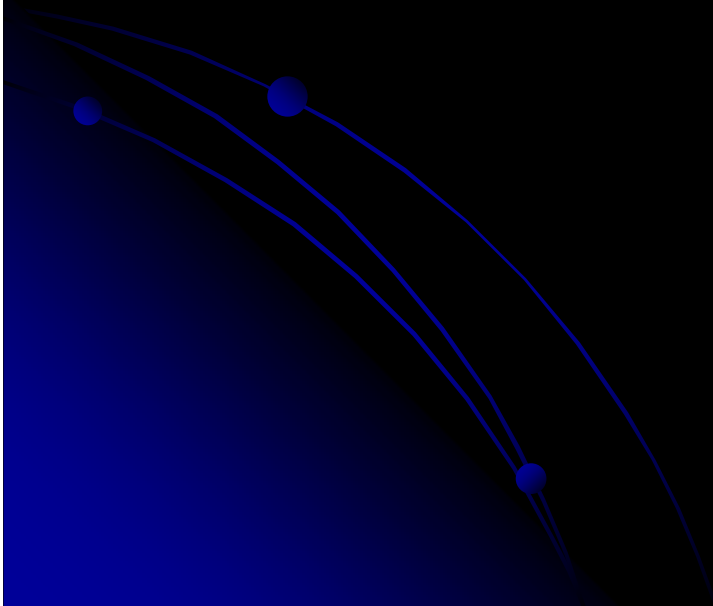
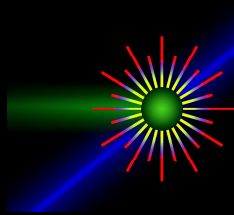


NIGHTLASE TECHNOLOGIES

Science, Technology and Engineering





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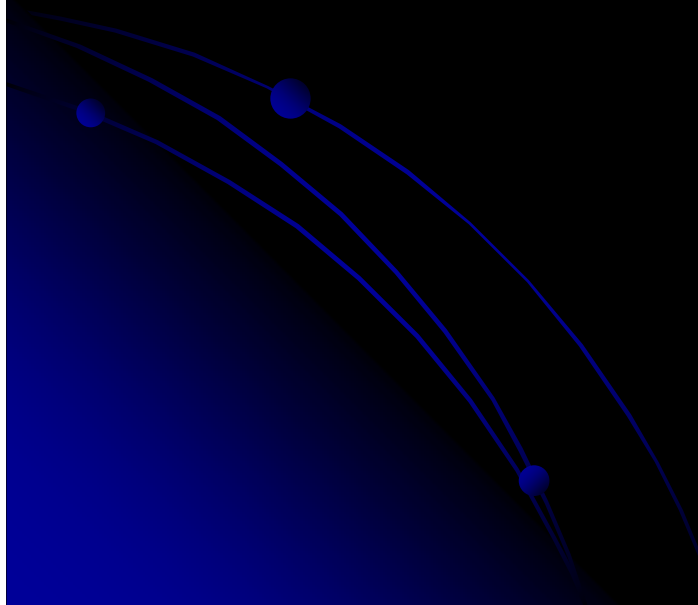
Science, Technology and Engineering

Lasers

An overview into the technological wonders of today

By Flavio Spedalieri

19th September, 2007



Introduction

- The Presentation will be broken into two components;
 - Theory Section - We will take an overview look at the following areas;
 - Laser history and its invention.
 - What defines a laser.
 - The components of a laser.
 - Laser fundamentals.
 - The laser resonator, types, stability and modes.
 - Laser output.
 - Laser safety, classification and labelling.
 - Practical Section – We will summarise what we have learned by taking a look at various lasers and components.

So lets begin...

Laser History

- 1917 – Albert Einstein proposed the process with which makes lasers possible;

Stimulated Emission

- 1953 – Charles H. Townes, James Gordon & Herbert Zeiger produced the first MASER (Microwave Amplification) at Columbia University operating at 24GHz.

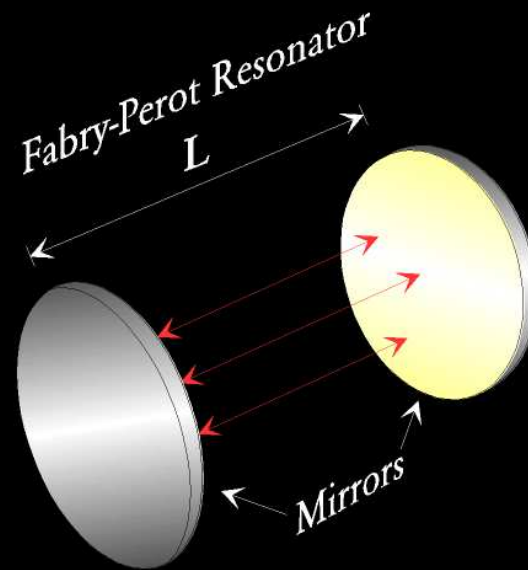
- 1957 – Charles Townes & Arthur L. Schawlow, then at Bell Labs began studies on infrared and optical masers. The research was published in the December 1958 *Physical Review*. This became the precursor to the race to develop the first laser.

Laser History

- At the same time, Gordon Gould, a graduate student at Columbia University was working on His doctoral thesis. Gordon had Ideas, He wrote down his ideas including the definition of ‘Laser’ as Light Amplification by Stimulated Emission of Radiation.
- Gordon’s Idea for a Laser suggested the use of an open resonator.
- For Laser oscillation to take place, there was a need for a resonant (optical) cavity.
- The simplest resonant cavity is half-wavelength long.
- This is an obvious problem, as light wavelengths are measured in nanometres compared with microwaves which are measured in cm.

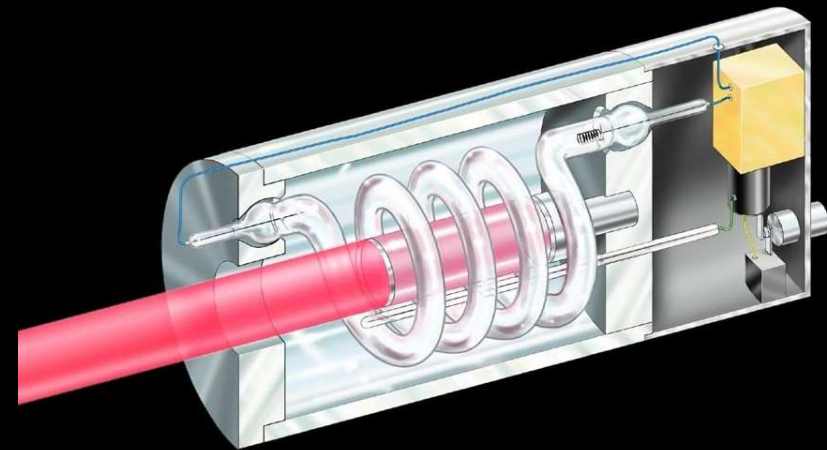
Resonant Cavity – The Solution

- Townes and Schawlow found the solution by implementing an optical device; The Fabry-Perot interferometer.
- The Fabry-Perot is simply two flat mirrors mounted in parallel and separated by many thousands of wavelengths.
- The Fabry-Perot cavity provides the optical feedback needed for oscillation to take place.
- In a laser, typically one of the mirrors is made less reflective so some light can leave the cavity.



The Laser Is Born

- In 1959 Schawlow considered Ruby as a laser material, but then publicly dismissed it as unsuitable.
- Meanwhile, at Huges Research Labs in Malibu, California, Theodore H. Maiman was working on Ruby materials doped with chromium as they were useful in masers.
- On 16th May, 1960, Maiman succeeded in making a ruby laser work for the first time. It produced a pulsed laser output at 694.3nm.



The First Laser



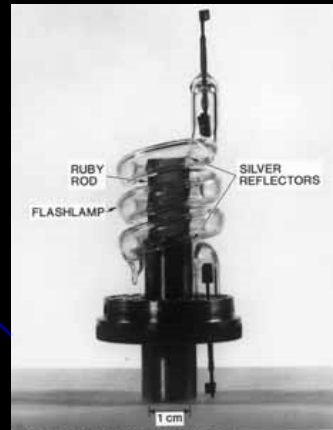
The photos on right are publicity shots, but are not of the actual 'first' laser (as seen left).



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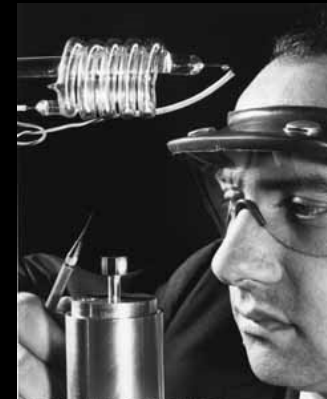
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Photos of Maiman's Ruby Laser.

Maiman's laser, was small and elegant: a ruby rod, with its ends silvered to reflect light, which he placed inside a spring-shaped flashlamp.



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Defining A Laser

- The term 'Laser' is an acronym. In its full form it describes the specific quantum mechanics which make the laser possible;

Light Amplification by Simulated Emission of Radiation

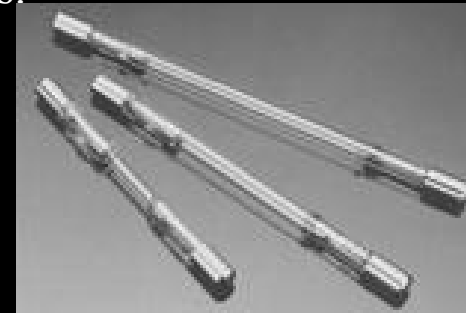
- Lasers emit light which has special characteristics;
 - Monochromatic (single well defined wavelengths).
 - Coherent (the wavelengths of light are in-step with each other).
 - Typically lasers emit light in a narrow, low-divergent highly directional beam.
- A Laser consists of a gain medium enclosed inside an optical resonator.
- The gain medium is 'excited' by application of external energy source.

Components of a Laser

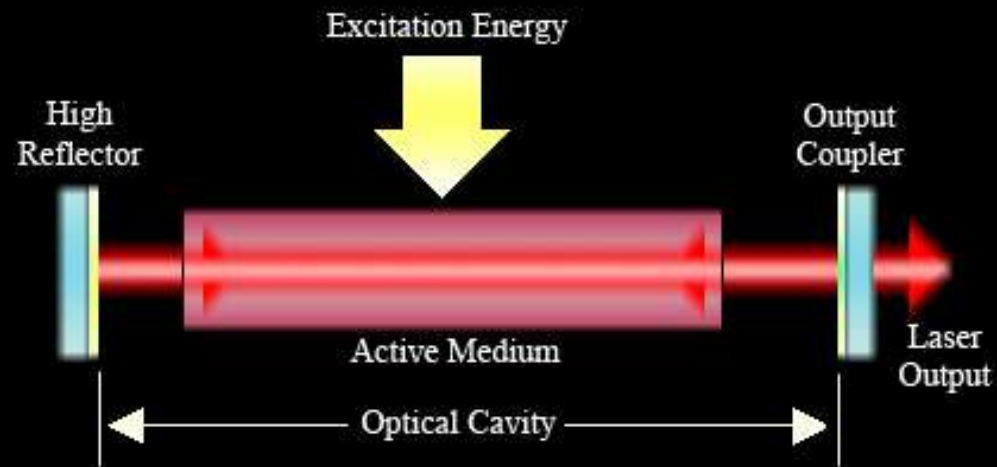
- The main components of a laser are;
 - The '*active medium*' – Generates laser emission.
 - Also referred to as the laser medium or gain medium.
 - Solid-State; such as Ruby and Nd:YAG.
 - Gas; Such as Helium-Neon, Argon and Carbon Dioxide.
 - Liquid; The dye laser uses an organic dye.
 - Optical resonator (Laser cavity).
 - Provides the optical feedback for laser oscillation to take place. The light is bounced back and forth between two mirrors arranged such as to allow the light to pass through the active medium multiple times before being emitted.
 - One of the mirrors is made less reflective as to allow some of the intra-cavity circulating power to 'leak out' of the cavity.

Components of a Laser

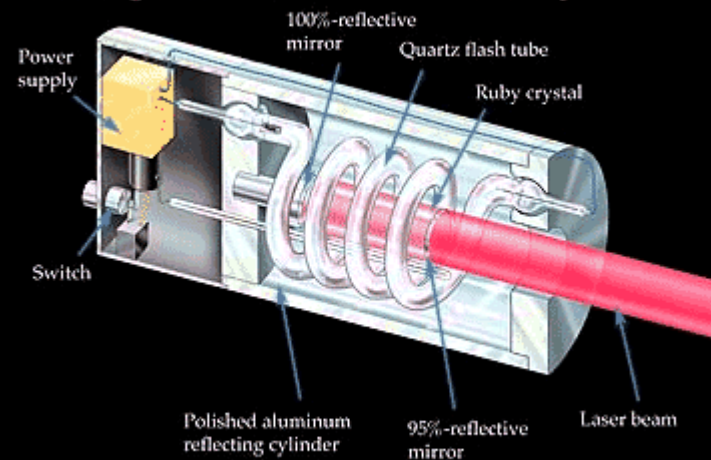
- The ‘*exciter*’ (or pump) – An external energy source to raise atoms from a lower state to a higher one within the active medium.
- The excitation energy is also known as ‘Pump Energy’. Examples of pump energy sources include:
 - Flashlamp – Produce powerful bursts of high-intensity (incoherent) light.
 - Lasers – Outputs from high-powered lasers.
 - Electrical discharge – Ionisation of rare gases.
 - Recombination of current carries in semiconductors.
 - Radio Frequency (RF).
 - Chemical Reactions.
 - Recombination of free electrons with ionised atoms.



Components of a Laser



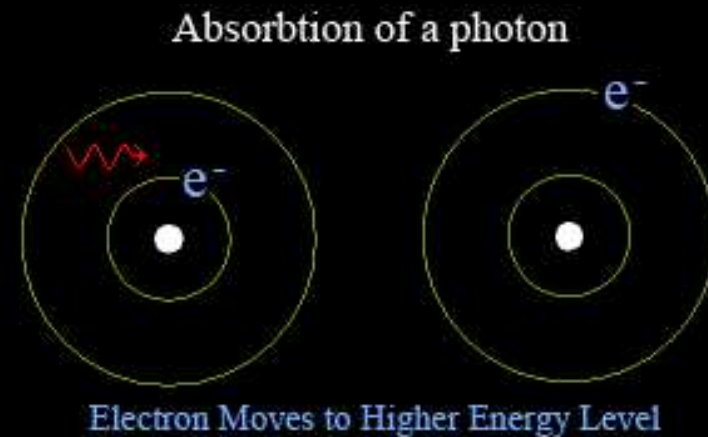
Components of the first ruby laser



Laser Fundamentals

- Absorption

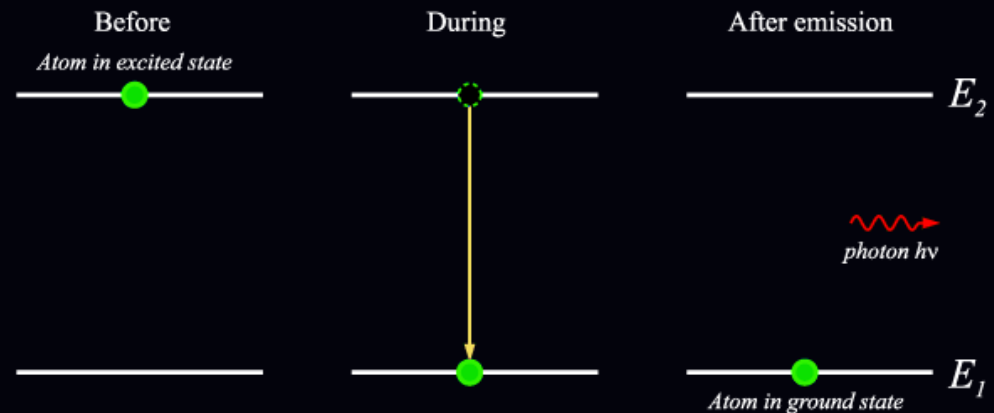
- Absorption is where the outer-most (valence) electrons absorb the energy of a photon. The electron then makes a transition to a higher energy level.
- When an atom, molecule or nucleus is at its lowest energy-state, it is known as the *ground state*.
- When an atom, molecule or nucleus is elevated above the ground state it is said to be in an *excited state*.



Laser Fundamentals

- Spontaneous Emission

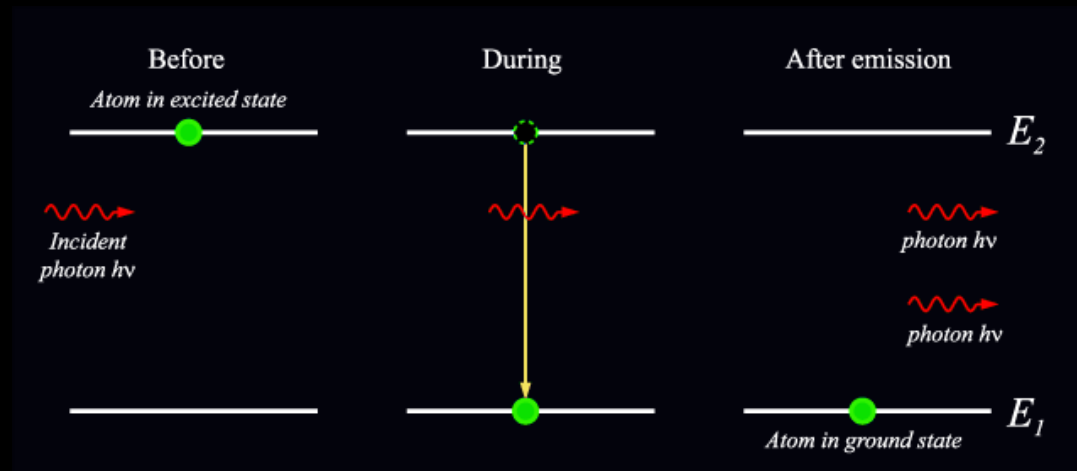
- When an atom, molecule or nucleus in an excited state drops to a lower-energy state without external intervention, resulting in the release (emission) of a photon.
- The light produced by the sun, an incandescent lamp or LED is an example of spontaneous emission.



Laser Fundamentals

- Stimulated Emission

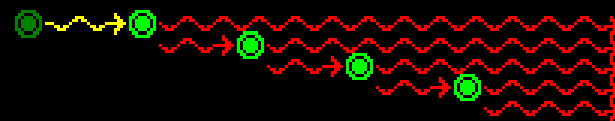
- When an atom, in an excited state is '*stimulated*' to release its energy by another photon with the same energy as the transition. The original photon is NOT absorbed.
- The result is that a second photon is released with the same wavelength, phase, polarisation and direction of travel as the original photon, that is, the two photons are coherent.



Laser Fundamentals

- Stimulated Emission is one key to laser emission.
- The second key to producing & sustaining stimulated emission is to create a *population inversion*, that is, to have more atoms in an excited state than in the ground state.
- The larger the population of atoms in the excited state, the more stimulated emissions will take place... resulting in L.A.S.E.R action. Typically referred to as '*Lase*' or '*Lasing*'.

Cascade Of Stimulated Emission

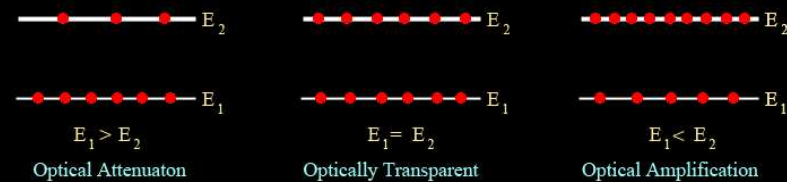


Laser Fundamentals

- Practically, a two – level system (such as a maser) does not work in laser mechanics as spontaneous and stimulated emissions will eventually cause the medium to reach equilibrium;

- The medium becomes optically transparent, but
- There is no net optical gain.

Two - Level Energy Diagram

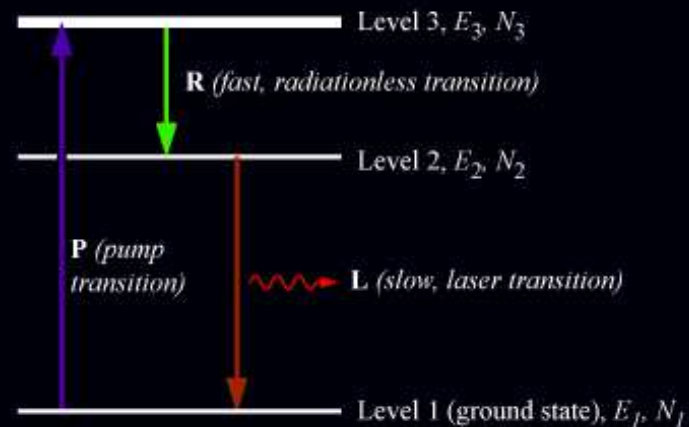


- To achieve a state of non-equilibrium, indirect methods of populating the excited states must be used;
 - Three-Level laser.
 - Four-Level Laser.
- The Ruby Laser is a three-level laser.

Laser Fundamentals

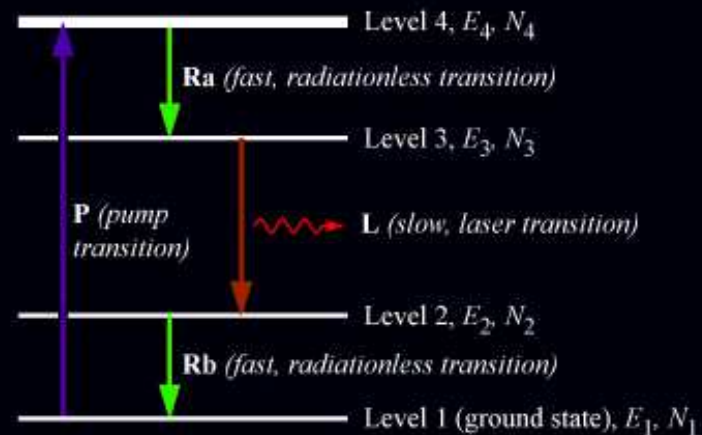
- Three–Level Laser

- External *pump energy* is applied to the medium which excites the atoms to the *pump level*.
- The atoms spontaneously decay quickly to the *Upper Laser Level*.
 - The energy released from this decay is typically as heat.
- The upper laser level has a long spontaneous lifetime, therefore the atoms will accumulate at this level creating a population inversion.
- Stimulated Emission takes place as the atom falls from this state to ground state.



Laser Fundamentals

- Four–Level Laser
 - Differs from a three–level laser in that it has a distinct *Lower Laser Level*.
 - The upper laser level typically has long lifetimes, and is referred to as a *metastable state*.
 - Stimulated emission takes place when the atom decays to the lower laser level.
 - Most common lasers are four – level.
 - Easier to create a population inversion.

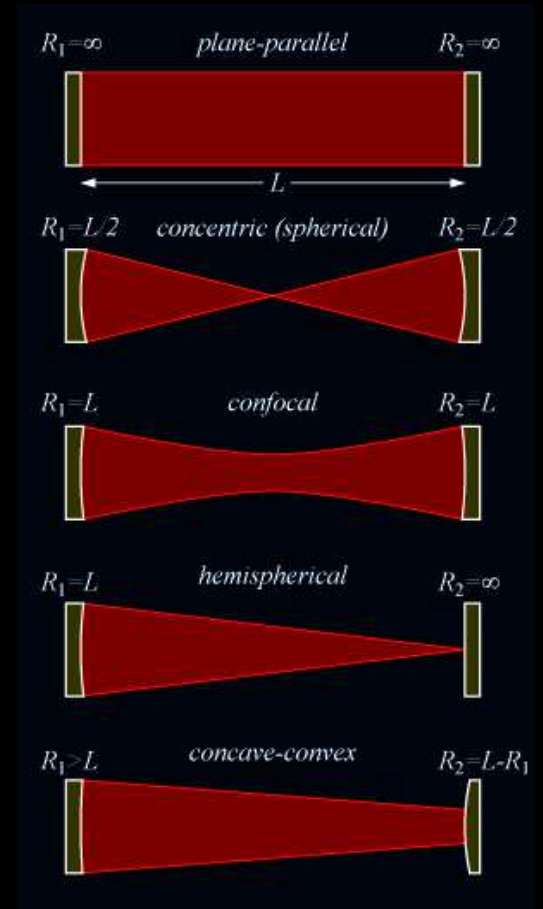


The Laser Resonator

- The laser resonator also called the optical cavity, is the component of a laser consisting of two opposing mirrors.
- The active medium is positioned between the two mirrors.
- One of the mirrors is 100% reflective, but one is made less reflective as to transmit or *couple* a small fraction of the light from the cavity – forming the output laser beam.
- A resonator provides a means of efficiently generating a sufficient *gain* in the active medium. By allowing light to be bounced back into the medium, this generates further stimulated emissions and increase the population inversion. This results in the most efficient manner to extract energy from the laser medium by concentrating the energy into a directional beam.

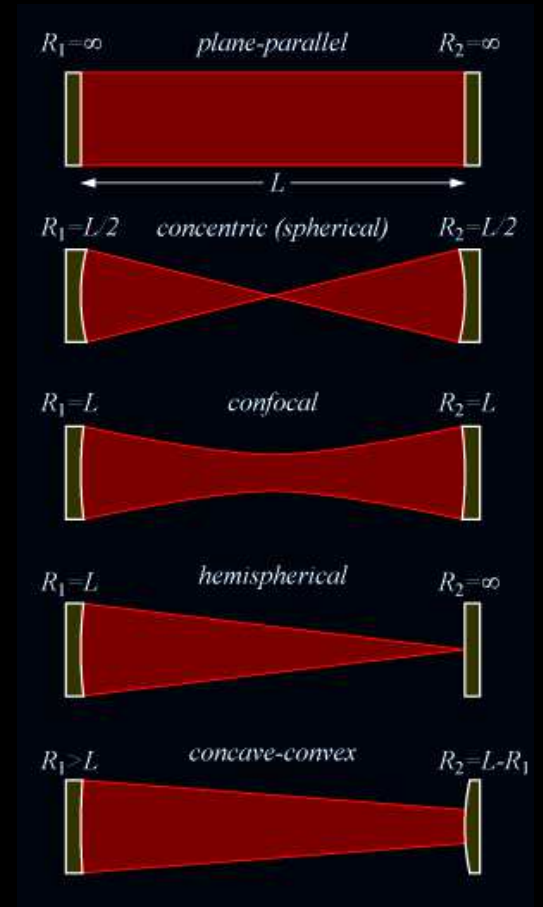
Laser Resonator Types

- The various configurations of laser resonators include:
- The Plane-Parallel is the Fabry-Perot cavity.
 - Mirrors are flat (Radius of curvature, R , is infinite).
 - Most difficult to align, therefore not common.
 - Used on lasers where the separation, $L < 1\text{ cm}$ such as semiconductor lasers.
- The spherical resonator.
 - Where $R_1 = R_2 = L/2$.
 - Diffraction-limited waist in center of cavity.
 - Large beam diameter at the mirrors.



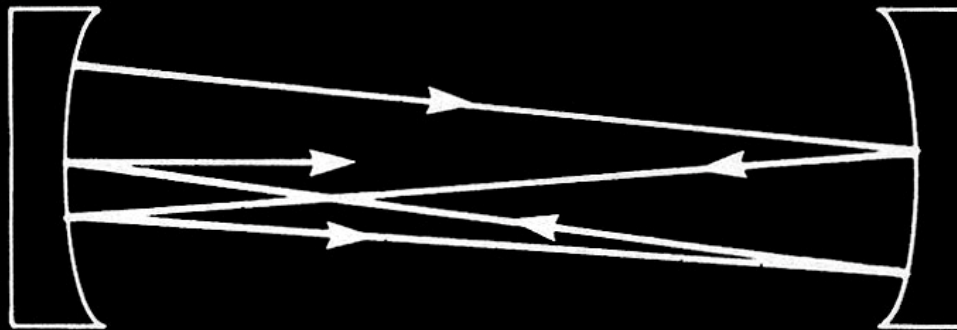
Laser Resonator Types

- The Confocal Resonator.
 - Where $R_1 = R_2 = L$.
 - Smallest beam diameter at the mirrors.
 - Used on lasers where the purity of the transverse mode pattern is important.
- The Concave-Convex Resonator.
 - Has no intra-cavity focus.
 - Used on very high powered lasers where the intra-cavity beam can damage the active medium if focused.



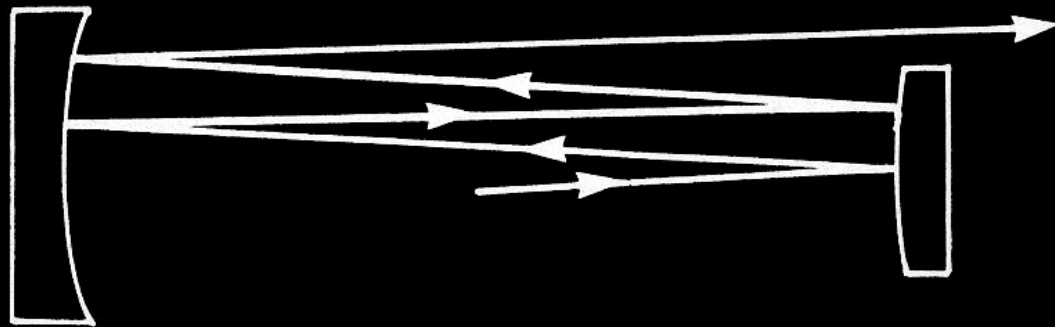
Resonator Stability

- Relates to the propagation of the beam in the cavity.
- Resonators fall under two types;
 - The *Stable* Resonator
 - The path of light is contained within the cavity.
 - Concentrates the light back towards the resonator axis.
 - Light can only escape *through* one of the mirrors.
 - Common to most lasers.



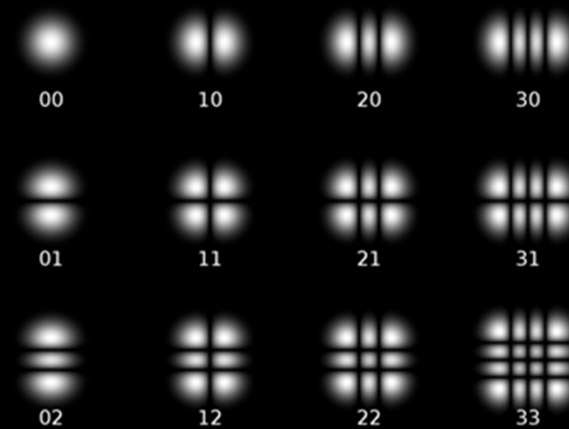
Resonator Stability

- *Unstable* Resonator
 - Uses two different mirror sizes.
 - The path of light is NOT contained within the cavity.
 - Light continues to move away from the resonator axis.
 - Produces larger intra-cavity beam volume thus more interaction with the population inversion – resulting in more power output.
 - The resultant output typically produces a doughnut beam profile caused by the shadow of the small mirror.
 - Used on high-powered, pulsed lasers.



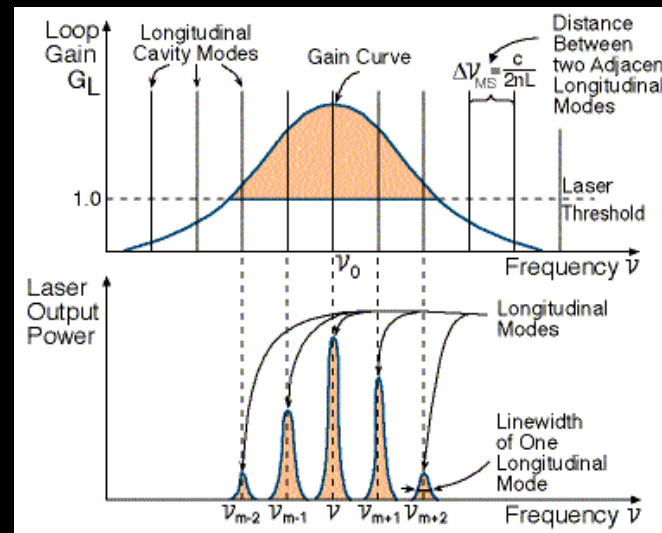
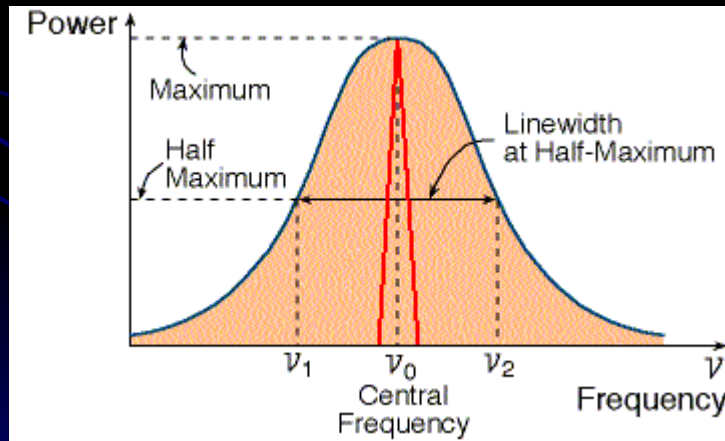
Laser Resonator Modes

- Relate to the spatial distribution of the light within the laser resonator, there are two kinds of modes;
 - Transverse (perpendicular to optical axis).
 - Results in output beam profile variations.
 - Longitudinal (along the optical axis).
 - Results in wide bandwidth of the laser output.
- Laser transverse modes are known as *TEM* – Transverse Electromagnetic Mode.
 - TEM_{00} is the most important (lowest order) mode, referred to as the *Gaussian mode*, the *fundamental mode* or *diffraction-limited mode*.



Laser Resonator Modes

- Longitudinal modes in a laser relate to the frequencies that are able to oscillate. Typically a laser will have a strong resonant wavelength (such as 632.8nm for a Helium-Neon laser) within a gain bandwidth of the laser.
- Due to *line broadening*, other wavelengths will also fall within the gain bandwidth and therefore also are resonant – The laser bandwidth is now much wider.



Laser Output

- External energy is applied to the active medium.
- Initially, spontaneous emissions and absorptions begin the process by exciting atoms in the ground state and pumping them to the pump level.
- Further spontaneous emissions trigger stimulated emissions. A population inversion occurs, and lasing begins. The laser resonator provides further (and ongoing) stimulated emissions through optical feedback resulting in laser oscillation and an effective net gain in the active medium.
- When the total gain of the laser medium is equal to the sum of the cavity losses plus output mirror transmission, this is termed the *Lasing Threshold*.
- When the total gain is less than the total losses, laser output is zero.

Laser Output

- When the total gain of the medium is greater than the cavity losses plus the transmitted energy at the output mirror, the laser is said to have reached a steady-state, and continuous-wave output is observed.
- The output power that is allowed to leave the cavity is determined by the gain of the laser medium, the circulating intra-cavity power and resonator design. Therefore if gain is low, this results in lower circulating intra-cavity power and less power allowed at the output.
- Lasers can be either pulsed or continuous wave,
- Lasers can produce output wavelengths in the Infrared, Visible, Ultraviolet, X-Ray and Gamma-Ray part of the electromagnetic spectrum.

Laser Safety

- Lasers pose several hazards including;
 - Optical;
 - Lasers produce highly directional and concentrated light. Exposure to laser beams can be hazardous to eyesight, even the beams from low-power lasers can be hazardous.
 - Lasers that produce light in the invisible parts of the spectrum in the infrared and ultraviolet are very hazardous as you cannot see the light or the location of reflections and will not be aware of the damage occurring.
 - High-power pulsed lasers are also very hazardous as a single pulse from either the direct optical axis or even diffused reflections can literally blast a hole in the retina.
 - High-power lasers can also pose skin hazards – causing burns to the skin.

Laser Safety

- Non-beam;
 - Electrical – High Voltage power supplies.
 - Mechanical – e.g.: vacuum / pressure pumps, glass tubes etc.
 - Chemicals associated with lasers e.g.: organic dye solvents , beryllium oxide etc.
 - High temperatures / fire.
- Maximum Permissible Exposure (MPE);
 - The highest acceptable power or energy density (in J/cm^2 or W/cm^2) that is considered 'safe' or poses little to no damage.
 - Calculations take into account wavelength, exposure times, pulsed or CW and spatial distribution of the energy in the light source (i.e. how well collimated the beam is).
 - Calculated based on the are of a fully opened pupil (0.39cm^2).

Laser Classification

The laser classifications was revised in 2007.

- **Class 1**

A class 1 laser is safe under all conditions of normal use. This means the maximum permissible exposure (MPE) cannot be exceeded. This class includes high-power lasers within an enclosure that prevents exposure to the radiation and that cannot be opened without shutting down the laser. For example, a continuous laser at 600 nm can emit up to 0.39 mW, but for shorter wavelengths, the maximum emission is lower because of the potential of those wavelengths to generate photochemical damage. The maximum emission is also related to the pulse duration in the case of pulsed lasers and the degree of spatial coherence.

- **Class 1M**

● A Class 1M laser is safe for all conditions of use except when passed through magnifying optics such as microscopes and telescopes. Class 1M lasers produce large-diameter beams, or beams that are divergent. The MPE for a Class 1M laser cannot normally be exceeded unless focusing or imaging optics are used to narrow the beam. If the beam is refocused, the hazard of Class 1M lasers may be increased and the product class may be changed. A laser can be classified as Class 1M if the total output power is below class 3B but the power that can pass through the pupil of the eye is within Class 1.

Laser Classification

- **Class 2**

A Class 2 laser is safe because the blink reflex will limit the exposure to no more than 0.25 seconds. It only applies to visible-light lasers (400–700 nm). Class-2 lasers are limited to 1 mW continuous wave, or more if the emission time is less than 0.25 seconds or if the light is not spatially coherent. Intentional suppression of the blink reflex could lead to eye injury. Many laser pointers are class 2.

- **Class 2M**

A Class 2M laser is safe because of the blink reflex if not viewed through optical instruments. As with class 1M, this applies to laser beams with a large diameter or large divergence, for which the amount of light passing through the pupil cannot exceed the limits for class 2.

Laser Classification

- **Class 3R**

A Class 3R laser is considered safe if handled carefully, with restricted beam viewing. With a class 3R laser, the MPE can be exceeded, but with a low risk of injury. Visible continuous lasers in Class 3R are limited to 5 mW. For other wavelengths and for pulsed lasers, other limits apply.

- **Class 3B**

A Class 3B laser is hazardous if the eye is exposed directly, but diffuse reflections such as from paper or other matte surfaces are not harmful. Continuous lasers in the wavelength range from 315 nm to far infrared are limited to 0.5 W. For pulsed lasers between 400 and 700 nm, the limit is 30 mJ. Other limits apply to other wavelengths and to ultra-short pulsed lasers. Protective eyewear is typically required where direct viewing of a class 3B laser beam may occur.

- **Class 4**

Class 4 lasers include all lasers with beam power greater than class 3B. In addition to posing significant eye hazards, with potentially devastating and permanent eye damage as a result of direct beam viewing, diffuse reflections are also harmful to the eyes within the distance called the Nominal Hazard Zone. Class 4 lasers are also able to cut or burn skin. In addition, these lasers may ignite combustible materials, and thus represent a fire risk.

Laser Labelling

- The following labels are examples that are required to be attached to lasers and also displayed outside the area where a laser is operating.



AVOID EXPOSURE
VISIBLE and/or INVISIBLE
LASER RADIATION EMITTED
FROM THIS APERTURE

**CLASS 1
LASER PRODUCT**

**LASER
APERTURE**



⚠ DANGER

Invisible laser
radiation when open.
**AVOID EXPOSURE
TO BEAM.**
Class 3B laser product.
(IEC 826-1)



⚠ CAUTION

Invisible laser radiation.
**DO NOT STARE
INTO BEAM.**
Class 2 laser product.



Conclusion of theory section

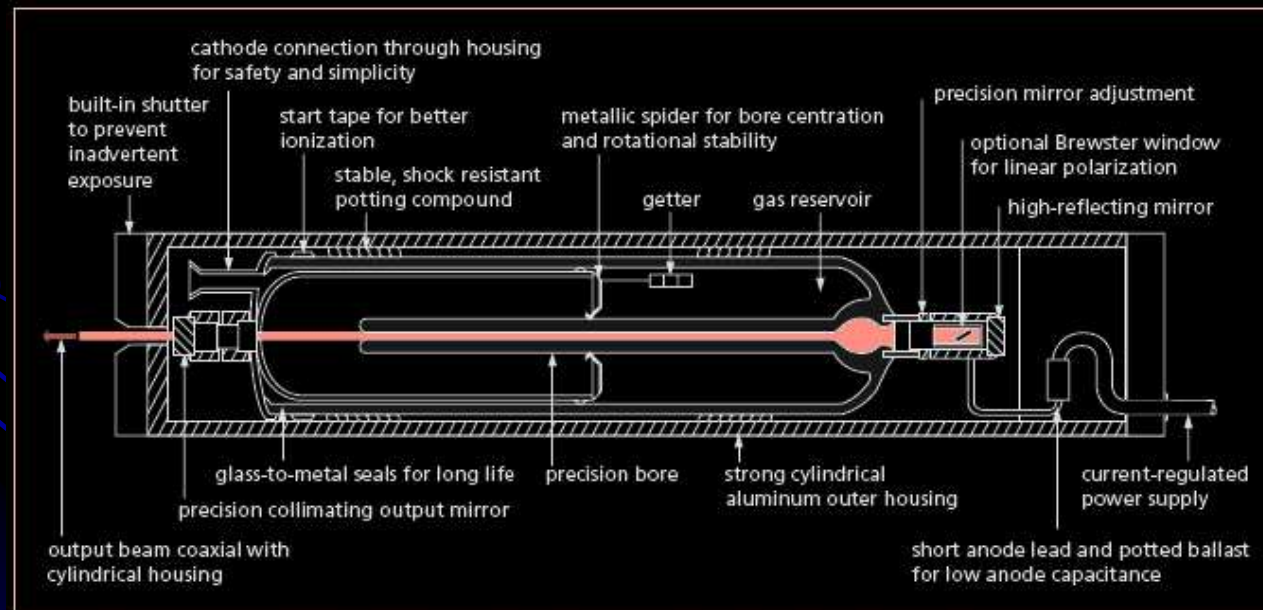
*Next section consists of practical demonstrations
to review key theoretical concepts just
learned.*

Practical Demonstrations

- In this section we will look at practical examples of some lasers and discuss each laser accordingly.
- We will look at the following lasers and turn them on:
 - Helium-Neon gas laser (632.8nm, 543.5nm, 594.1nm).
 - Argon-Ion gas laser (454.6nm-528.7nm).
 - Laser diode (405nm 635nm, 650nm, 670nm).
 - Diode-Pumped Solid-State (DPSS) Laser (532nm).
- We will also have look at;
 - Ruby Laser (694.3nm).
 - Nd:YAG (1024nm).
 - Carbon Dioxide (10,600nm).
 - Laser dye.

The Helium-Neon Gas Laser

- Gas mixture of Helium and Neon in ratios between 5:1 to 20:1.
- Most common wavelength is 632.8nm (red).
- Electron collision (from discharge) with He atoms. Energy transfers to Ne atoms.
- A high-voltage (typically around 10kV) to ionise the gas, operating voltage between 1kV and 4kV at around 5-15mA depending on size of tube.

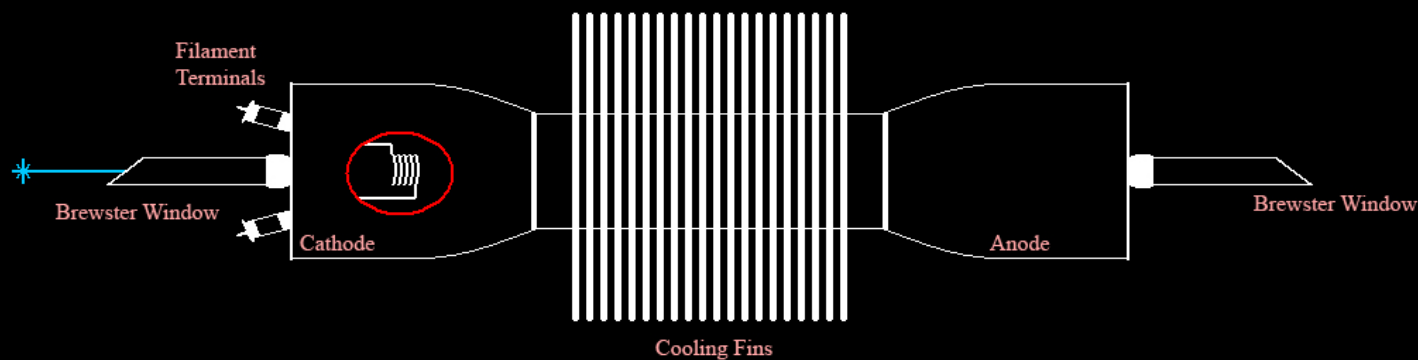


Cross-sectional view of cylindrical helium neon laser head showing details of the plasma tube

The Argon-Ion Gas Laser

- Produce high powers in the visible and UV.
- Tube design is somewhat similar in terms of using a very small bore.
- High currents are needed as it takes a lot of energy to excite the ionic transitions.
- Operate at much higher currents – typically small air-cooled lasers operate at around 10 Amps.
- Large-frame Argon lasers require water-cooling.
- Mixed Argon & Krypton lasers can produce white-light output.

Typical Air-Cooled Argon Laser Tube design

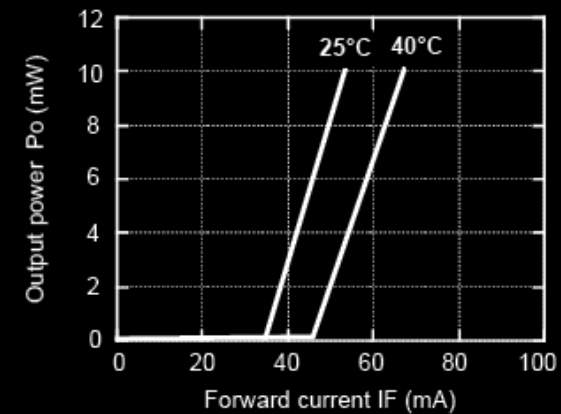


Semiconductor Laser Diode

- Based on P-N semiconductor junctions.
- When forward biased, recombination in the junction causes light emission (LED).
- A Laser diode has a resonant cavity which provides feedback (as opposed to LED that do not). The mirrors are built into the diode by cleaving the semiconductor.
- Higher operational currents than LED.
- Laser Diodes have a characteristic threshold current. Below the threshold, they behave similar to an LED producing spontaneous emission. Above threshold, the laser diode produces Stimulated Emission.. (Laser Light).
- The laser beam from a diode is highly divergent and requires a collimation lens to bring back to a tight beam.

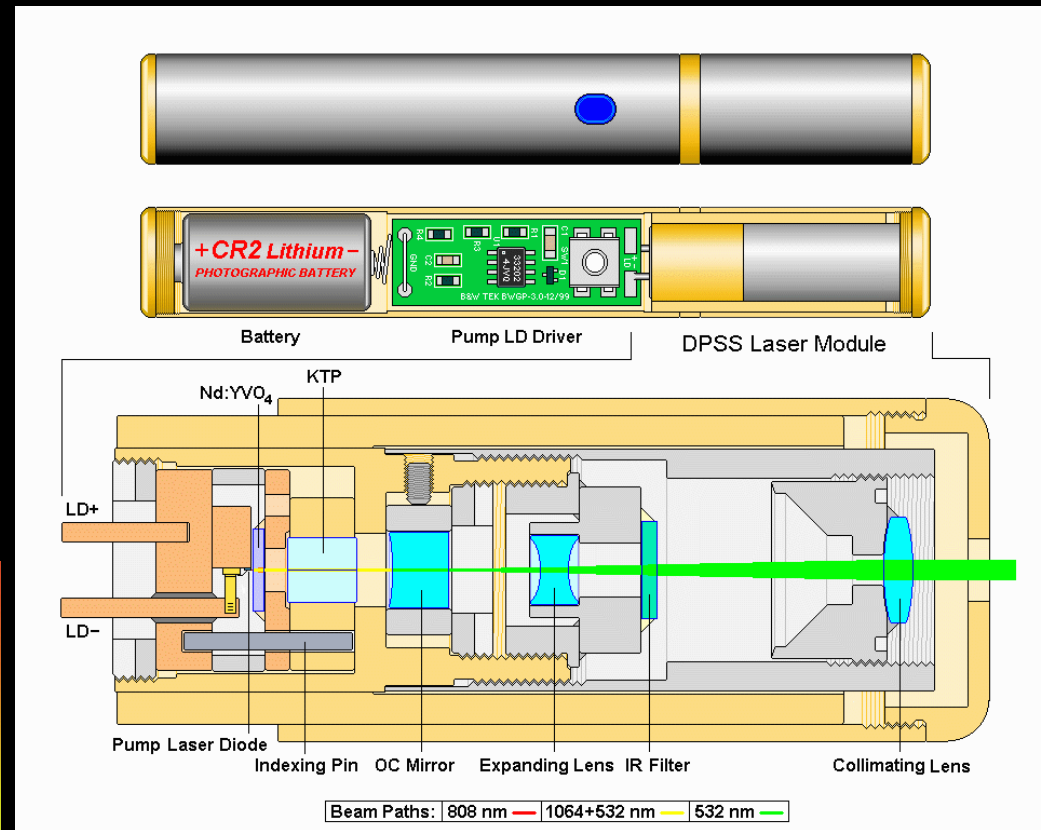
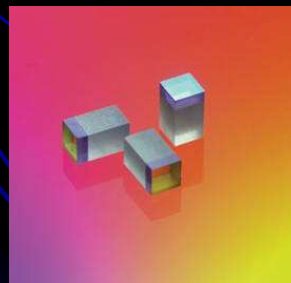


Output power vs. Forward current



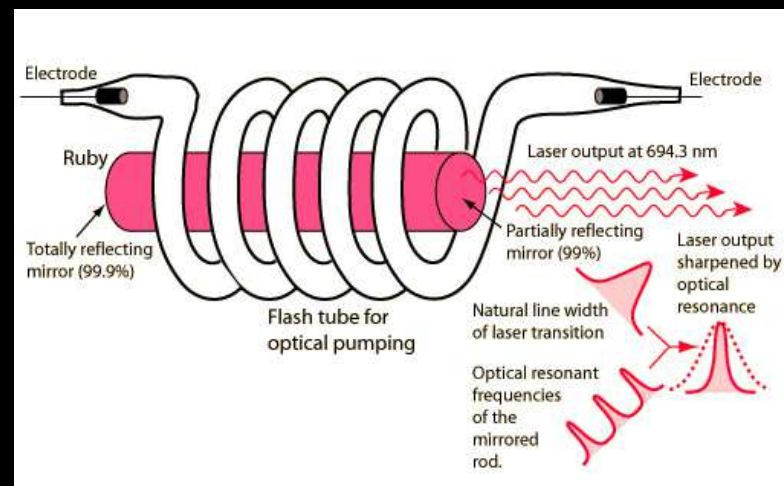
Diode-Pumped Solid-State Laser

- A Laser diode with a typical wavelength of 808nm is used as the pump source.
- Neodymium Doped Yttrium Orthovanadate generates the 1064nm laser line.
- Potassium Titanium Phosphate (KTP) is a non-linear crystal which generates the second harmonic 532nm line.
- Conversion efficiency typically around 80%.



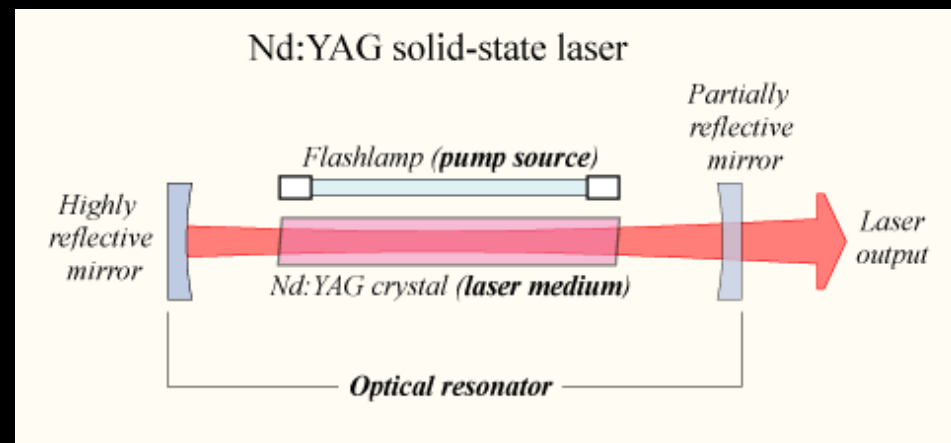
The Ruby Laser

- The first laser to be successfully operated (T.H. Maiman 16th May 1960).
- Absorption wavelength band: 404nm and 554nm (Blue-violet & Green).
- Typical wavelength: 694.3nm (Deep Red).
- Flashlamp pumped.
- Pulsed operation only.
- Ability to be Q-Switched – An optical switch that is inserted into the laser cavity. It operates by allowing the laser medium to ‘store’ the laser energy (I.E maximum population inversion) by preventing the optical feedback, then at the critical moment (at maximum population inversion), the Q-Switch becomes transparent, (high-quality cavity) and optical feedback is restored – this then dumps the stored energy from the medium in one high energy pulse.



Nd:YAG Laser

- Nd:YAG – Neodymium-doped Yttrium Aluminium Garnet.
- Absorption wavelength bands: 570-600nm (visible) 730-760nm and 790-820nm (Infrared).
- Typical wavelength: 1064nm (Infrared).
- Can be pumped using flash lamps (Xenon or Krypton), arc lamps or laser diodes.
- Able to operate in both pulsed and continuous modes.
- Ability to be Q-Switched.



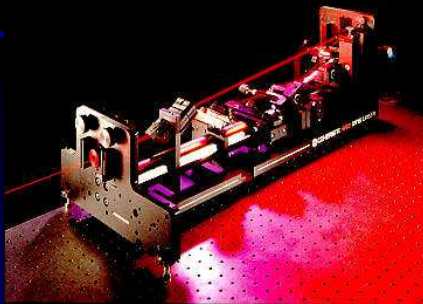
Carbon Dioxide Gas Laser

- One of the most efficient and versatile lasers. Typical efficiency around 20%
- Main emission wavelength in deep infrared at 10,500nm.
- Operates on vibrational-rotational transitions of the CO₂ molecules.
- Typically CO₂ lasers produce high-powers with small sealed CO₂ lasers capable of producing 10 Watts or more.
- All CO₂ lasers require active (water) cooling.

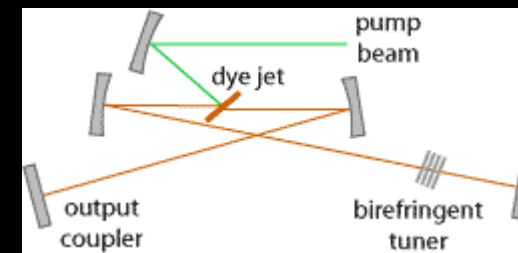


Dye Laser

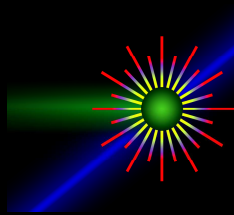
- Dye Lasers use a liquid medium of dissolved organic dyes in solvents as a host.
- Are able to be tuned across many wavelengths.
- Pump sources include; flash lamps, argon lasers, and diode lasers / DPSS lasers.
- The most frequently used laser dye is Rhodamine 6G.
 - Absorption of R6G is 530nm
 - Solvents; Ethylene Glycol most predominantly used for CW and Argon pumped Dye. Methanol (for pump wavelength 532nm pulsed), Ethanol (for flashlamp pumped).
 - Fluorescence (lasing) range: 555 to 625nm.
- For CW pumped, the dye is circulated through a jet which creates a laminar flow in air.
- For flashlamp pumped, the dye is held in a dye cell.



Lasers - By Flavio Spedalieri



NightLase Technologies



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Conclusion of presentation