properties:

- In phase with the incident photon
- Same wavelength as the incident photon
- Travel in same direction as incident photon

Population Inversion

- A state in which a substance has been energized, or excited to specific energy levels.
- More atoms or molecules are in a higher excited state.
- The process of producing a population inversion is called pumping.
- Examples:

→by lamps of appropriate intensity

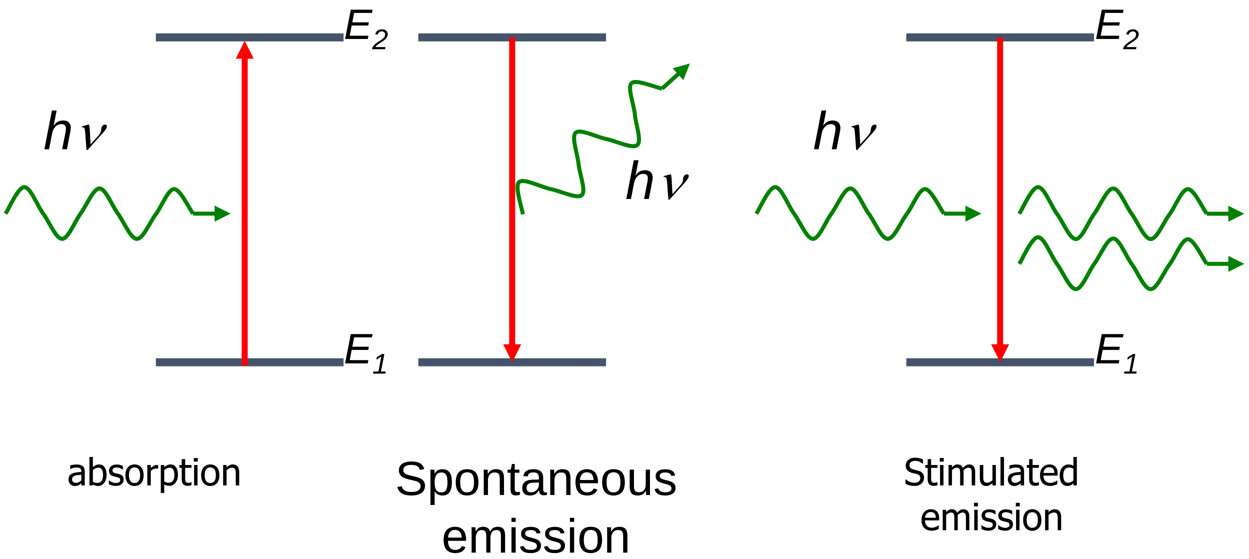
→by electrical discharge

Pumping

- Optical: flashlamps and high-energy light sources
- Electrical: application of a potential difference across the laser medium
- Semiconductor: movement of electrons in "junctions," between "holes"

Two level system

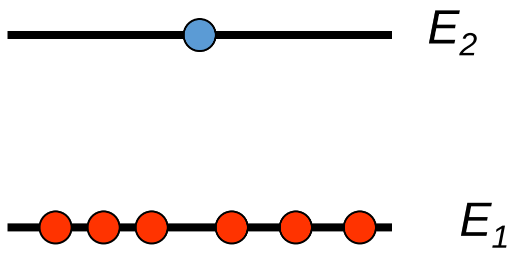
$h\nu = E_2 - E_1$



Boltzmann's equation

$$\frac{n_2}{n_1} = \exp\left(\frac{-(E_2 - E_1)}{kT}\right)$$

- n_1 - the number of electrons of energy E_1
- n_2 - the number of electrons of energy E_2



example: T=3000 K E_2-E_1=2.0 eV

$$\frac{n_2}{n_1} = 4.4 \times 10^{-4}$$

- *Population inversion- n2>>n1*

Types of Laser

- Gas Laser: He-Ne, Argon ion and CO_2
- Solid state Laser : Ruby, Nd:YAG, Nd:glass
- Semiconductor Laser
- Tunable dye Laser

RUBY LASER

- First laser to be operated successfully
- Lasing medium: Matrix of Aluminum oxide doped with chromium ions
- Energy levels of the chromium ions take part in lasing action
- A three level laser system

Working:

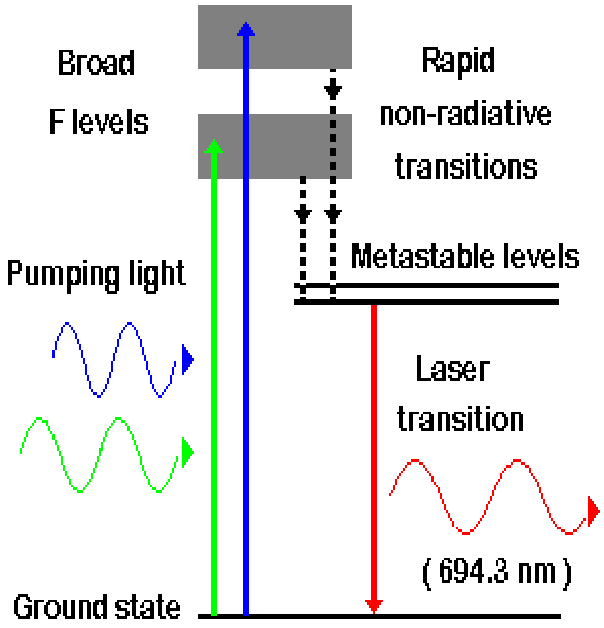
Ruby is pumped optically by an intense flash lamp

This causes Chromium ions to be excited by absorption of

Radiation around 0.55 μm and 0.40μm

Ruby lasers…..

- ➢Chromium ions are excited to levels E1 and E2
- ➢Excited ions decay non-radiatively to the level M – upper lasing level
- ➢M- metastable level with a lifetime of ~ 3ms
- ➢Laser emission occurs between level M and ground state G at an output wavelength of 0.6943 μm
- ➢One of the important practical lasers
- ✓Has long lifetime and narrow linewidth
- ✓(Linewidth – width of the optical spectrum or width of the power Spectral density)



Energy levels of chromium ions in ruby

Ruby lasers……

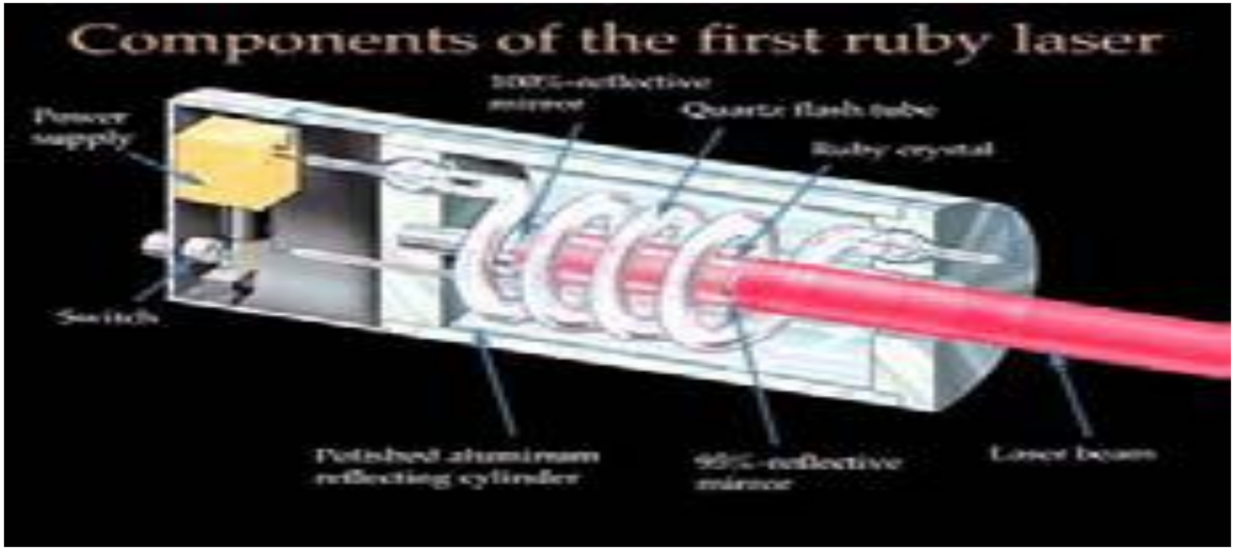
- ✓Output lies in the visible region – where photographic emulsions and Photodetectors are much more sensitive than they are in infrared region
- ✓Find applications in holography and laser ranging

- Flash lamp operation – leads to a pulsed output of the laser
- Between flashes, lasing action stops

<u>Laser spiking:</u>

- Output is highly irregular function of time
- Intensity has random amplitude fluctuations of varying duration

<u>A typical set up:</u>



Neodymium based lasers

- **Nd:YAG laser** (yttrium aluminium garnet) and **Nd:glass** laser are important Solid state lasers
- Energy levels of the Neodymium ion takes place in lasing action
- Both are 4 level laser systems
- YAG and glass are hosts in which Neodymium ions are used

Nd:YAG laser:

- For continuous or very high pulse rate operation – Nd:YAG preferred
- Nd:YAG laser – emission at 1.06 μm
- Pump band for excitation are 0.81 μm and 0.75 μm
- Spontaneous lifetime of the laser transition is ~ 550 μs

Nd:YAG…….

- Has a much lower threshold of oscillation than a ruby laser
- Output energy in the order of 100mJ per pulse
- Used in resistor trimming, scribing, micromachining operations, welding Hole drilling etc…..

Nd:glass laser

- Four level system
- Various silicate and phosphate ions are used as the host material
- Spontaneous lifetime of the laser transition is ~ 300 µs
- More suitable for high energy pulsed operation
- Output energy is in the order of several kilojoules
- Used widely in welding and drilling operations

Advantages of Nd ions in a YAG or glass host:

- In glass, the linewidth is larger than in YAG, and hence in glass the Laser threshold is higher
- In Nd:glass lasers Mode locking phenomena can be used to achieve Ultrashort Pulses of narrow pulsewidth
- Larger linewidth in Nd:glass allows to store a larger amount of power or Energy before saturation when used along with Q switches
- Excellent optical quality and excellent uniformity of doping in glass host
- Compared to YAG, glass has lower thermal conductivity
- Optical distortion is higher in glass host

He-Ne laser

- Laser medium is mixture of Helium and Neon gases in the ratio 10:1
- Medium excited by large electric discharge, flash pump or continuous high power pump
- In gas, atoms characterized by sharp energy levels compared to solids
- Actual lasing atoms are the Neon atoms

Pumping action:

Electric discharge is passed through the gas

Electrons are accelerated, collide with He and He atoms and excite them to higher energy levels

- Helium atom accumulates at levels F2 and F3
- Levels E4 and E6 of neon atoms have almost same energy as F2 and F3
- Excited Helium ions collide with Neon atoms and excite them to E4 and E6

Transitions:

✓Transition between E6 and E3 produce 6328 A line output

✓From E3 to E2 spontaneous emission takes place – 6000 A

✓E2 – metastable state – tends to collect atoms

✓From E2 atoms relax back to ground level

(Energy levels of helium and neon - diagram)

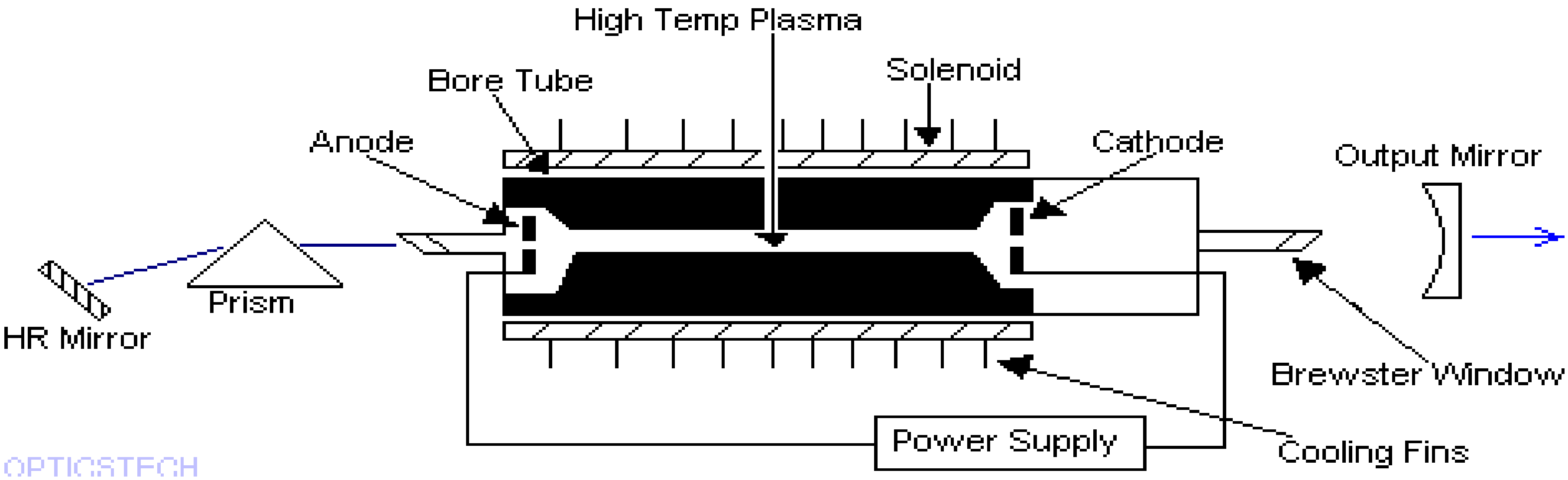
- Other important wave lengths:
- E6 to E5 – 3.39 μm ; E4 to E3 – 1.15μm
- Both share the same lasing level (E6)

Difficulties:

Gain at 3.39 μm is much higher than that at 0.6328 and hence
Oscillations will tend to occur at 3.39 μm
This prevents further build up of population in E6 difficult

Atoms in level E2 tend to re-excite to E3 by absorbing the
spontaneous emitted radiation between E3 and E2
This alters inversion between E6-E3

Argon Ion Laser



- Used often for ……..
    - Eye surgery,
    - Holography
    - Spectro-chemistry
    - Optical imaging
    - Semiconductor processing,
    - Printing, copying, scanning

Argon ion Laser

- Uses energy levels of ionized argon atoms
- Emits various discrete wavelengths between 3500 – 5200 A
- Involves large energy for excitation
- Laser discharge is very intense
- Particular wavelength out of the many possible lines is chosen by using Dispersive prisms
- Output power is in the range of 3 to 5 W
- Some important emissions are 5145A, 4880A, 4765A and 4576A

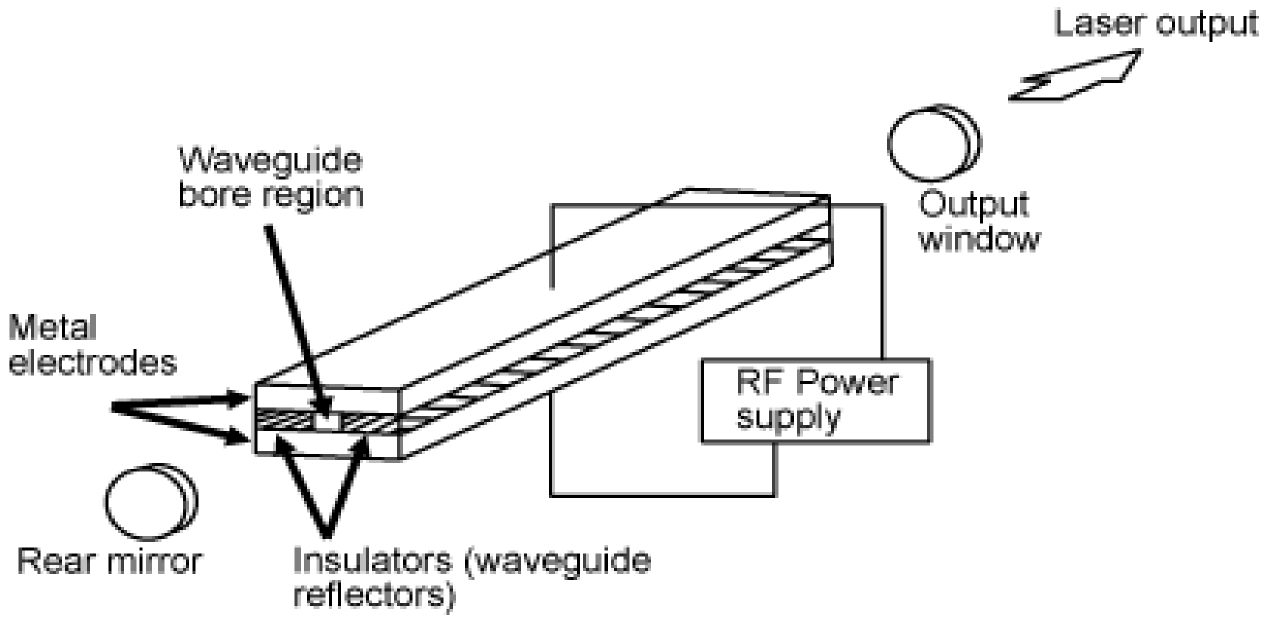
The CO2 LASER:

- Lasers discussed above – use transitions among various excited electronic states of an atom or ion
- CO2 laser – uses transition between different vibrational states of CO2 molecule
- One of the earliest Gas lasers
- Highest power continuous wave laser currently available
- The filling gas within the discharge tube consists primarily of:

Carbon dioxide
Hydrogen
Nitrogen
Helium

(proportions vary according to a specific laser)

- Electron impact excites vibrational motion of the nitrogen.
- Collision energy transfer between the nitrogen and the CO2 molecule causes vibrational excitation of the carbon dioxide
- Excite with sufficient efficiency to lead to the desired population inversion necessary for laser operation.
- Laser transition occurs at 10.6µm



•*CO2 laser……*

- CO2 laser possesses an extremely high efficiency
- *Atomic quantum efficiency* – Ratio of energy difference corresponding to the laser transition to the energy difference of the pump transition
- Atomic quantum efficiency is very high for a CO2 laser
- Large portion of input power is converted into useful output power
- Output power of several watts to several kilowatts can be obtained

DYE LASER

One of the most widely used tunable lasers in the visible region

DYE – organic substances dissolved in solvents (water, ethyl alcohol,

Methanol ethyl glycol etc)

- Exhibit strong and broad absorption and fluorescent spectra
- Can be made tunable
- Tunability from 0.3 μm to 1.2 μm

(Energy level diagram)

States….

S_o – Ground state

S_1 – first excited singlet state

T_1, T_2 – excited triplet states of the dye molecule

Working….

- Each state consists of a large number of closely spaced Vibrational and rotational sublevels
- Dye molecules are excited by radiation
- Molecules are excited to various sublevels of state S1
- From there they relax quickly to the lowest level V2 of S1
- Molecules from V2 emit spontaneously and de-excite to different sublevels of So
- Thus emitting a fluorescent spectrum

- Molecules from S1 can also make a nonradiative relaxation to T1
- This is called intersystem crossing
- Experimental dye lasers use flash lamps, pulsed lasers or continuous lasers as pumping sources
- Pump lasers include Nitrogen Lasers, Argon Lasers, Krypton Lasers, YAG laser

Pump	Tuning range (nm)	Avg. Output Power (W)	Peak output Power (W)	Pulse duration (ns)
Nitrogen laser	350-1000	0.1 – 1	10000	1 – 10
Flashlamp	400-960	0.1 – 100	100000	10^2 -10^5
Argon laser	400-800	0.1 – 10	Max reported 40	CW
YAG laser	400-800	0.1 - 1	10000	5 - 30

Semiconductor Lasers

- Use semiconductors as the lasing medium

Advantages:

- Capability of direct modulation into Gigahertz region
- Small size and low cost
- Capability of Monolithic integration with electronic circuitry
- Direct Pumping with electronic circuitry
- Compatibility with optical fibers

- ❖ Basic mechanism of light emission from a semiconductor
- ❖ Homojunction and Heterojunction lasers
- ❖ Threshold current density
- ❖ Carrier and Photon confinement

- ✓ Most SC lasers operate in 0.8 – 0.9 μm or 1 – 1.7 μm spectral region
- ✓ Wavelength of emission determined by the bandgap
- ✓ Different SC materials used for different spectral regions
- ✓ 0.8 – 0.9 μm : Based on Gallium Arsenide
- ✓ 1 – 1.7 μm : Based on Indium Phosphide (InP)

Future Scope and relevance to industry

- The Laser Physics Centre undertakes research and training at the highest international level on a range of topics with a balance between fundamental, strategic and applied laser-based research. The research program spans many of the most exciting aspects of contemporary laser physics and quantum electronics.
- Research of more strategic nature includes work on photorefractive devices; on the properties of solitons and other nonlinear waves; on nonlinear optical materials for photonics; and aspects of solid-state physics for quantum computing. Applied research includes the development of novel high power lasers, parametric oscillators and amplifier; techniques for waveguide, photonic crystal and other photonic devices.