Optical Sources

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Fiber Optic Sources

Two basic light sources are used for fiber optics: lasers and light-emitting diodes (LED). Each device has its own advantages and disadvantages as listed in Table

Characteristic	LED	Laser
Output power	Lower	Higher
Spectral width	Wider	Narrower
Numerical aperture	Larger	Smaller
Speed	Slower	Faster
Cost	Less	More
Ease of operation	Easier	More difficult

Output Power	Linearly proportional to drive current	Proportional to current above the threshold
Current	Drive Current: 50 to 100 mA Peak	Threshold Current: 5 to 40 mA
Coupled Power	Moderate	High
Speed	Slower	Faster
Output Pattern	Higher	Lower
Bandwidth	Moderate	High
Wavelengths Available	0.66 to 1.65 µm	0.78 to 1.65 µm
Spectral Width	Wider (40-190 nm FWHM)	Narrower (0.00001 nm to 10 nm FWHM)
Fiber Type	Multimode Only	SM, MM
Ease of Use	Easier	Harder
Lifetime	Longer	Long
Cost	Low ($5-$300)	High ($100-$10,000)

LASER

LASAER = light amplification by stimulated emission of radiation

Invented dated to 1958 with the publication of the scientific paper, Infrared and Optical Masers, by Arthur L. Schawlow, then a Bell Labs researcher, and Charles H. Townes, a consultant to Bell Labs

Property of Laser Light

- **Nearly"monochromatic: consists of an extremely narrow range of wavelengths**

- **Highly Directional: travel in a single direction within a narrow cone of divergence**

- **Highly Coherence: coherence is the most fundamental property of laser light and distinguishes it from the light from other sources**

Laser gain medium

Atoms such as in the red helium-neon (HeNe) laser, the visible and ultraviolet argon ion and helium-cadmium (HeCd) lasers, and the green and yellow copper vapor lasers (CVL)

Molecules such as in the infrared carbon dioxide (CO_2) laser, the ultraviolet excimer lasers such as ArF and KrF, and the pulsed N_2 laser

Liquids such as those involving various organic dye molecules dilute dissolved in various solvent solutions

Dielectric solids such as those involving neodymium atoms doped in YAG or glass to make the crystalline Nd:YAG or Nd:glass lasers

Semiconductor materials such as gallium arsenide or indium phosphide crystals or various mixtures of impurities blended with those and other semiconductor species

Examples of Current Laser system

Type of Laser	λ_{21}(nm)	$\Delta\lambda_{21}$(Hz)	σ_{21}(cm^2)	ΔN_{21}(cm^{-3})	g_{21}(cm^{-1})	I_{sat}(W/cm^2)
HeNe	632.8	2×10^{9}	3×10^{-13}	7×10^{9}	2×10^{-3}	6.2
Argon	488.0	2×10^{9}	2.5×10^{-12}	1×10^{15}	5×10^{-3}	16.3
HeCd	441.6	2×10^{9}	9×10^{-14}	4×10^{12}	3×10^{-3}	7.1
Copper Vapor	510.5	2×10^{9}	8×10^{-14}	6×10^{13}	5×10^{-2}	9.0
CO_2	10,600	6×10^{7}	3×10^{-18}	5×10^{15}	8×10^{-3}	1.6×10^{-2}
Excimer	248.0	1×10^{13}	2.6×10^{-16}	1×10^{16}	2.6×10^{-2}	3.4×10^{5}
Dye (Rh6-G)	577	5×10^{13}	2×10^{-16}	2×10^{18}	2.4	3.4×10^{9}
Ruby	694.3	3×10^{11}	2.5×10^{-20}	4×10^{19}	1.0	3.8×10^{7}
Nd:YAG	1064.1	1.2×10^{11}	6.5×10^{-19}	3×10^{19}	2.0	1.2×10^{7}
Ti:Al_2O_3	760	1.5×10^{14}	3.4×10^{-19}	3×10^{18}	1.0	2.0×10^{9}
Semiconductor	800	1×10^{14}	1×10^{-15}	1×10^{18}	10^{3}	2.5×10^{9}

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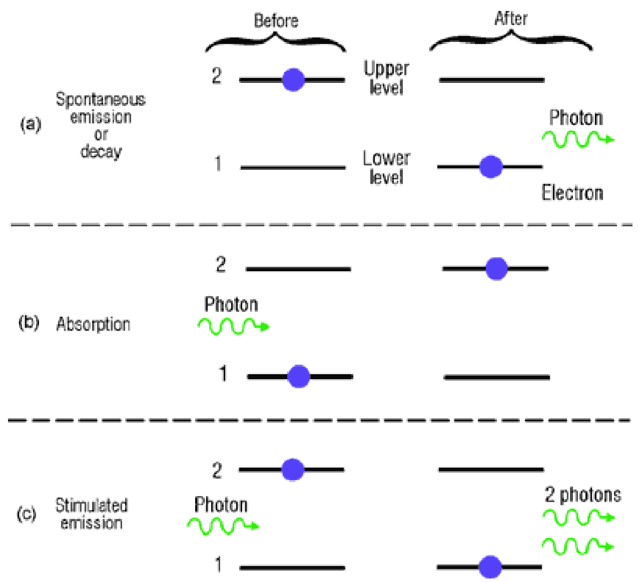
Requirements for a laser

There are three types of processes involving the interaction of light beams with atoms that have electrons residing in various energy levels:

SPONTANEOUS EMISSION

ABSORPTION

STIMULATED EMISSION



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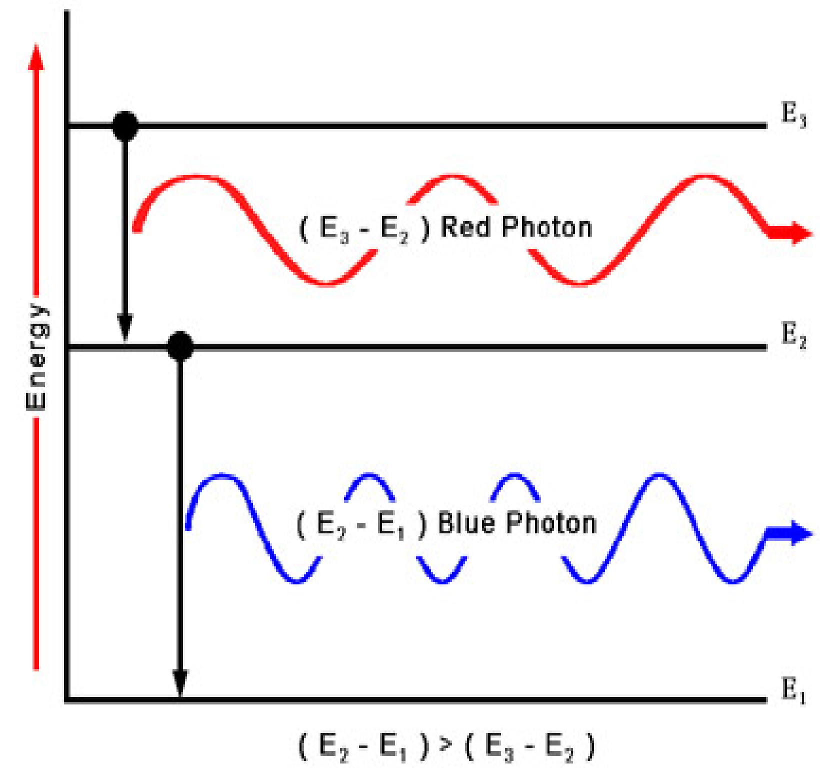
SPONTANEOUS EMISSION

An atom in an excited state is unstable and will release spontaneously its excess energy and return to the ground state. This energy release may occur in a single transition or in a series of transitions that involve intermediate energy levels. For example, an atom in state E_3 could reach the ground state by means of a single transition from E_3 to E_l, or by two transitions, first from E_3 to E_2 and then from E_2 to E_1. In any downward atomic transition, an amount of energy equal to the difference in energy content of the two levels must be released by the atom.



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Most excited energy levels undergo spontaneous emission. Each level has a specific lifetime τ over which it will remain in that level before decaying to a lower-lying level. That lifetime is determined by the interactions of the electron with the other electrons and nuclei of that atom. Typical lifetimes of electrons residing in specific levels that decay by radiating in the visible portion of the spectrum are of the order of 10–100 nsec. The photon radiated during spontaneous emission has the exact wavelength λ_{21} and frequency ν_{21} corresponding to the difference in energy ΔE_{21} of the two involved energy levels (1 and 2 in this case) according to the relationship

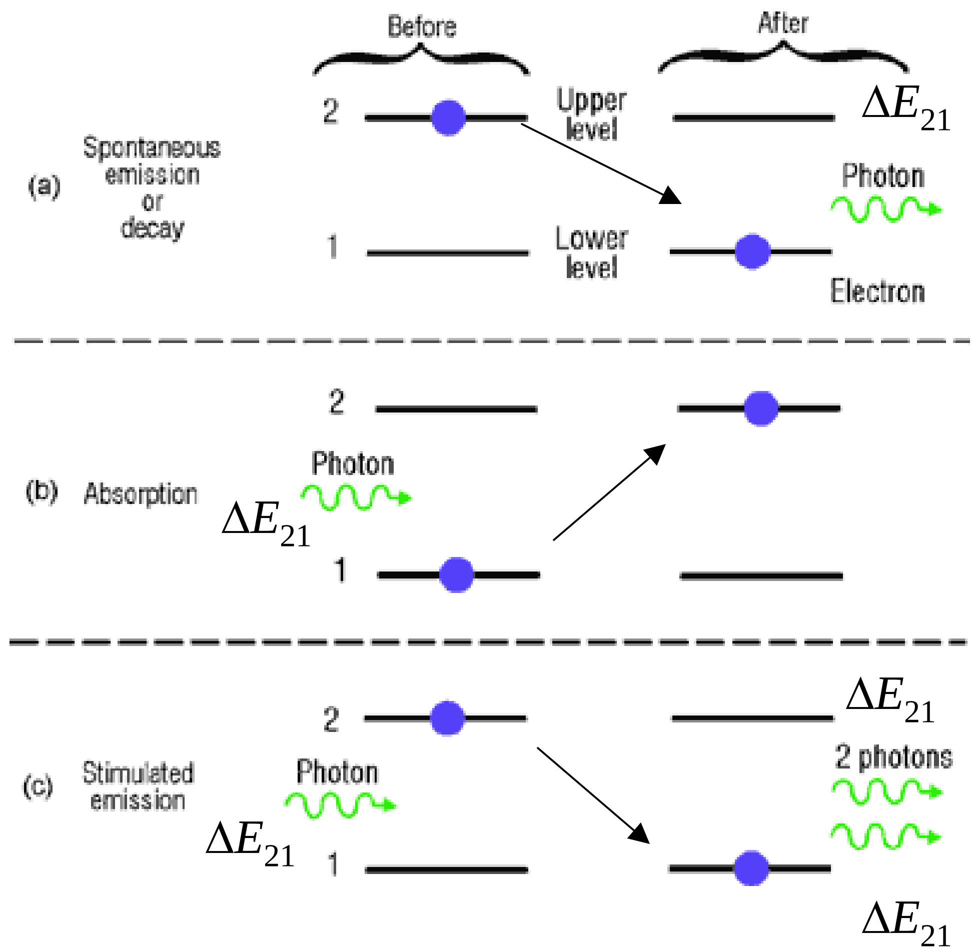
$$\Delta E_{21} = h\nu_{21} = \frac{hc}{\lambda_{21}}$$

in which h is Planck's constant such that $h = 6.63 \times 10^{-34}$ joule-sec and c is the speed of light, $c = 3 \times 10^{8}$ m/sec.

Because different materials have different energy-level arrangements, they radiate at different wavelengths and thus emit different colors or frequencies of light that are specific to the material.

ABSORPTION OF LIGHT

The second process is *absorption*, shown in Figure b, which occurs if the atom has its electron in level 1 and a photon of light of wavelength λ_{21} collides with the atom. During the collision, the photon is absorbed by the atom and the electron is moved up to the higher energy level 2. This process is the way light interacts with practically all of matter. It can happen from any energy level that is occupied (generally the ground state) and always boosts the atom to a higher-lying level while eliminating the photon. This often results in heating of the absorbing material



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ABSORPTION

When a large group of atoms is assembled and irradiated with light, most of those atoms are in the ground-state energy level. If the photons of the impinging light have the appropriate energy ΔE_{20} for example, the light will be absorbed according to the following expression for the variation of intensity I with the distance L into the material (known as (**Lambert Law**):

$$I = I_0 e^{-\sigma_{20} N_0 L}$$

Where I_0 = intensity of the beam when it first reaches the atoms

σ_{20} = cross section for absorption or emission of those two levels (cm^2),

N_0 = population density of atoms residing in level 0 (atoms/cm^3),

$\sigma_{20} N_0$ = absorption coefficient

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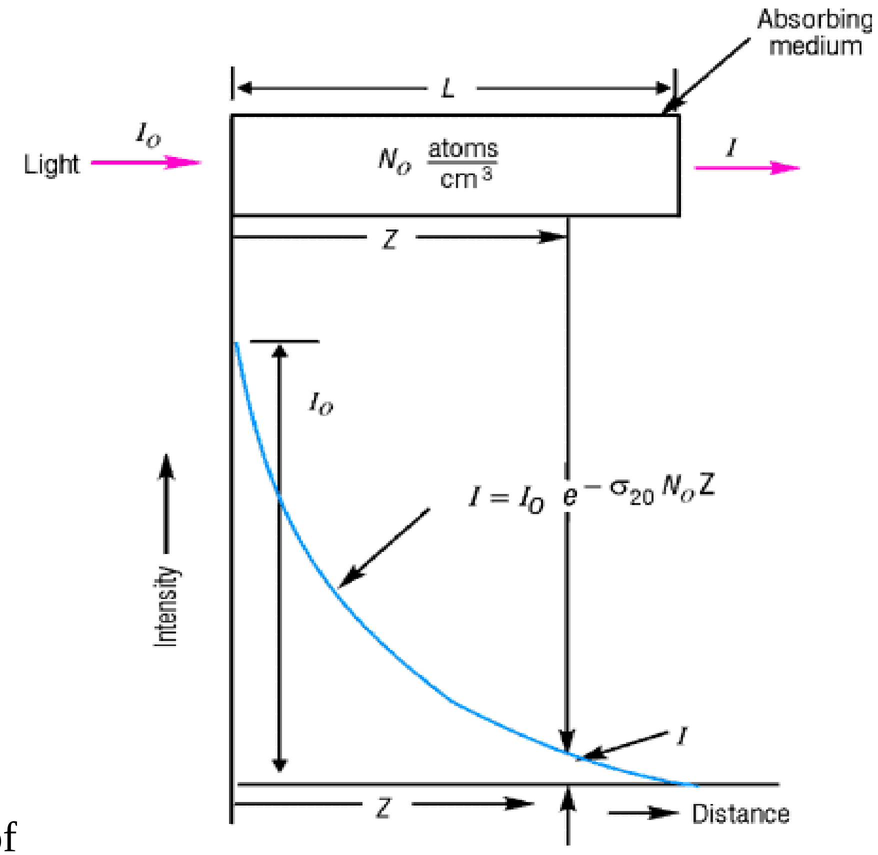

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Intensity variation versus depth z *into an absorbing sample*

Stimulated Emission

The third process, shown in Figure c is referred to as *stimulated emission*. It results when an electron is in a higher-lying level, such as level 2, and a photon of light of wavelength λ_{21} collides with the atom. <u>During the collision the photon stimulates the atom to radiate a second photon having exactly the same energy ΔE_{21}</u> as that of the <u>incident photon and traveling in exactly the same direction in order to satisfy the laws of conservation of energy and momentum</u>. Hence, one photon leads to two identical photons, which, in effect, leads to an amplification process. <u>A photon has been gained at the expense of the loss of energy stored within the atom.</u>

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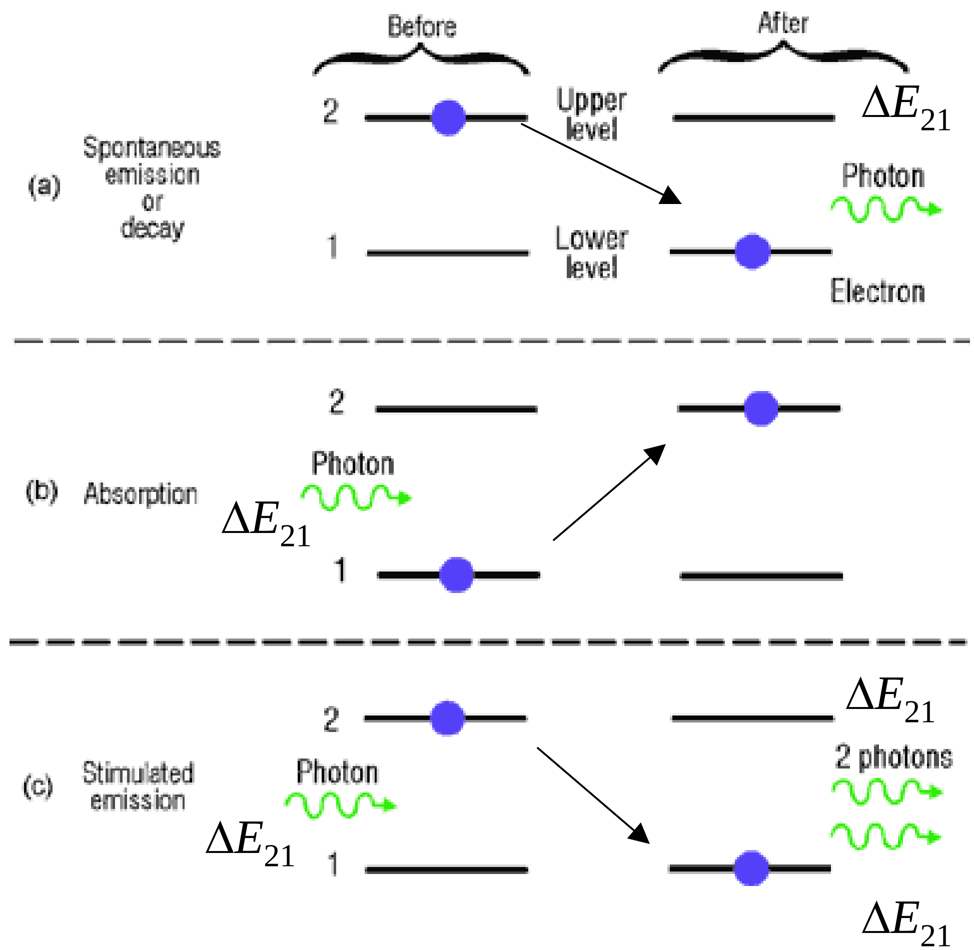

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Stimulated Emission

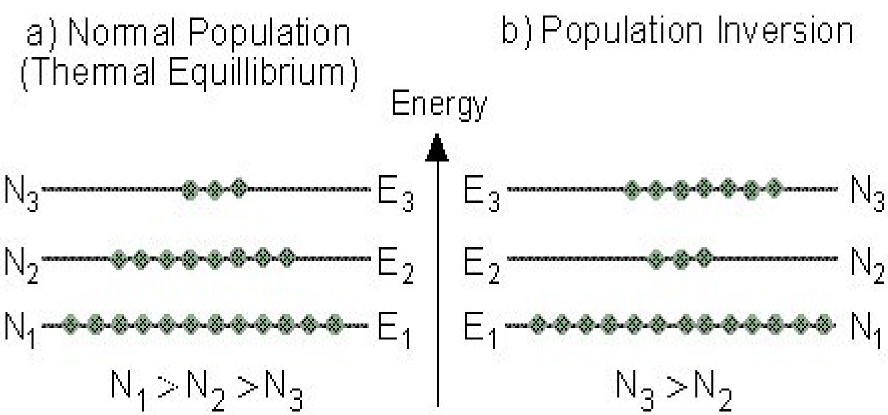
Suppose that we were able to "pump" (excite) a significant amount of population of the medium from level 0 to level 2. Also, for the time being let us assume that there is no population in level 1. (This is an unlikely scenario but we will do this as a "thought" experiment for illustrative purposes.) Then again, let us consider having a beam of photons of energy ΔE_{21} and wavelength λ_{21} enter the medium. According to the earlier discussion, and considering the process that can occur is stimulated emission, and we would expect more photons to be generated as the beam progresses. This can be described mathematically in the equation below

$$I = I_0 e^{+\sigma_{21} N_2 L}$$

in which we now have the population density N_2 in the expression along with the appropriate cross section σ_{21}.

POPULATION INVERSION

A **population inversion** exists whenever more atoms are in an excited atomic state than in some lower energy state. The lower state may be the ground state, but in most cases it is an excited state of lower energy. Lasers can produce coherent light by stimulated emission only if a population inversion is present. And a population inversion can be achieved only through external excitation of the atomic population.



Rami Arieli: "The Laser Adventure" Chapter 2.6 page

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POPULATION INVERSION

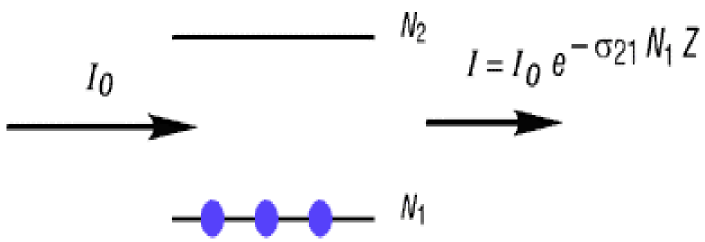
Now, if population is allowed to be in both level 1 and level 2, both absorption and stimulated emission will occur within the medium and therefore

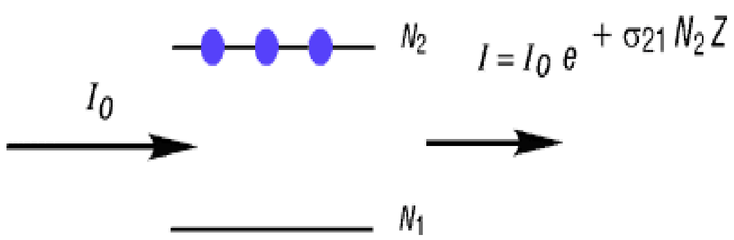
$$I = I_0 e^{+\sigma_{21}(N_2 - N_1)L}$$

Hence, if more population exists in level 2 than in level 1, N_2 will be greater than N_1 and the exponent of above equation will be positive. The beam will grow and emerge from the medium with a greater intensity than when it entered. In other words, for amplification or gain to occur, the condition must be

$$\frac{N_2}{N_1} > 1$$

Having N_2 be larger than N_1 is known as having a *population inversion*, which is not a normal, naturally occurring relationship.





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Small-signal-gain coefficient

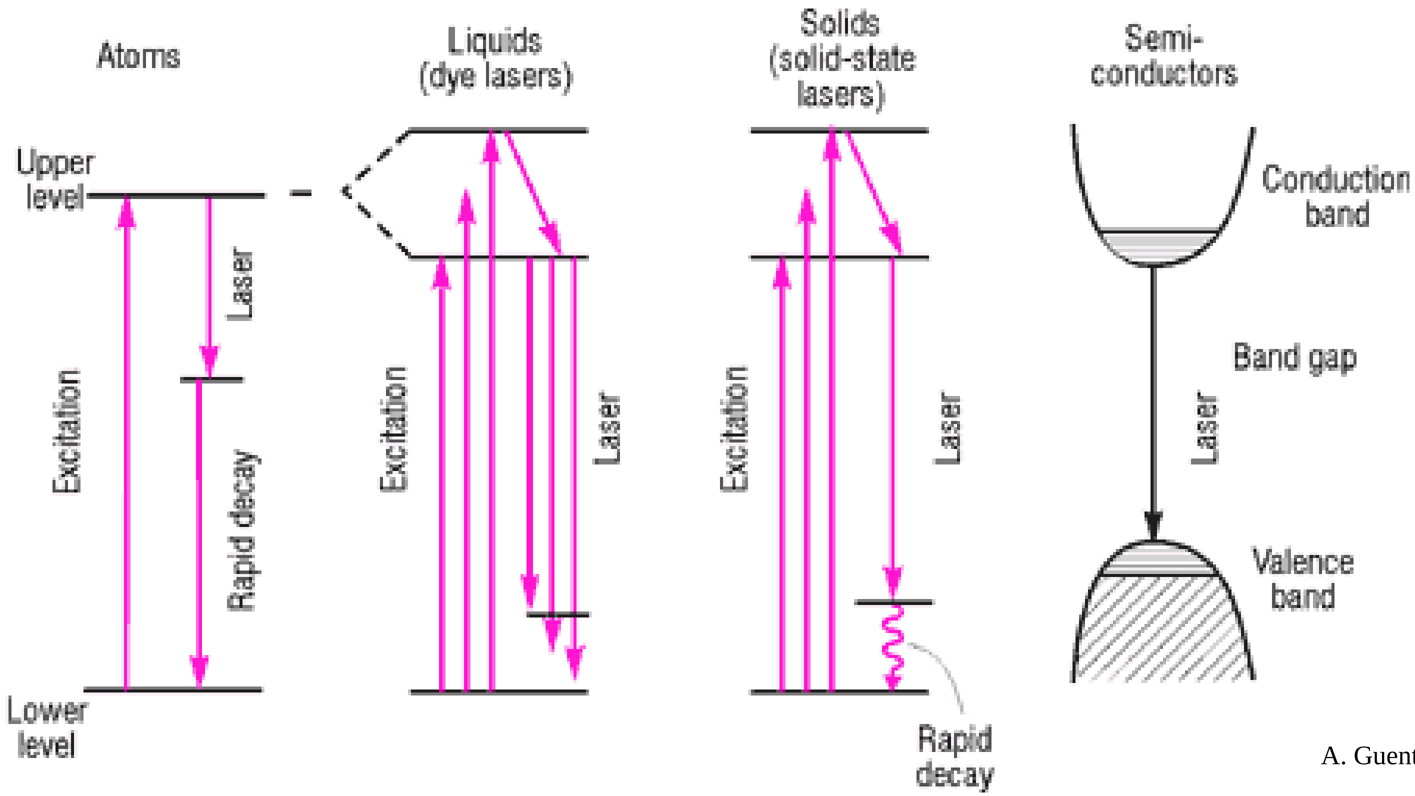
It is useful to describe the product of σ_{21} and ΔN_{21} as the small-signal-gain coefficient g_{21} or

$$g_{21} = \sigma_{21}\Delta N_{21}$$

$$I = I_0 e^{g_{21} L}$$

By considering the units of both σ_{21} (length^2) and ΔN_{21} (l/length^3) we can see that g_{21} has the units of 1/length. Hence, if σ_{21} is given in units of cm^2 and ΔN_{21} is given in units of (1/cm^3), g_{21} will be given in (1/cm), more commonly expressed as cm^{-1}. Values of the cross sections σ_{21} and ΔN_{21}, and the small-signal gain g_{21}

Population Inversion in lasing mediums



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Gas Laser

ATOM

•He-Ne (Helium-Neon)

Metal Vapor Lasers

•Cu (Copper) Vapor

•Au (Gold) Vapor

Ionized vapor Lasers

***He-Cd (Helium-Cadmium)**

MOLECULE

•CO_2 (Carbon Dioxide)

•N_2 (Nitrogen)

•Chemical (HF-DF)

•FIR - Far Infrared

•Excimer Laser

ION

•Ar+ (Argon ion)

•Kr+ (Krypton ion)

Population Inversion in gas laser

- Applied voltage produces an electric field accelerates the electrons within the gas.

- Excited electrons collide with the gas atoms and excite the atoms to excited energy levels, some of which serve as upper laser levels.

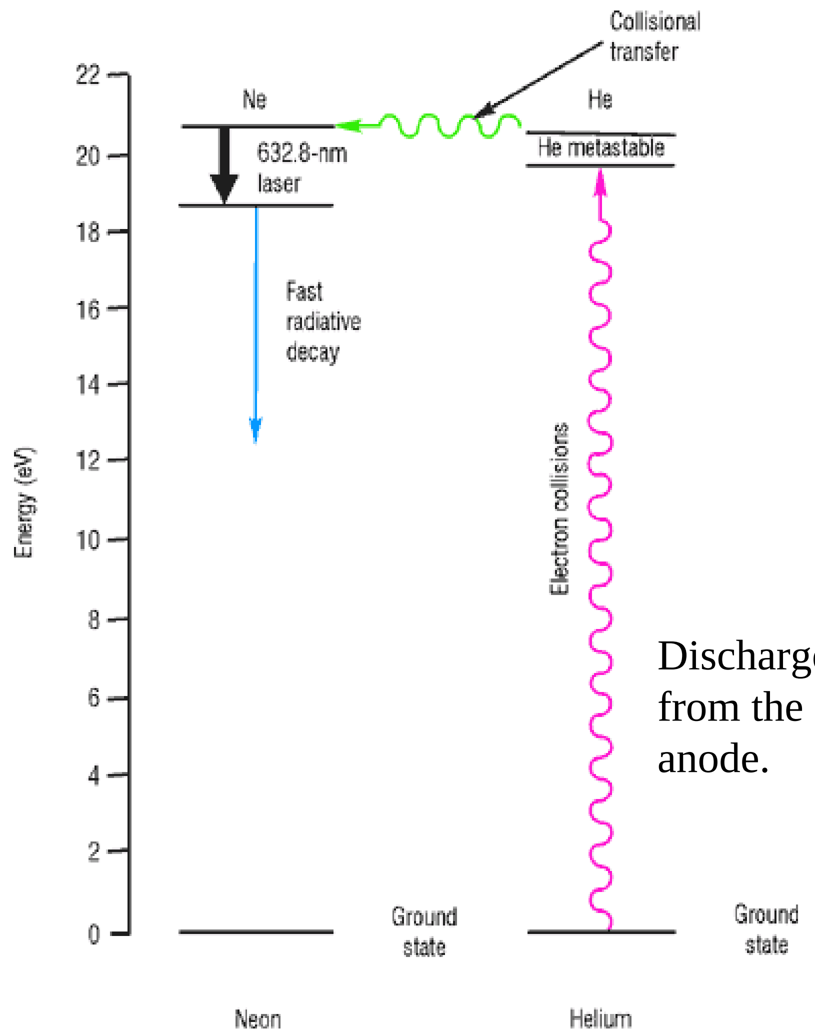
- Lower-lying levels, those to which higher-lying levels can transition, typically decay to the ground state faster than the higher-lying levels, thereby establishing a population inversion between some of the higher and lower levels.

- The laser light then occurs when the higher-lying levels decay to the lower levels while radiating photons at the wavelengths corresponding to the energy separation between the levels.

- In many instances the excitation is a two-step process in which the electrons
    * first excite a long-lived or metastable (storage) level or they ionize the atom, leaving an ion of that species and another electron. In either case, that level
    * then transfers its stored energy to the upper laser level via a subsequent collision with the laser species.

HeNe laser

The current pumps the helium atoms to an excited atomic state. The energy of the excited helium atoms is transferred to neon atoms through collisions, and the neon atoms then undergo a transition to a lower energy state that results in lasing.



Discharge electrons flowing from the cathode toward the anode.

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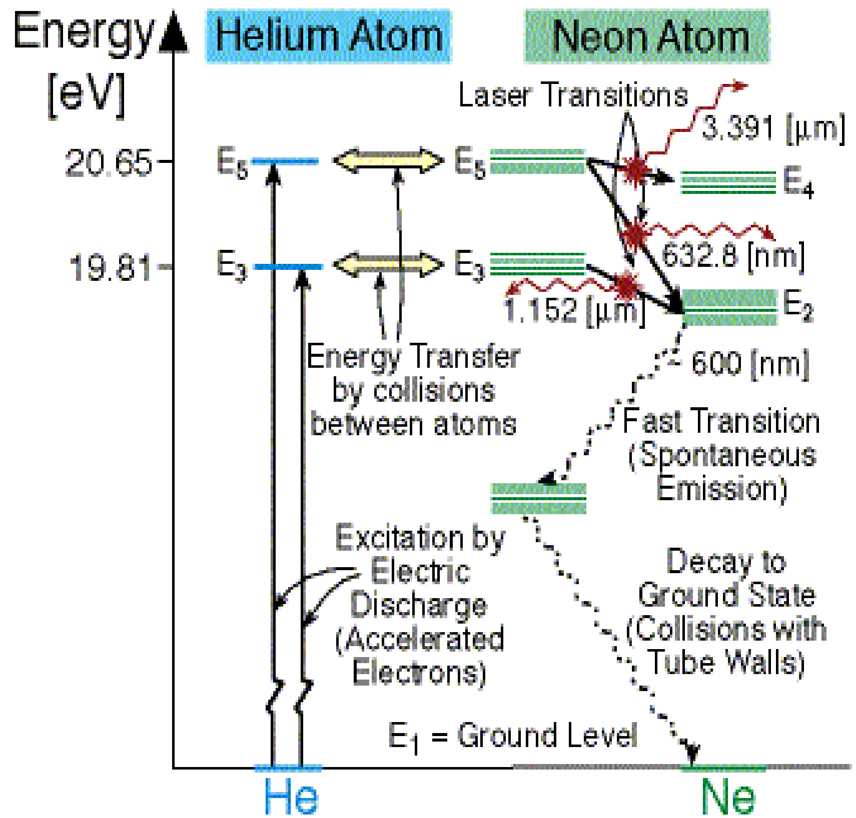
HeNe laser

It was first built in 1961 by Ali Javan. **The** **active medium** **is a noble gas Neon (Ne)**, and it is a **4 level laser**. Two **meta-stable energy levels** act as **upper laser levels.** The He-Ne laser have two lower laser levels, so quite a few wavelengths can come out of the transitions between these levels. **The important wavelengths are**: λ_1=0.6328 [μm] (632.8 [nm]), λ_2=1.152 [μm], λ_3=3.3913 [μm], λ_2=0.5435 [μm]



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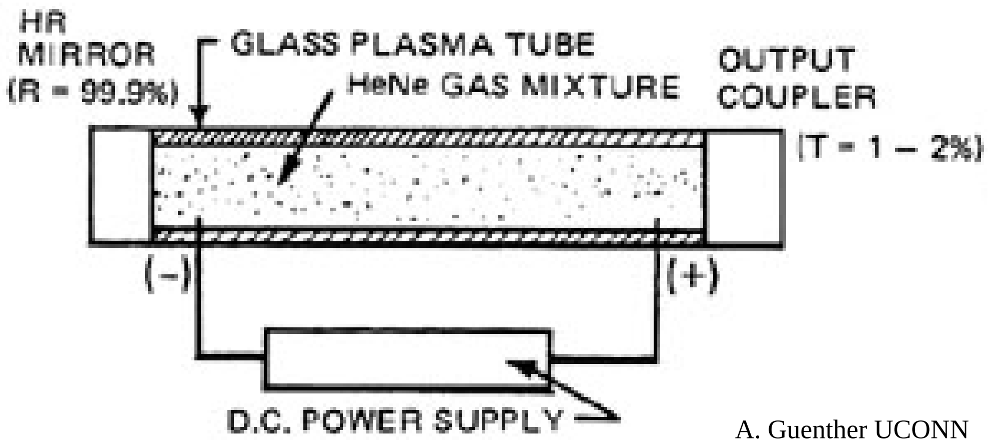
Rami Arieli: "The Laser Adventure" Chapter 6, Helium-Neon Lasers, page

Gas laser



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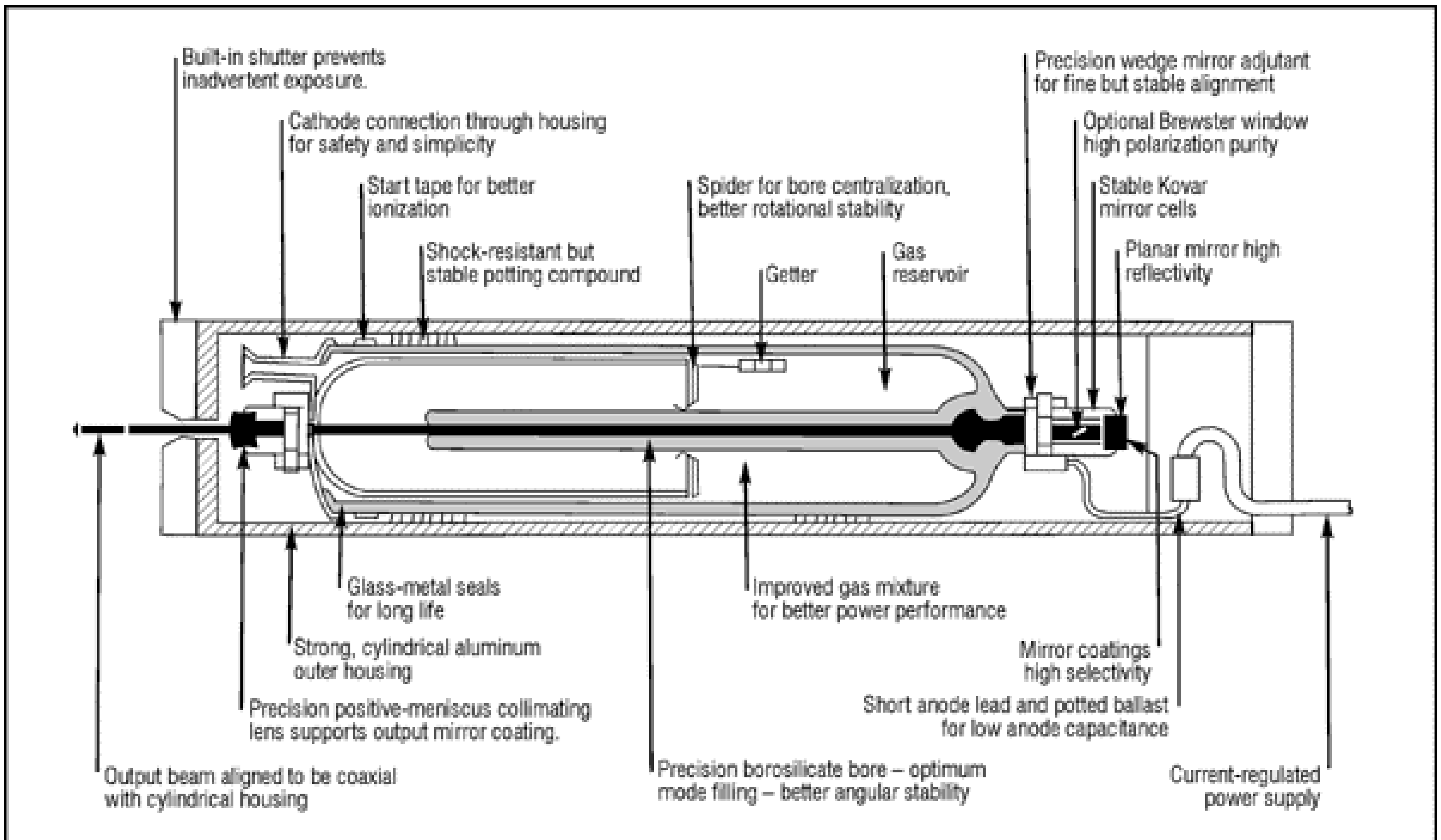
One popular type of gas laser contains a mixture of helium (He) and neon (Ne) gases and is illustrated in Figure. The gas mixture is contained at a low pressure within a sealed glass tube called the "plasma tube. The feedback mechanism consists of a pair of mirrors sealed to the ends of the plasma tube. One of these mirrors, the output coupler, transmits 1-2 percent of the light to form a continuous (CW) output beam.

Laser structure



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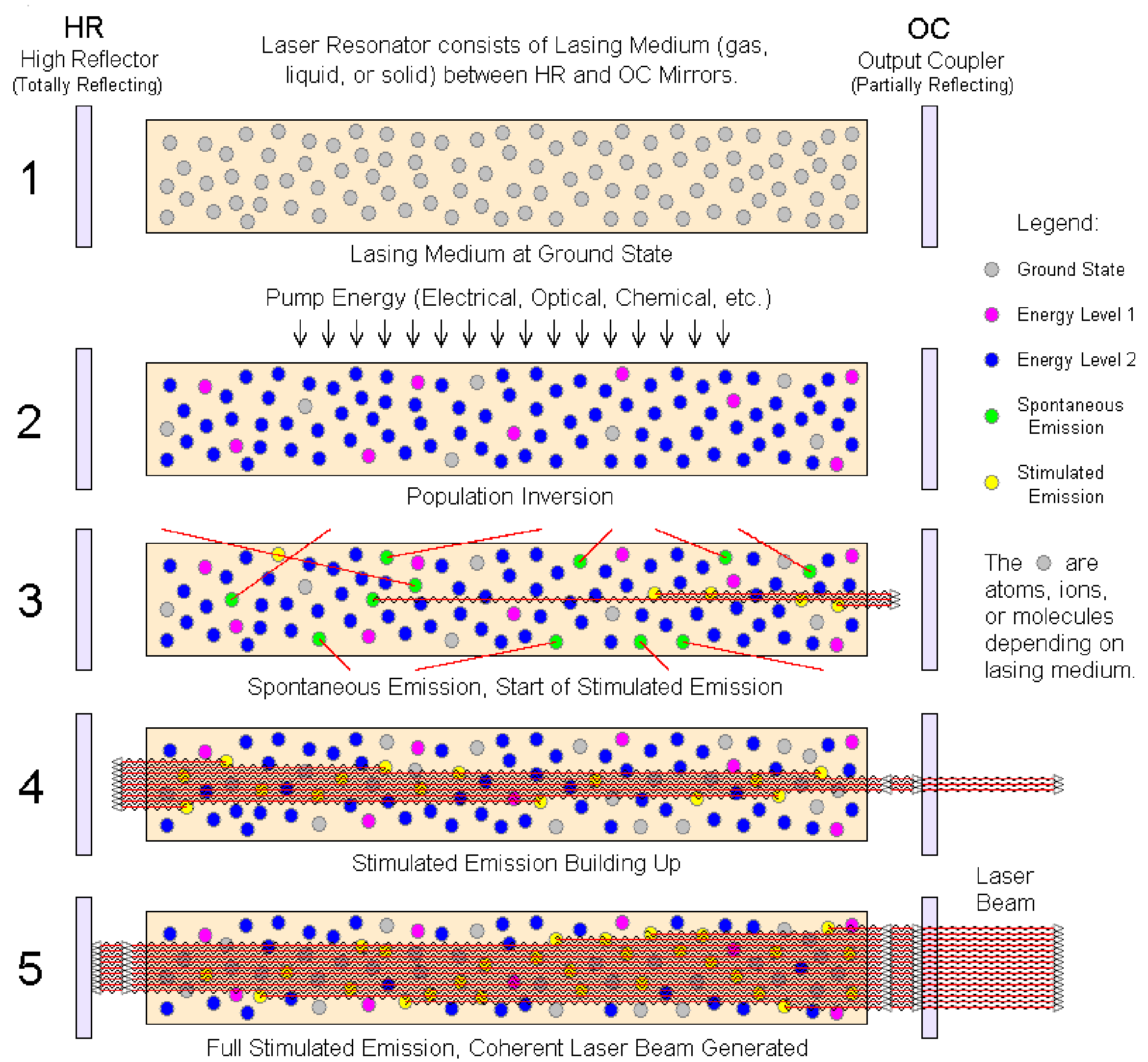

Basic Laser Operation

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Gain coefficient

For a laser in which the amplifier length has a value of *L* and the mirrors have identical reflectivities *R*, with no other losses in the cavity, the threshold condition for the gain coefficient *g* is given as

$$\boxed{g = \frac{1}{2L} \ln \frac{1}{R^2}}$$

which has dimensions of 1/length. Any value of *g* higher than above equation will produce a laser beam within the cavity. For a more complex laser cavity in which the mirrors have different reflectivities R_1 and R_2, and a_1 and a_2 represent other losses within the cavity (beyond the amplifier), the expression for the threshold gain *g* is given as

$$\boxed{g = \frac{1}{2L} \ln \left[\frac{1}{R_1 R_2 (1-a_1)(1-a_2)} \right] + \alpha}$$

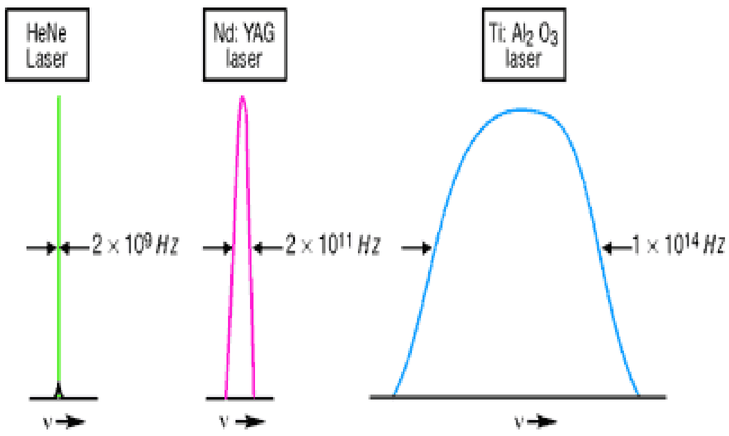
The term α represents a potential absorption loss within the amplifier itself, which is present in only a few types of lasers. It is a distributed loss expressed in the same units as *g* or (1/length). For example, in solid-state lasers it is termed excited state absorption.

Bandwidth of laser gain medium

The bandwidth of the laser gain medium determines the range of wavelengths over which amplification can occur for any specific laser. This bandwidth is expressed in either a wavelength range $\Delta\lambda_G$ or a frequency range Δv_G. These two expressions are related by

$$\boxed{\Delta\lambda_G = \frac{\lambda^2}{c}\Delta v_G}$$

in which λ is the laser wavelength and c is the speed of light. The bandwidth of the gain medium is usually determined by the bandwidth over which the spontaneous emission occurs for a given laser transition.



Laser gain bandwidths for the HeNe, Nd:YAG, and Ti:Al_2O_3 *lasers*

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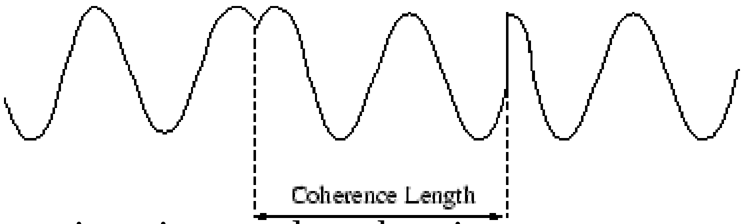
Coherence

For longitudinal or temporal coherence, the coherence length ℓ_C is related to the wavelength λ and the total frequency bandwidth of the laser $\Delta\lambda$ by

$$\boxed{\ell_c = \frac{\lambda^2}{\Delta\lambda}}$$



Note: $\Delta\lambda$ is the actual bandwidth of the laser beam given in wavelength units.

For transverse or spatial coherence, the transverse coherence length ℓ_t is related to the laser wavelength λ, the laser source diameter at its origin *s*, and the distance *r* the beam has propagated from its origin, by the following relationship.

$$\ell_t = \frac{r\lambda}{s}$$

Argon Ion Laser

The Argon laser was invented in 1964 by **William Bridges** at Hughes.
Argon ion laser contains a tube filled with Argon gas which transforms into **plasma** in an excited state.
(**Plasma** is a state of matter in which the electrons are separated from the atoms and molecules, which means that it contains free electrons and ions).

The two main laser transitions are at visible wavelengths:

Blue 0.488 [μm]

green 0.5145 [μm],

but the Argon ion laser emits also in the **UV spectrum**:

0.3511 [μm]

0.3638 [μm].

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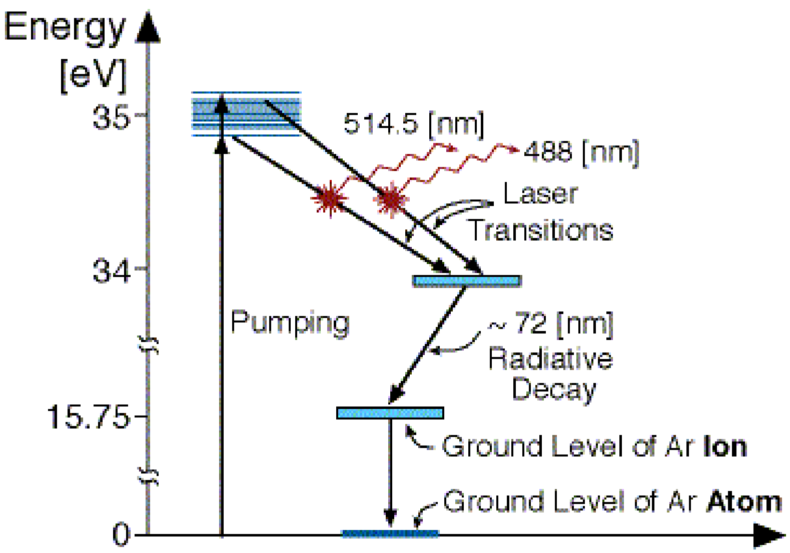


Energy Level Diagram of Ion Argon Laser.

Rami Arieli: "The Laser Adventure" Chapter 6, Ion Gas Lasers, page 1

Krypton Laser

The Krypton laser is very similar to the **Argon laser**, but its efficiency is lower.

This laser has many lines in the visible spectrum, especially in the **yellow to red** part of the spectrum.

The **maximum output power** in each line is about 100 [mW].

The main applications of this laser are in the **art and entertainment** business, to create **fantastic visual effects**.

Nitrogen Laser

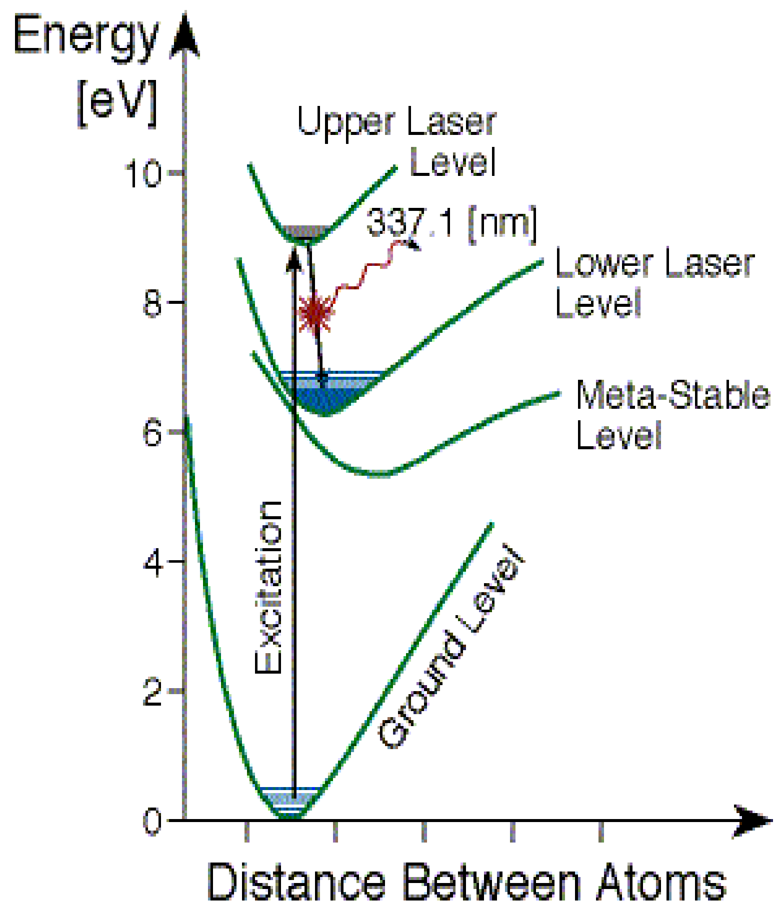
The Nitrogen laser was first developed in 1963 and has been sold as a commercial product since 1972.

Laser Action:

The active medium in Nitrogen lasers is Nitrogen gas at pressures of 20 [torr] up to 1 [At].

In some Nitrogen lasers the **gas flows** in the tube, while others have a **sealed tube**.

Like most gas lasers, the Nitrogen laser is based on **transitions between vibration energy levels**, and is electrically excited.

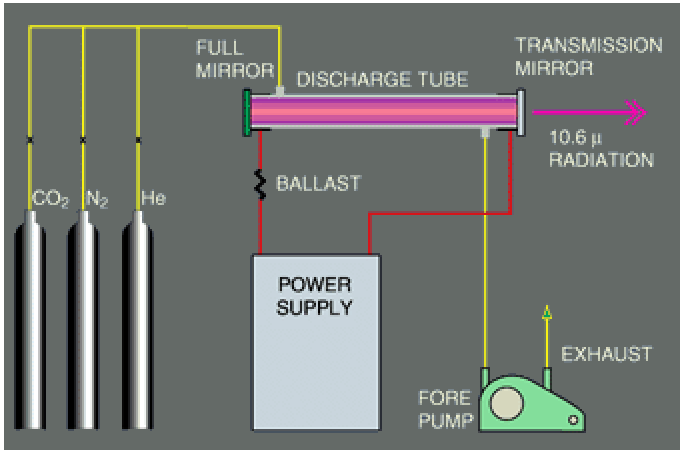


CO2 laser

Lasing action in a CO_2 molecule was first demonstrated by C. Patel in 1964. He transmitted an electric discharge pulse through pure CO_2 gas in a laser tube, and got a small laser output.

CO_2 is the gas in which the lasing process occurs, but other gas additives to the laser tube improve the total efficiency of the laser.
The standard CO_2 laser includes in the active medium a mixture of CO_2 with N_2 and He. The optimal proportion of these 3 gases in the mixture depends on the laser system and the excitation mechanism. In general, for a continuous wave laser the proportions are:

CO_2:N_2:He - 1:1:8



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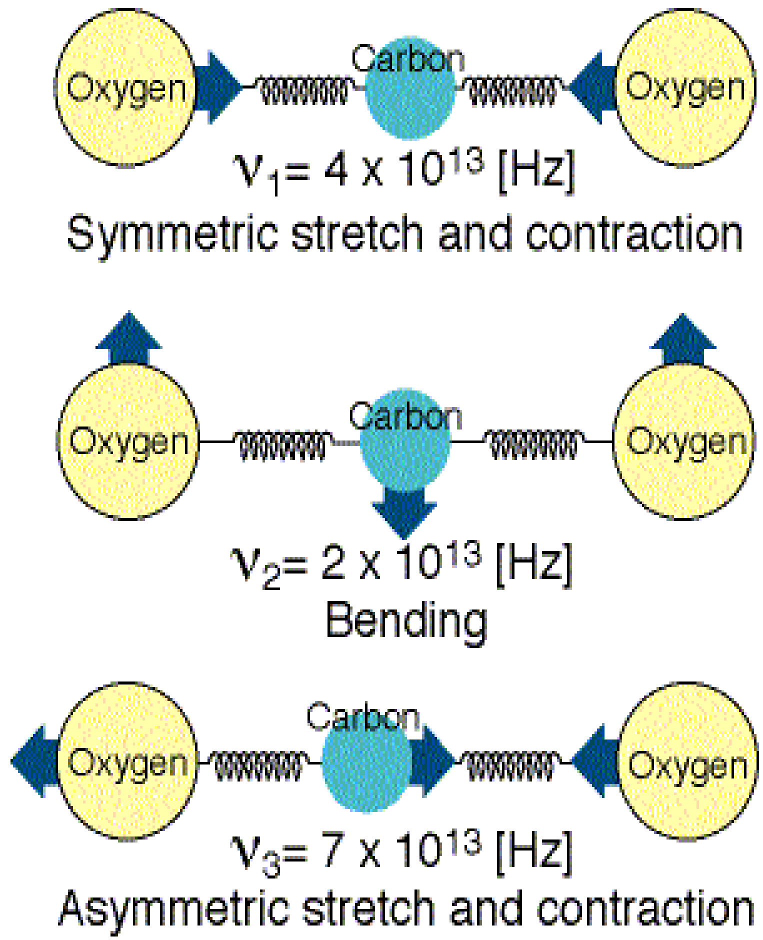
CO2 laser

CO_2 is a linear molecule, and the three atoms are situated on a straight line with the Carbon atom in the middle. **Three vibrational modes of CO_2 molecule** are illustrated:

1. Symmetric stretch mode (ν_1).
2. Bending mode (ν_2).
3. Asymmetric stretch mode (ν_3).



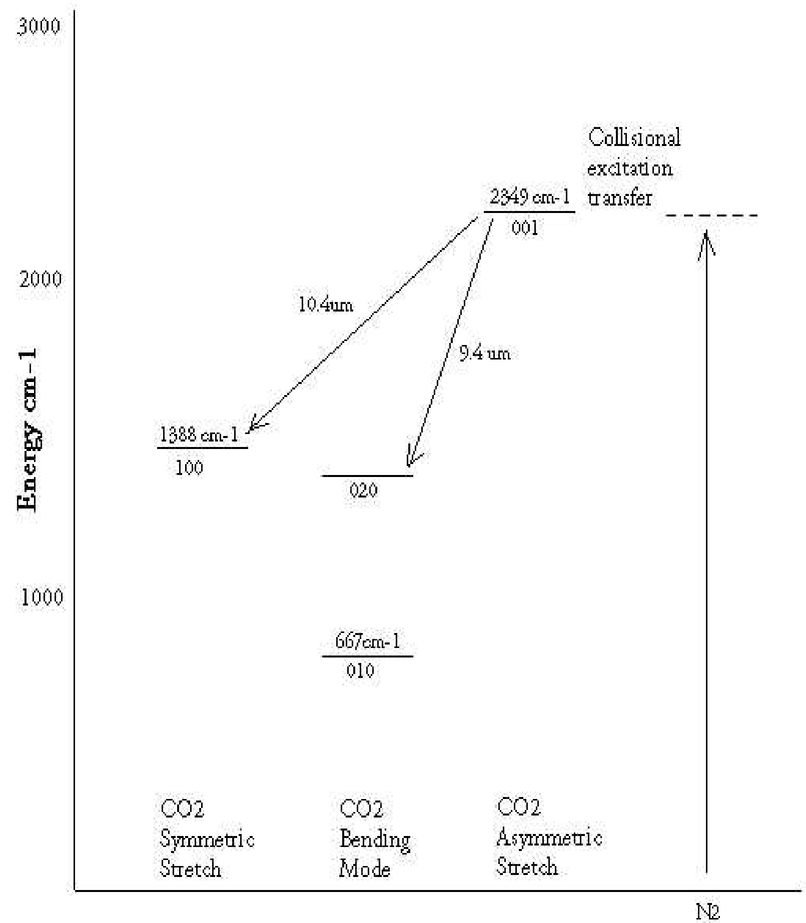
Rami Arieli: "The Laser Adventure" Chapter 6, Carbon Dioxide Lasers page 1

CO2 laser

Transitions between vibrational energy states/levels results in photon emission in the infrared, while transitions between rotational states emit photons in the microwave region.

Necessary mechanisms for operation of the CO2 laser are,

1. Excitation of N2 vibration by electron impact
2. Transfer of vibrational energy from N2 to the nearly resonant v3 mode of CO2
3. Laser transition from v_3 to v_1 mode.
4. Sharing of population between v_1 and $2v_2l$ modes and relaxation within the v_2 manifold
5. The vibrational energy in the v_2 manifold converted into translational energy by collisions with He.



http://www.phy.davidson.edu/StuHome/sethvc/Laser-Final/co2.htm

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Chemical Laser

The chemical laser is an example of a laser where the **pump energy** comes from a **chemical reaction** between two atoms.

The chemical laser is a member of the family of **Gas Dynamic Lasers:**

Gas dynamic lasers are based on **rapid expansion** of hot, high pressure gas, through nozzles into a near vacuum. This rapid expansion reduce the gas temperature.

As a result, since the transfer of the molecules to the ground state takes more than the time of rapid expansion, we get at low temperature many molecules at excited levels. Thus, "**population inversion**".

The gas usualy flow through the nozzles in a transverse flow (perpendicular to the optical axis of the laser), so many nozzles can operate at the same time, yielding **high power from the laser**.

The first chemical laser, which was operated in the pulsed mode, was developed in 1965 by J. V. V. Kasper, and G. C. Pimental.

The lasing action of the chemical laser is usually based on **vibrational transitions of diatomic molecule**.

Far Infra-Red (FIR) Lasers

Far Infra-Red (FIR) lasers emit radiation in the **Far-Infra-Red spectrum** (wavelength range 12-1000 [μm].

The wavelength range greater than 100 [μm] is sometimes called **sub-millimeter wave**.

Far Infra-Red (FIR) lasers are gas lasers, and their **lasing action occur between rotational levels of the gas molecules of the active medium**. Usually these transitions are within the same vibrational level.

The active medium in FIR lasers is usually a gas of simple organic molecule such as:

$$C_2H_4,\ CF_4,\ NH_3,$$

Because of the **very narrow width** of each energy level of these materials, it is inefficient to optically pump them with ordinary light sources.

The best way to achieve **population inversion** in these lasers is to **pump them with another laser** at shorter wavelength. Usually CO_2 laser is used for pumping.

Excimer Laser

There are lasers in which the required conditions for lasing are achieved in exotic ways.

As an example, we shall examine a family of lasers in which the radiation is emitted from a molecule which only exists for a very short time.

This molecule is composed of an atom of **noble gas**: Argon, Krypton or Xenon, and an atom of **halogen**: Fluorine, Chlorine, Bromine or Iodine.

An Excimer is **a molecule which has a bound state (existence) only in an excited state**.

In the ground state this molecule does not exist, and the atoms are separated.

The excited state exists for a very short time, less than 10 nanoseconds.

The name **Excimer** comes from the combination of the two words: ***exited dimer***, which means that the molecule is composed of two atoms, and exists only in an excited state.

(Some scientists consider this molecule to be a complex, and they call the laser "**Exiplex**").

Copper vapor laser (CVL)

This laser was attractive because of its **relative high efficiency (up to 1%) for lasers in the visible spectrum range, and the high pulse power achieved**.

Copper Vapor Laser Structure

Copper vapor laser is a gas laser, build as a tube with windows at both ends. The tube is filled with an inert gas and a small quantity of pure copper.

In order to have **copper vapor**, the metal needs to be at very high temperatures, so the tube is build from Alumina or Zirkonia, which are high temperature resistant materials.
The tube diameter is 10-80 [mm], and it contain Neon gas at a pressure of 25-50 [Torr].

Rami Arieli: "The Laser Adventure" Chapter 6, Metal Vapor Lasers, page 2

Helium-Cadmium Laser

Helium-Cadmium lasers can be categorized among either:

- Metal vapor lasers - Cadmium is a metal, the lasing action in Helium Cadmium laser occurs between energy levels of **Cadmium ions**, so the lasing medium **is ionized metal vapor**.
- Ion gas lasers - The properties of Helium-Cadmium laser are similar to those of Helium-Neon laser which is a neutral atom gas laser.

The He-Cd laser is a gas laser, and the metal Cadmium can be transform into the gas phase by heat.

The excitation to the upper laser level of the Cadmium atoms in the gas is similar to the excitation process of the Neon gas in a Helium-Neon laser: Helium atoms are excited by collisions with accelerated electrons, and than they pass their energies to Cadmium atoms by collisions.

Thus, the main application of the He-Cd laser is in the optics laboratory, for fabricating holographic gratings. (UV, 351nm)

Dye Laser

A **dye laser** can be considered as a special device to convert electromagnetic radiation from one wavelength, to another wavelength which can be tuned.

The output of a dye laser is always a **coherent radiation tunable over a specific spectrum region, determined by the Dye material**.

History:

Dye laser was first demonstrated in 1965 at IBM laboratories in the US, by **Peter P. Sorokin and J. R. Lankard**.

They discovered the dye laser action during a fluorescence research of organic dye molecules, which were excited by **Ruby laser**.

In 1967 scientists discovered the possibility to tune the emitted wavelength, using a grating at the end of the optical cavity

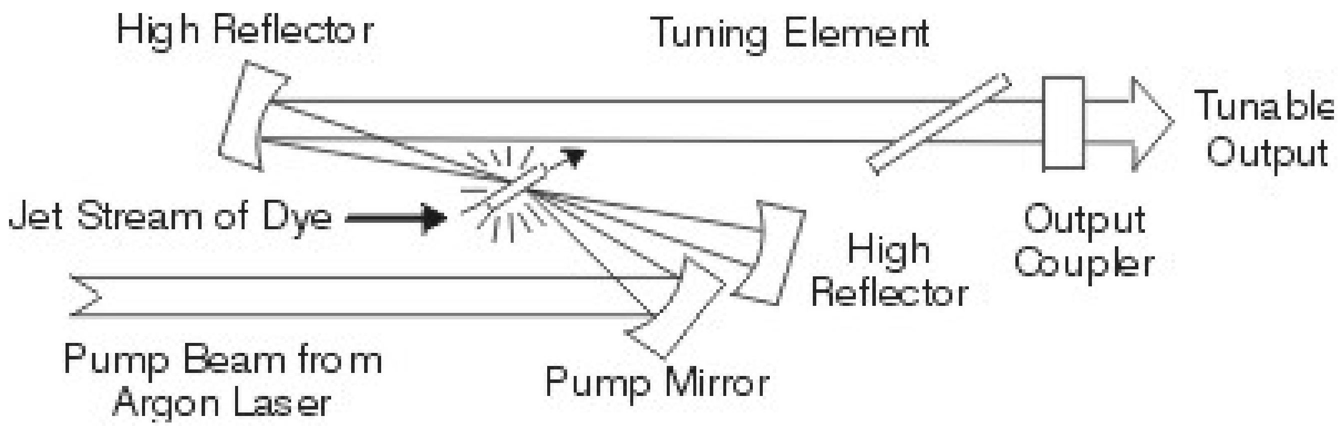
Population inversions in liquids

There are some molecules however, namely organic dye molecules, that do have a sufficiently long lifetime in an upper energy level (of the order of 1–5 nsec) so they can participate in the laser process by being excited to an upper laser level. These molecules also have the ability to radiate the energy from that level rather than lose the energy due to decay by collisions. Those molecules are the dyes that are used to color cloth and other objects that we use in our everyday life

When dissolved in a solvent such as alcohol or water, they can be concentrated in sufficient quantity to be used as a laser gain medium.

When the light is applied to the dye solution, it is absorbed at certain wavelengths by the dye as described by absorption equation, placing the dye molecules in highly excited upper laser levels. A population inversion is then produced between those levels and a very broad range of lower-lying energy levels, thereby allowing the possibility for a *wide range of laser wavelengths* to be produced within the gain medium. Those lower levels are not initially pumped by the light and therefore are sufficiently empty to produce the inversion. Dye lasers thus allow the possibility of wide wavelength *tunability* and have been used extensively in doing a variety of spectroscopic studies in which very specific laser wavelengths are desired.

Population inversions in liquids



A. Guenther UCONN

The pump source is an argon laser, whose beam is focused to a small spot. The argon laser is a gas laser which emits blue and green light. The dye flows in a high velocity jet with the argon laser beam focused on the jet. The wavelength of the output is adjusted by the tuning element. One of the most important features that dye lasers offer is tunability, that is, the color of the output beam can be varied by adjusting the intercavity tuning element and also by changing the type of dye that is used. The monochromatic output of available dye lasers can be tuned over a broad range, from the ultraviolet, to the near infrared.Liquid dye lasers that can be tuned to any visible wavelength, and to portions of the infrared and ultraviolet, are commercially available in both pulsed and continuous models. Dye lasers are chosen for applications, like spectroscopy, in which tunability is important.

Solid State Lasers

Insulator

- Ruby Laser
- Nd-Yag and Nd-Glass Lasers
- Color Center Laser
- Alexandrite Laser
- Ti - Saphire Laser

Semiconductor

- Laser Diodes

Population inversions in crystalline solids and glasses

As in the case of liquids, when energy levels in solids are excited, typically by irradiating those solids with light, the levels tend to decay much more rapidly via collisions with their surrounding neighbors rather than by radiating their energy in the form of light. In a few cases, however, specific types of atoms are embedded into a transparent host material (such as a specific crystalline solid or a glass) at concentrations of up to 1 part in 100, and the atoms radiate their energy rather than decay by collisions. These specific types of atoms, such as chromium or neodymium, consist of a radiating electron surrounded by a "screen" of other electrons that protect that radiating electron from being bombarded by collisions from neighboring atoms. The consequence is that the atoms can absorb pump light that passes through the transparent host medium and can then subsequently radiate that energy. Gemstones such as rubies fall into that category. Ruby, a desired gemstone and also the material that comprised the gain medium for the first laser, consists of chromium atoms doped into a transparent sapphire (Al_2O_3) host crystal. The color of the ruby crystal is determined by the chromium atoms, which absorb light in the blue and green regions of the spectrum and radiate in the red.

Ruby Laser

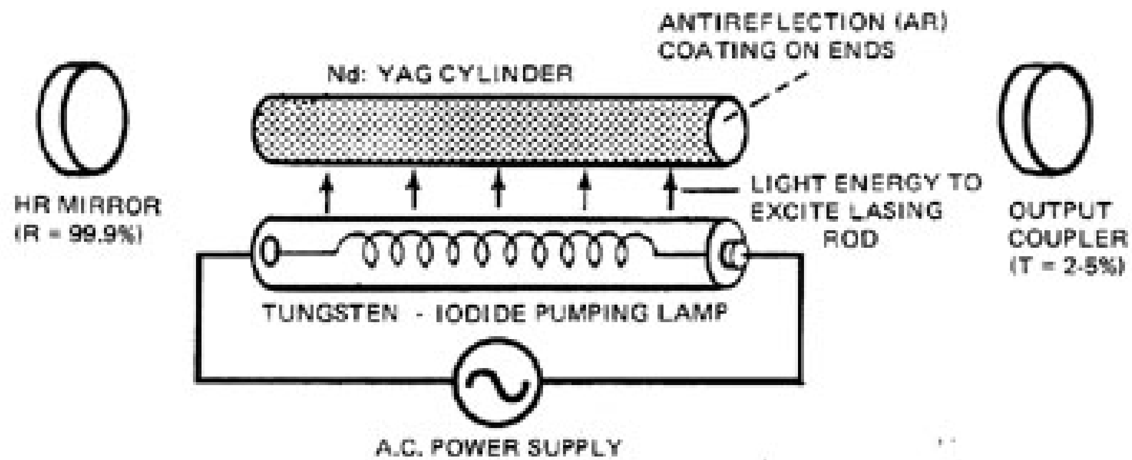
Ruby laser was the **first man made laser**, which was build by **Theodore Maiman in 1960**.

Ruby is a synthetic crystal of Aluminum Oxide (Al_2O_3), and is more familiar in daily life as a **precious stone** for jewel.

The chemical structure of Ruby is of **Al_2O_3** (which is called **Sapphire**), with impurity of about 0.05% (by weight) of Chromium Ions (Cr^{+3}).

The active ion is Cr^{+3}, which replace **Al** atom in the crystal. This ion causes the red color of the crystal. The impurity ion of Cr^{+3} is responsible for the energy levels which participate in the process of lasing.

SOLID CRYSTALLINE AND GLASS LASERS



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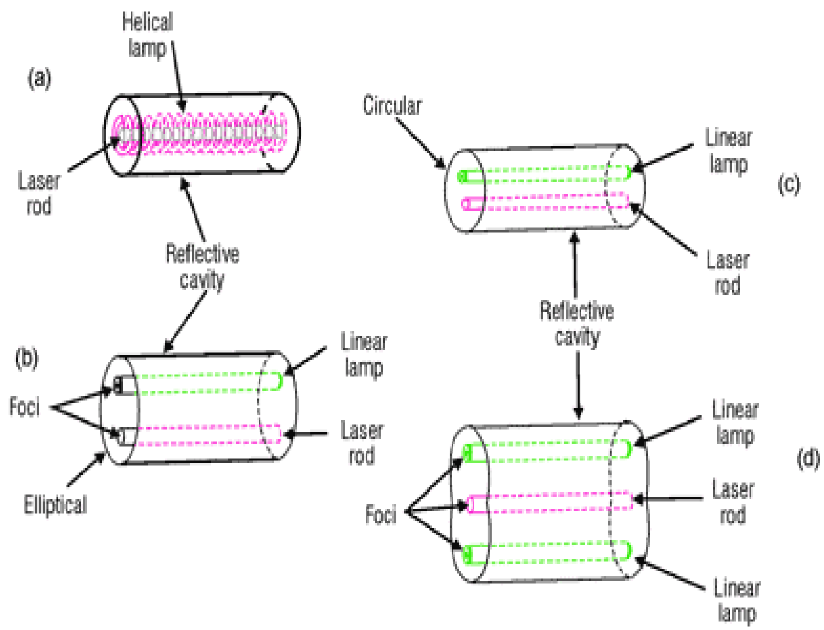
The active medium is a cylinder of laser crystal whose ends have been cut parallel and polished. Antireflection coatings have been applied to the rod ends to reduce losses. The excitation mechanism for this particular laser is a <u>tungsten filament lamp attached to an ac power source</u>. Larger models utilize do <u>krypton arc</u> (gas discharge) lamps as pumping sources. Both types of lamps provide continuous optical pumping to the laser crystal. The mirrors of the Nd:YAG (yttrium-aluminum-garnet) laser usually are mounted separately from the active medium as shown, but one of the mirror coatings sometimes is applied directly to one end of the rod.

Pump Sources



The most common types of flashlamps used for pumping lasers are narrow, cylindrical quartz tubes with metal electrodes mounted on the ends, filled with a gaseous species such as xenon that serves as the radiating material within the lamp. Xenon is the most common species because of both its radiating efficiency and its emission of a broad spectrum of wavelengths from which to choose in matching the lamp emission to the pumping absorption bands of the laser.

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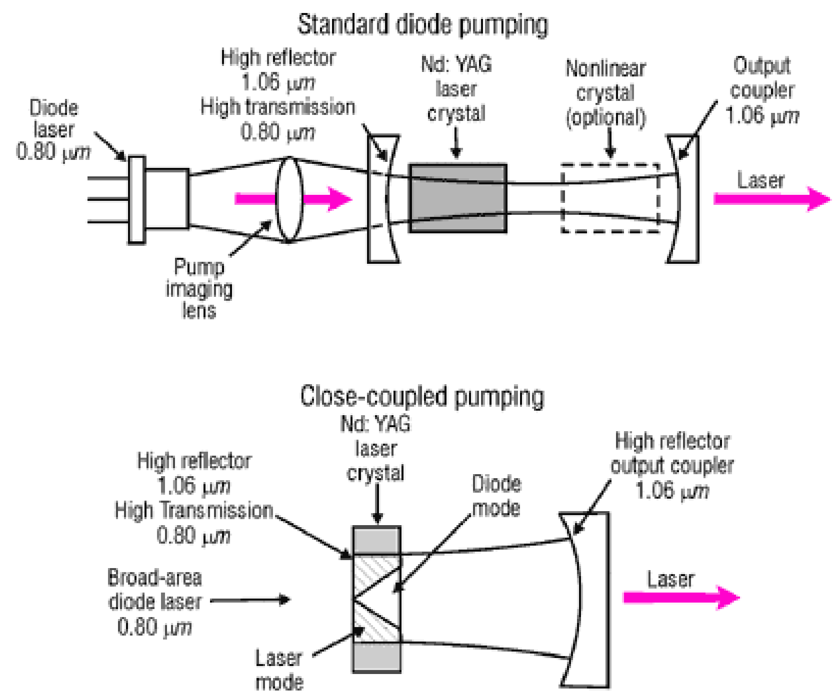

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Pumping lasers include the argon ion or doubled Nd:YAG cw lasers for pumping titanium-sapphire lasers, excimer lasers for pumping dye lasers, and gallium arsenide semiconductor lasers for pumping Nd:YAG lasers.

Nd Laser

In Nd laser **Nd^{+3} ions** (as impurities of up to a few percent by weight) are replacing the atoms of the solid host in the active medium.

Three **known solid hosts** are used for Nd-YAG laser where Nd^{+3} ions are added as impurities:

- **Glass**.
- **YAG (Yttrium Aluminum Garnet)** Crystal.
- **YLF ($LiYF_4$)** Crystal.

The choice between the three possible hosts is according to the intended use of the laser:

- **Glass** is used as the host material when a **pulsed laser** is needed, with each pulse at high power, and the pulse repetition rate is slow.

  The active medium of Nd-Glass Laser can be manufactured in a shape of **disk or rod**, with diameters of up to 0.5 meter (!) and length of up to several meters (!). Such dimensions are possible because glass is isotropic material, cheap, and can be easily worked to the right shape.

  High percentage (up to about 6%) of Nd ions can be added to glass as impurity.

  The **problem** with glass as a host is its **poor thermal conductivity**. Thus cooling the laser when it operates continuously or at high repetition rate is difficult.

- **YAG crystal** is used for **high repetition rate pulses** (more than one pulse per second). In this case a large amount of heat need to be transferred away from the laser, and **the thermal conductivity of the YAG crystal is much higher than that of glass.**
- YAG crystal with the high quality needed for lasers can be made with diameters of 2-15 [mm] and at lengths of 2-30 [cm].
- **<u>The price of a YAG laser rod is high, since growing crystals is a slow and complicated process</u>**.
- The percentage of Nd ions in the YAG host is 1-4% by weight.

Erbium fiber

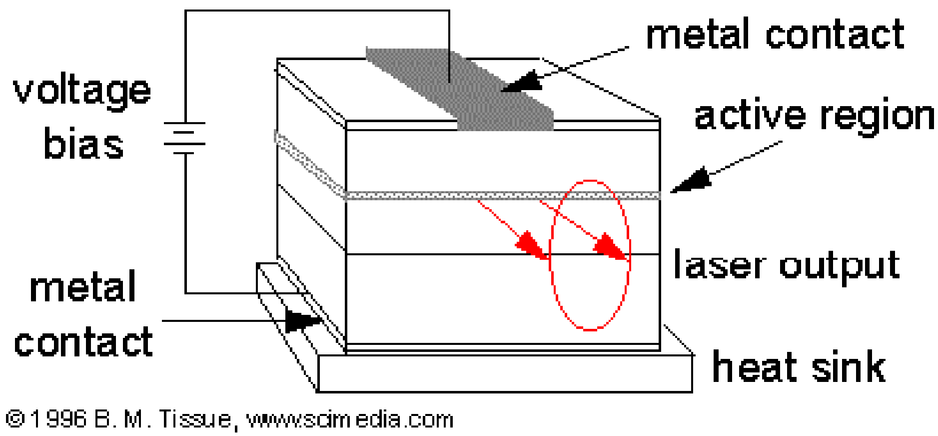
Fiber lasers were first operated in Nd-doped glass fibers, but the fiber laser of major current interest is the erbium-doped fiber laser operating at 1.4 to 1.6 μm. This fiber laser can be spliced into a normal transmitting optical fiber, and, when optically pumped with a semiconductor laser at either 980 nm or 1.48 μm, it provides amplification to a communication signal that is being transmitted through the fiber. The pump light is fed into the fiber line—with a beam-combining device—thereby merging with the signal. This laser amplifier is especially useful in undersea optical fiber cables transmitting phone and data information between continents.

Erbium Fibre Amplifier
Courtesy E-Bay

Population inversions in semiconductors

Inversions in semiconductors are produced when joining a *p*-doped semiconductor material with an *n*-doped semiconductor material in a similar way to that of producing a transistor to create a *pn* junction. The *n*-doped material contains an excess of electrons and the *p*-doped material has an excess of holes (a material with excess positive charge). When a voltage is applied across the junction, with the positive voltage on the *p* side, the electrons are pulled through the junction toward the positive electrode and the holes are attracted to the negative side, producing an electrical current flow across the junction. The electrons and holes meet within the junction and are attracted to each other because of opposite charges. When they meet, they recombine and emit radiation and also can produce a population inversion. <u>This inversion occurs between energy levels located above and below the semiconductor bandgap, the gap in energy below which the material is transparent.</u> <u>This energy typically corresponds to a wavelength in the infrared, and hence most semiconductors radiate in the infrared and are not transparent in the visible spectral region like glass is</u>. However, semiconductor lasers are under development to operate in the green and blue regions of the spectrum. <u>At very low currents, a population inversion does not occur even though recombination radiation is emitted. In fact, such nonlaser-like emission is the source of radiation from a light-emitting diode (LED).</u> In comparision, to produce a population inversion, a very high current density is applied within the junction region. However, this high current density leads to excessive heat deposition in the material; therefore a significant part of the development of semiconductor lasers involves how to remove the heat, or to make smaller junctions so that less current is required. The material and its corresponding energy bandgap determine the laser wavelength.

Semiconductor Lasers



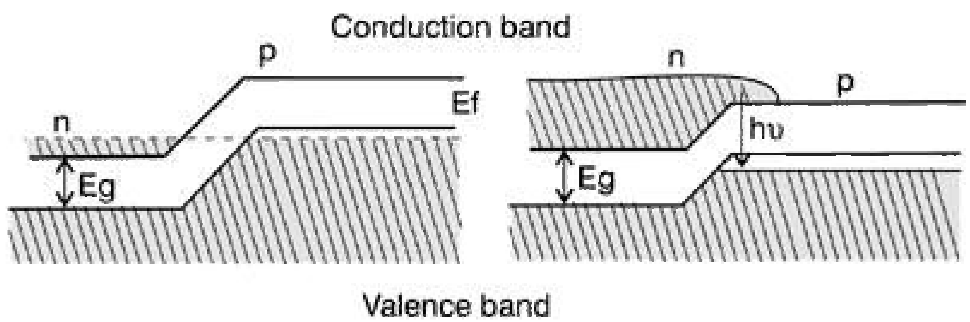
Semiconductor lasers are light-emitting diodes within a resonator cavity that is formed either on the surfaces of the diode or externally. An electric current passing through the diode produces light emission when electrons and holes recombine at the p-n junction. Because of the small size of the active medium, the laser output is very divergent and requires special optics to produce a good beam shape. These lasers are used in optical-fiber communications, CD players, and in high-resolution molecular spectroscopy in the near-infrared. Diode laser arrays can replace flashlamps to efficiently pump solid-state lasers. Diode lasers are tunable over a narrow range and different semiconductor materials are used to make lasers at 680, 800, 1300, and 1500 nm.

Semiconductor Lasers

Semiconductor lasers are quite different from conventional lasers. In particular:

1. **The gain of the laser material is very high and is generated by a population inversion between the conduction and valence bands of the semiconductors. In some sense, a semiconductor laser is a two-state laser system.**
2. **Since the electromagnetic mode is on the order of the size of the laser device, then the transverse mode of the semiconductor laser is quite different from that of a conventional laser. In particular, the beam is *not Gaussian*, the beam profile tends to be elliptical, and the beam divergence tend to be large.**
3. **The gain spectrum is quite large (many THz or hundreds of angstroms).**
4. **The short cavity (several hundred microns) means that the longitudinal mode spacing is much larger than that of a conventional gas or solid state laser (on the order of GHz or angstroms).**

Semiconductor Lasers

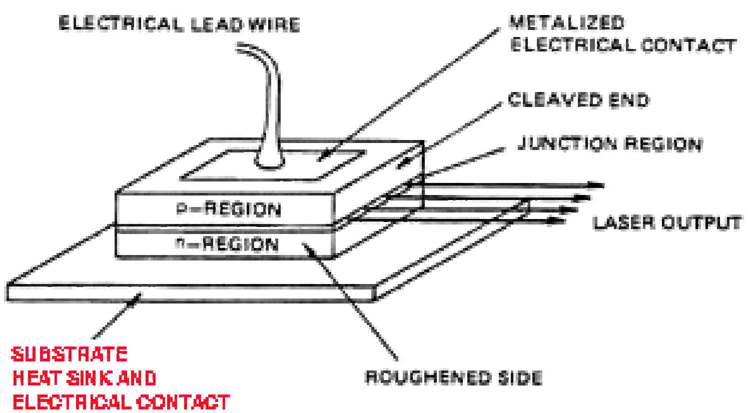


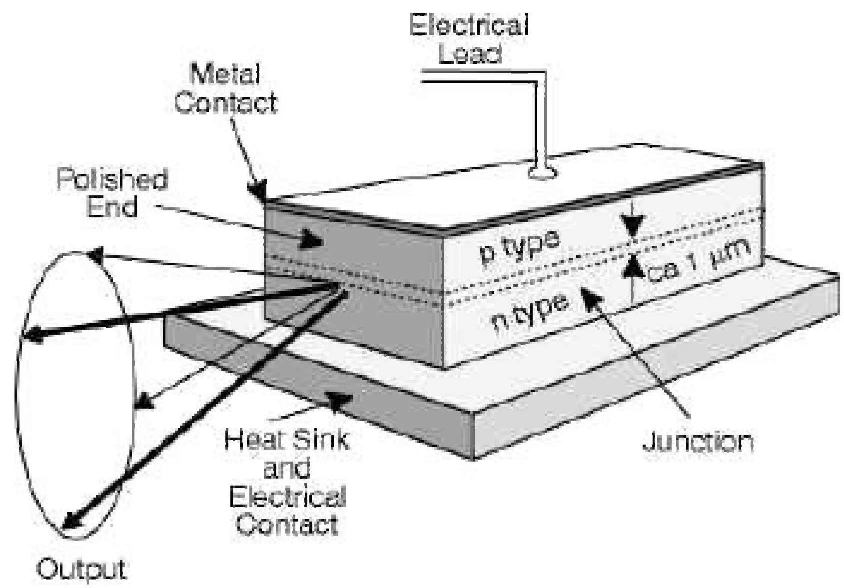
Band structure near a semiconductor p-n junction.
Left: No forward-bias voltage. Right: Forward-bias voltage present

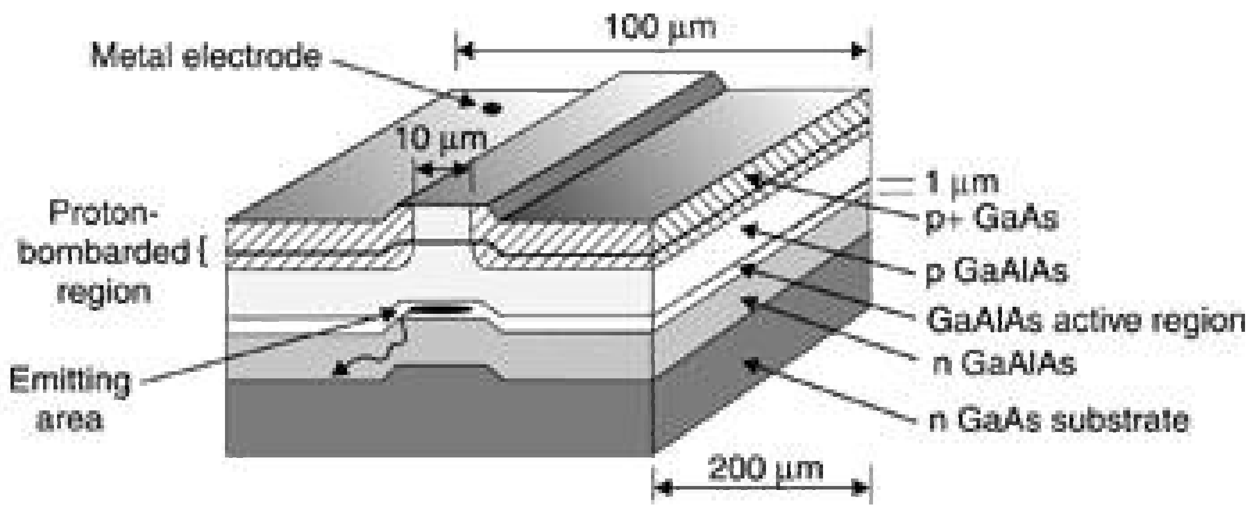
shows the relative populations of the energy bands or both sides of a p-n junction with no voltage applied to the diode. The n-type material contains electrons which behave as the current carriers in its conduction band, whereas the p-type material has holes for carriers in its valence band. When a forward voltage is applied to the diode, the energy levels are caused to shift. Under these conditions there is a significant increase in the concentration of electrons in the conduction band near the junction on the n-side and the concentration of holes in the valence band near the junction on the p-side.

The electrons and holes recombine and energy is given off in the form of photons. The energy of the photon resulting from this recombination is equal to that associated with the energy gap. In light-emitting diodes (LED) this light energy is transmitted out through the sides of the junction region. For the LED, all of the light is created by spontaneous emission due to electron and hole recombination. <u>In semiconductor lasers the junction forms the active medium, and the reflective ends of the laser material provide feedback. Because of this feedback in diode lasers, most of the light is created by stimulated emission.</u>

Simplest (and earliest) type of gallium arsenide laser







Modern diode lasers are formed of structures that contain several thin layers of material of varying composition.

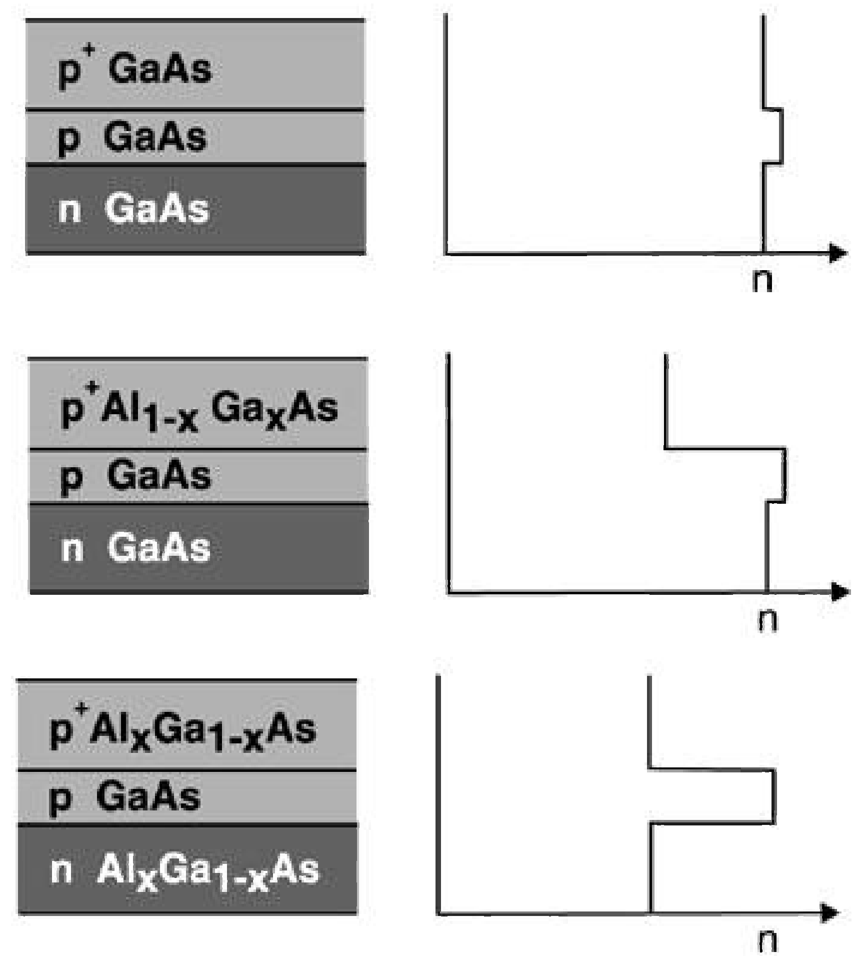
Homojunction diode lasers

Structure and index of refraction
for various types of junction
in the aluminum gallium arsenide
system.

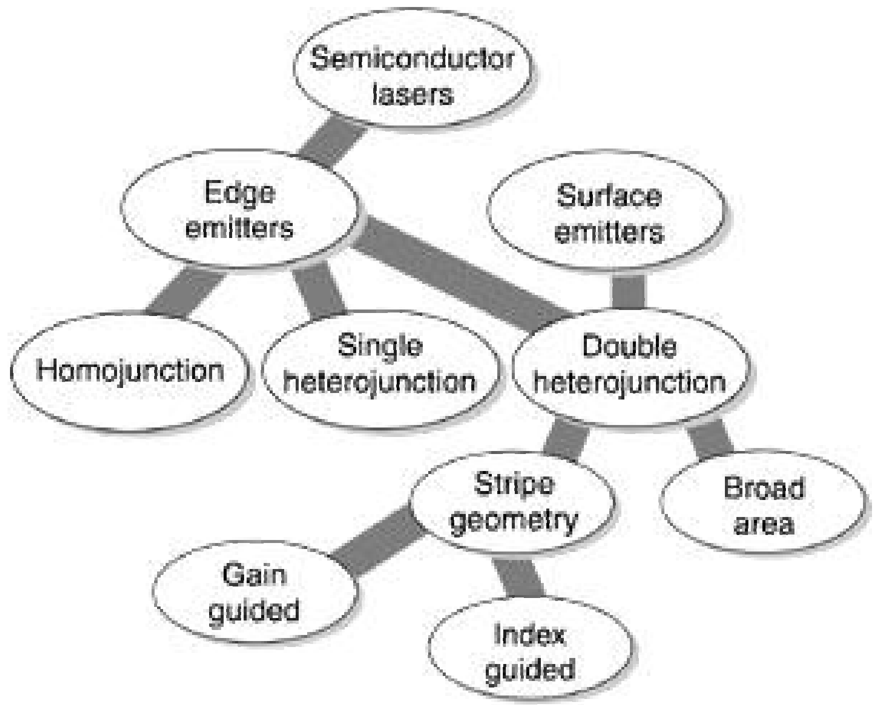
Top: Homojunction.

Middle: Single heterojunction.

Bottom: Double heterojunction

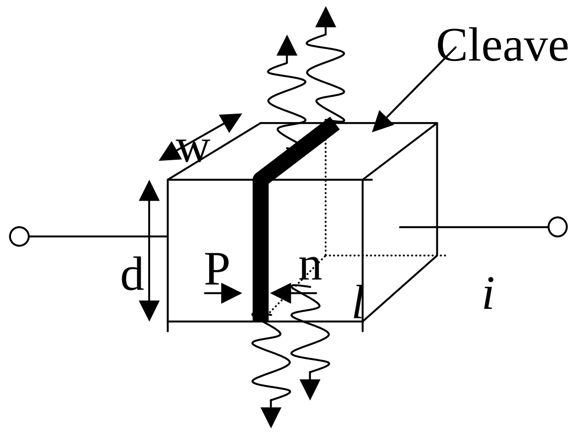


a simplified classification scheme showing some of the major subdivisions of diode lasers and their relationship



Amplification

A semiconductor laser amplifier is a forward bias heavily doped p-n junction fabrited From a direct gap semiconductor materials. The injected current is sufficiently large To provide optical gain. The gain coefficient ro(v) of the laser amplifier has a peak value Rp that is approximately proportional to the injected carrier concentration, which In turn, proportional to the injected current density J



$$r_p \sim \alpha(J/Jt - 1), \quad Jt = \Delta n_T el/\eta_{int}\tau_r$$

Where τ_r = electron-hole recombination lifetime

$\eta_{in} = \tau/\tau_r$ is the internal quantum efficiency

l = thickness of the active region

α = thermal equilibrium absorption coefficient

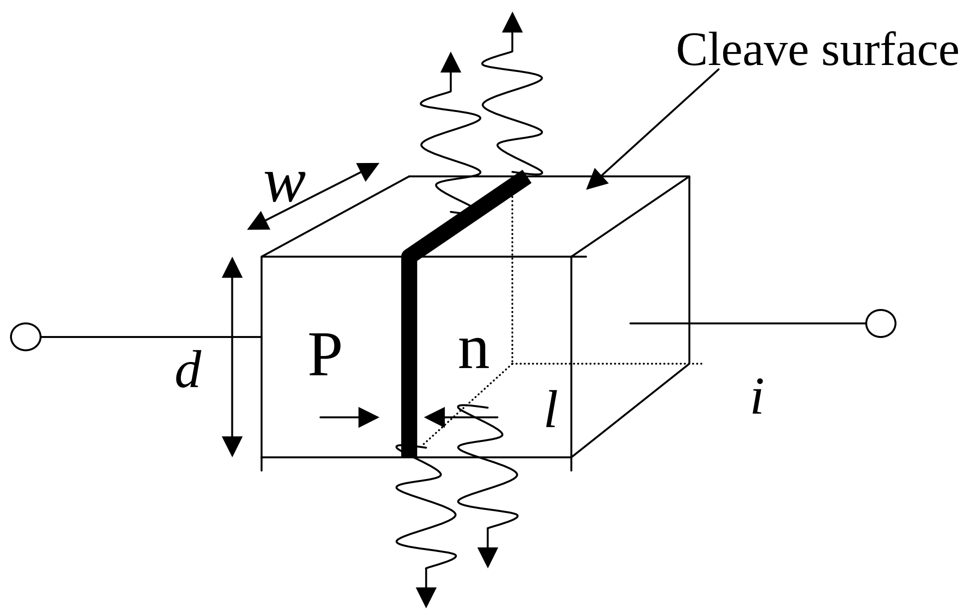
Δn_T *and* J_t are injected-carrier concentration and current density just to make the semiconductor transparent.

Feedback

The feedback is usually obtained by cleaving the crystal planes normal to the Plane of the junction, or by polishing two parallel surfaces of the crystal. The active region serves as a planar-mirror optical resonator of length d And cross-sectional area lw. The reflectance at the Semiconductor-air interface is

$$R = (n-1/n+1)^2$$

For GaAs, $n=3.6$ and $R=0.32$



Resonator Losses

The principle source of resonator loss arises from the partial reflection at the surfaces of the crystal. For a resonator of length d the reflection loss coefficient is

$$\alpha_m = \alpha_{m1} + \alpha_{m2} = (1/2d)ln(1/R_1R_2)$$

If two surfaces have the same reflectance $R_1=R_2=R$, *then* $a_m= (1/d)ln(1/R)$.

Include confinement factor Γ which represents the fraction of the optical Energy lying within the active region *(l), the total loss*

$$\alpha_r = 1/\Gamma(\alpha_s + \alpha_m)$$

Where α_s represents other sources of loss including free carrier absorption in and scattering from optical inhomogeneities.

Gain Condition: Laser threshold

The laser oscillation condition is the gain exceed the loss, $r_p > \alpha_r$, as discussed in the earlier section. The threshold gain coefficient is therefore α_r. Set $J = J_t$ and $r_p = a_r$, the threshold injected current density J_t is

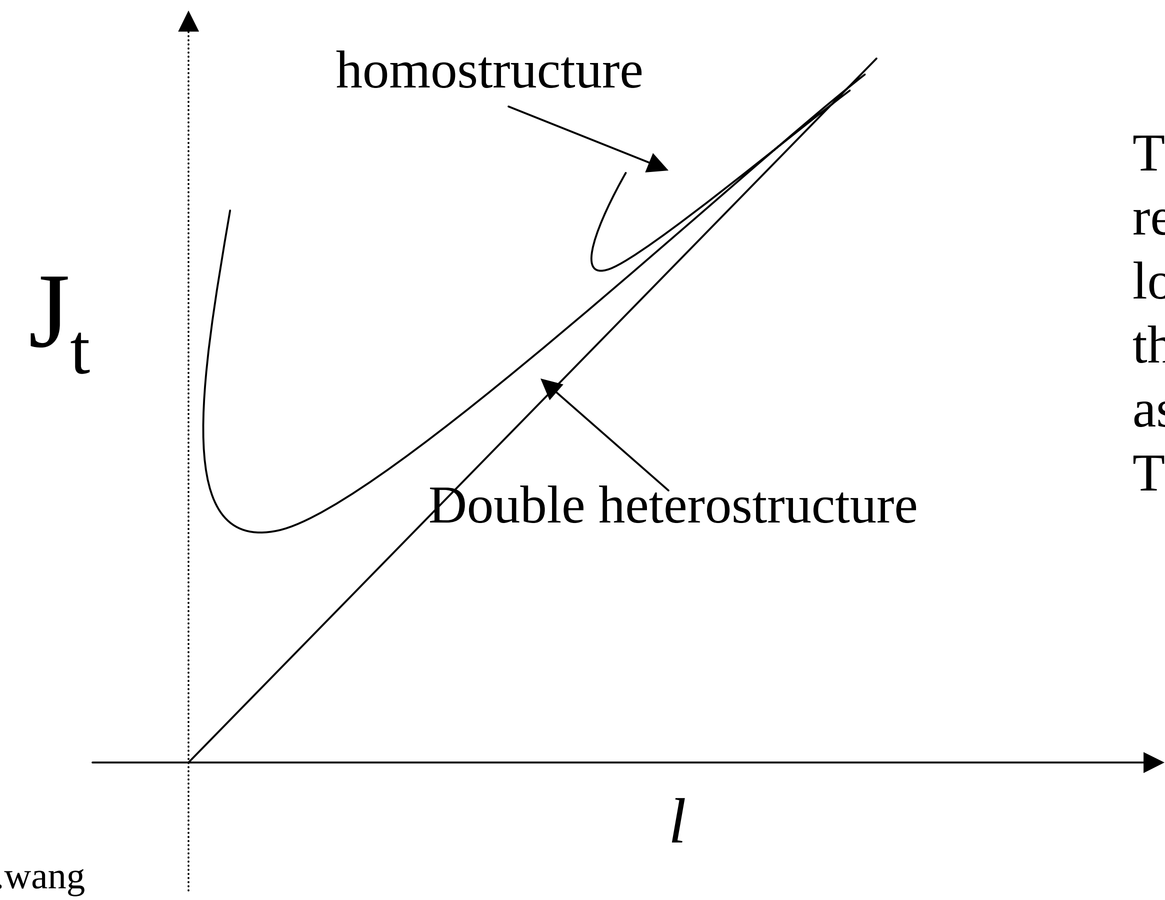
$$J_t = J_T(\alpha_r + \alpha)/\alpha \quad or \quad I = JA$$

Where the transparency current density,

$$J_T = el\Delta n_T/(\eta_\iota \tau_r) \quad or \quad i_T = J_T A; A = wd$$

Smaller J_t indicates superior performance, maximize η_ι and minimize $\alpha_{r,}$ minimize transparent injected-carrier concentration Δn_T and $_{l.}$ however, l is reduced beyonda point the $\alpha_{r,}$ increases because the confinement factor Γ

Gain Condition (Laser Threshold)



The confinement factor remains near 1 for lower values *l* because the active layer behaves as an optical waveguide The result is a lower J_t

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Internal Photon Flux

When laser current density is increased above its threshold value ($J > J_t$), the amplifier peak gain γ_p exceeds loss coefficient α_r. Stimulated emission then outweights absorption and other Resonator losses so oscillation begin and the photon flux increases

$$\Phi = \eta_{int}\,(i\text{-}it)/e \quad , \; i > i_t \text{ (steady-state laser internal photon flux)}$$

$$= 0 \qquad , \; i \leq i_t$$

Photons per second generated within the active region

The internal laser power above threshold is simply related to the internal photon flux by $P=h\nu\,\Phi$
So we have

$$P = 1.24\ \eta_{int}\ (i\text{-}it)/\lambda_o$$

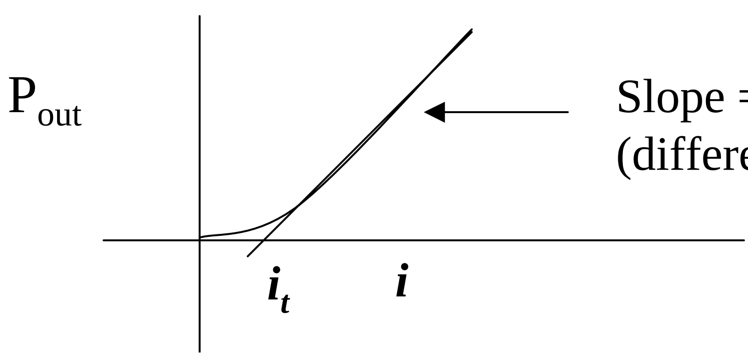
Output Flux and Efficiency

The output flux is the product of internal flux and emission efficiency , which is the ratio of the loss associated with the useful light transmitted through the mirrors to the total resonator loss $\eta_e = \alpha_m / \alpha_r = \alpha_{m1} + \alpha_{m2} = [(1/2d)\ln(1/R_1R_2)]/\alpha$

$$\Phi_{o\upsilon\tau} = \eta_e\eta_{\mathrm{int}}\ (i\text{-}it)/e$$

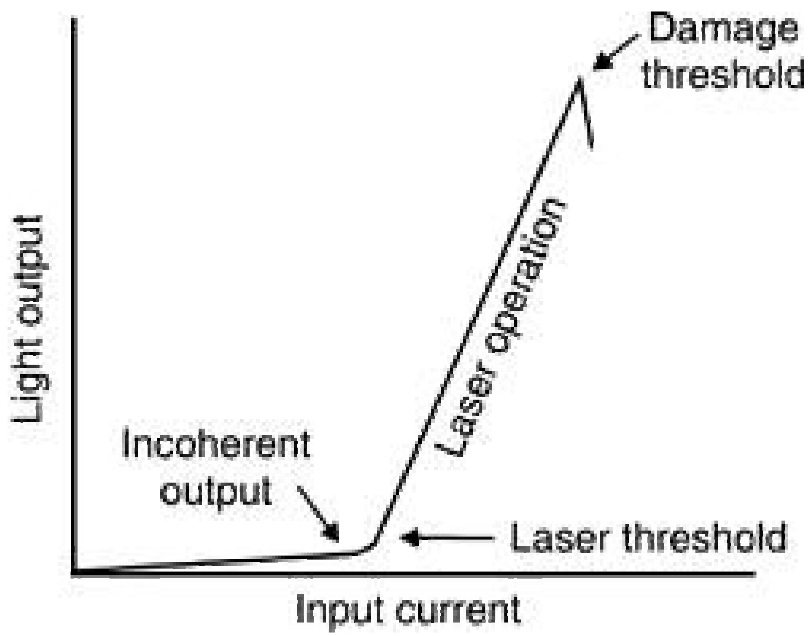
The laser output power above threshold is

$$P_{out} = 1.24\eta_d\ (i\text{-}it)/\lambda_o\ ,\ \eta_d\ =\ \eta_e\eta_{\mathrm{in}}\ \text{(differential quantum efficiency)}$$



Slope = $dP_{out}/di = 1.24\eta_d/\lambda_o$
(differential responsivity)

Output Characteristics



At low values of the input, the device acts as a light-emitting diode (LED), producing a relatively small amount of incoherent light.

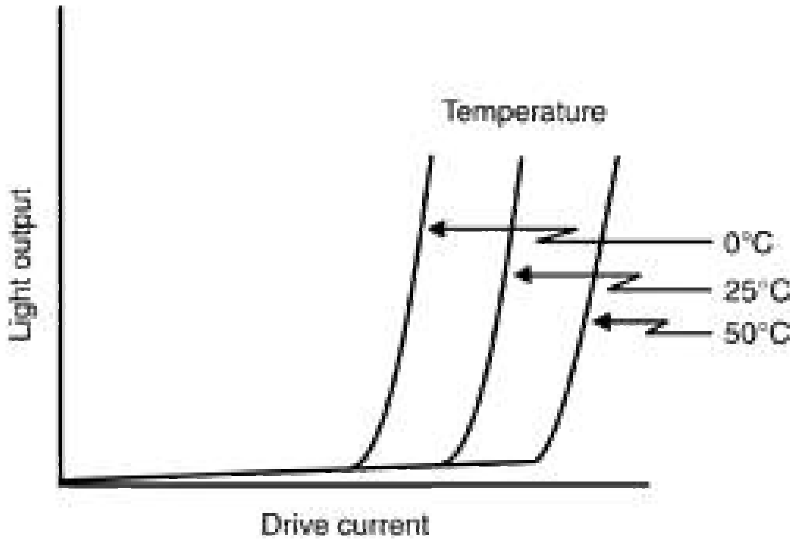
At a threshold value, where the population inversion is large enough so that gain by stimulated emission can overcome the losses, the laser threshold is reached. As current increases above the threshold value, the light output increases much more rapidly than in the LED region.

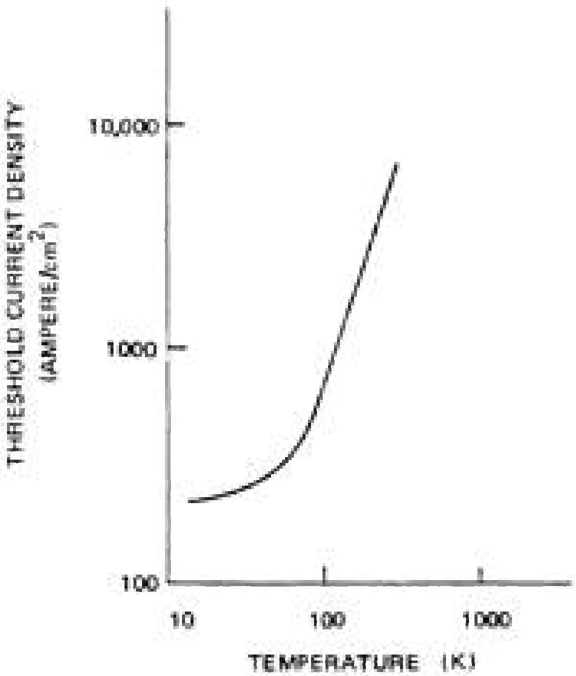
Overall Efficiency

The overall efficiency (Power-conversion efficiency) is defined as the ratio of the emitted laser light power to the power to the electrical input power *iV*

$$\eta = \eta_d (1-(i_t/I))h\nu/eV$$

Temperature Dependence of Laser Output





a) Schematic sketch of the output of a typical laser diode as a function of drive current for three different operating temperatures. b) Temperature dependence of threshold current.

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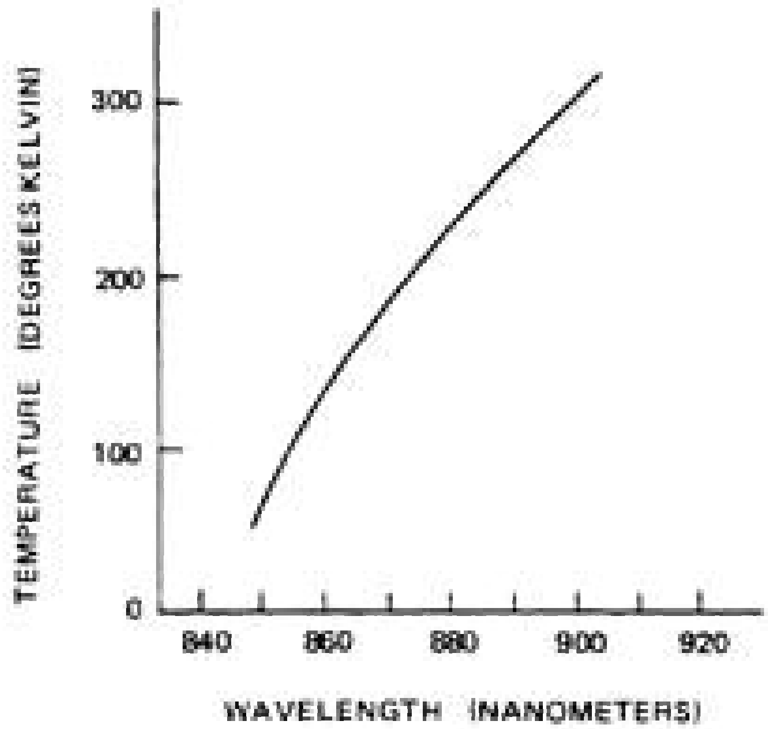
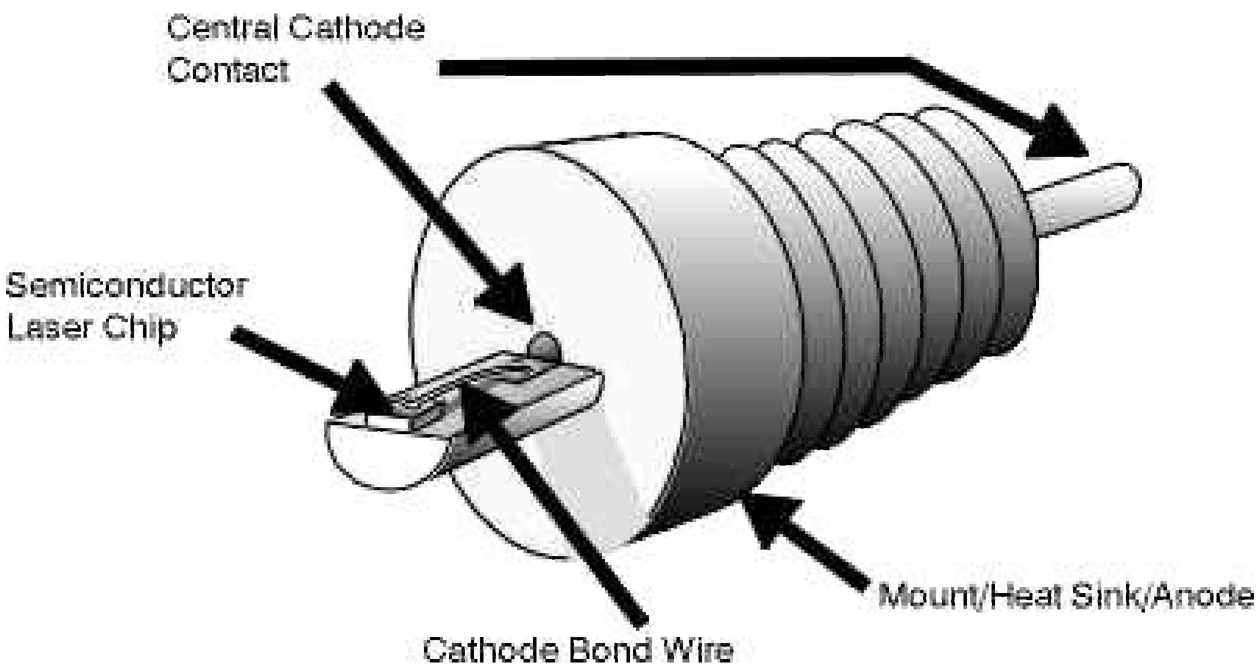
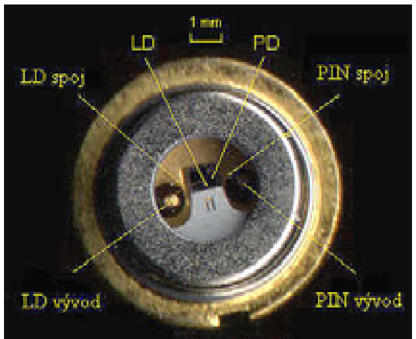
Wavelength as a function of Temperature

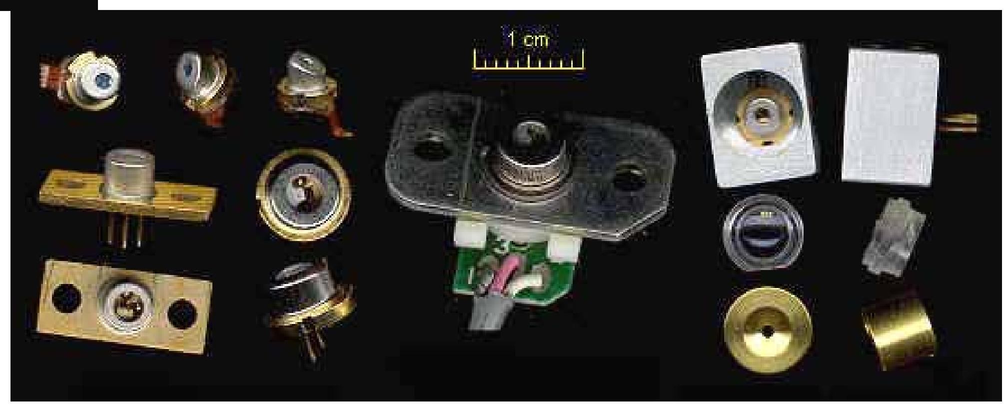


Gallium arsenide lasers emit radiation in the near infrared portion of the spectrum. The exact wavelength depends on the temperature at which the laser is operated.

Cooling of Laser Diodes







Infineon Technologies, Agilent Technologies, Hitachi, Intelite, Laser Components Instrument Group, Alcatel, Furukawa Electrics, Mitshubishi

Spectral Characteristics

The spectral distribution is governed by three factors

1. Spectral width B within which the active medium small signal gain is greater the loss coefficient α_r
2. Homogeneous and inhomogeneous nature of the line-broadening mechanism

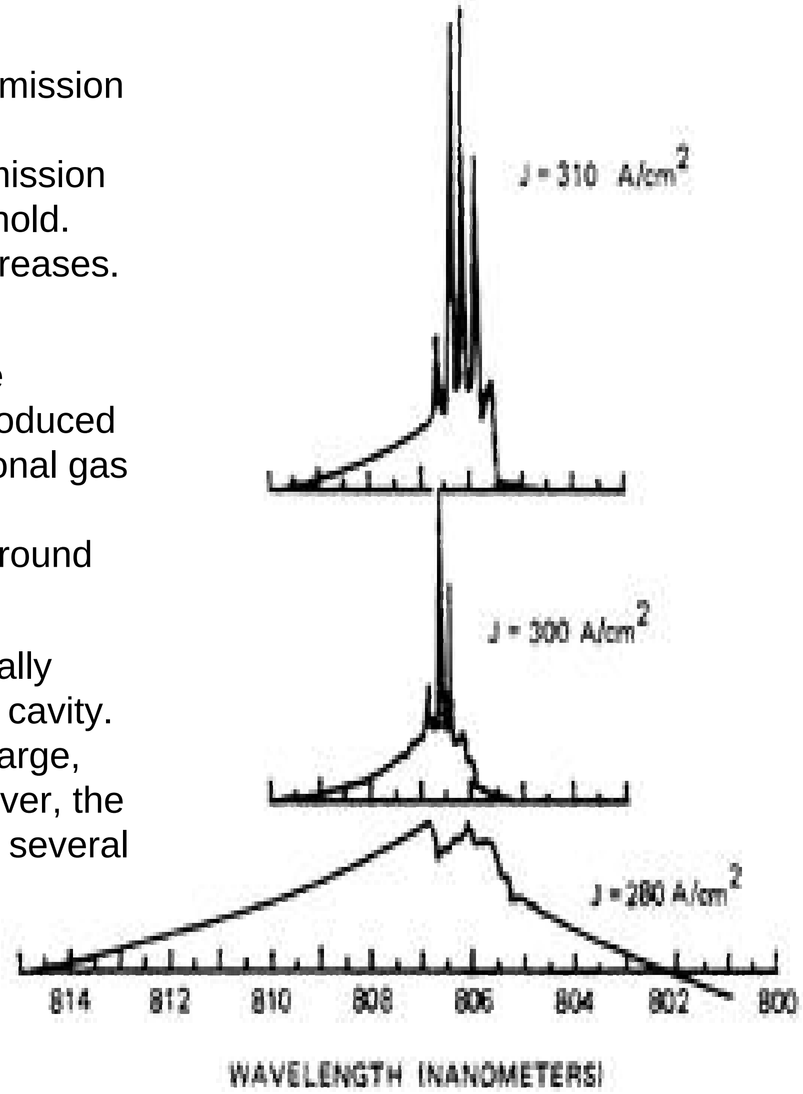
3. Resonant modes $v_f = C / 2nd$

Spectral Characteristics

When the threshold current density is exceeded, the emission spectrum narrows dramatically and the intensity of the emission increases considerably. Figure shows the emission spectrum of a laser diode below and also above threshold. At higher currents the linewidth of the laser output decreases.

The width of the spectral band represented by the spontaneous emission is much greater than that of the stimulated emission. However, stimulated emission produced by the laser is still much broader than that of conventional gas and crystalline lasers. It is of the order of two or three nanometers, as compared to a typical spectral width around 10^{-3} nanometers for a HeNe laser.

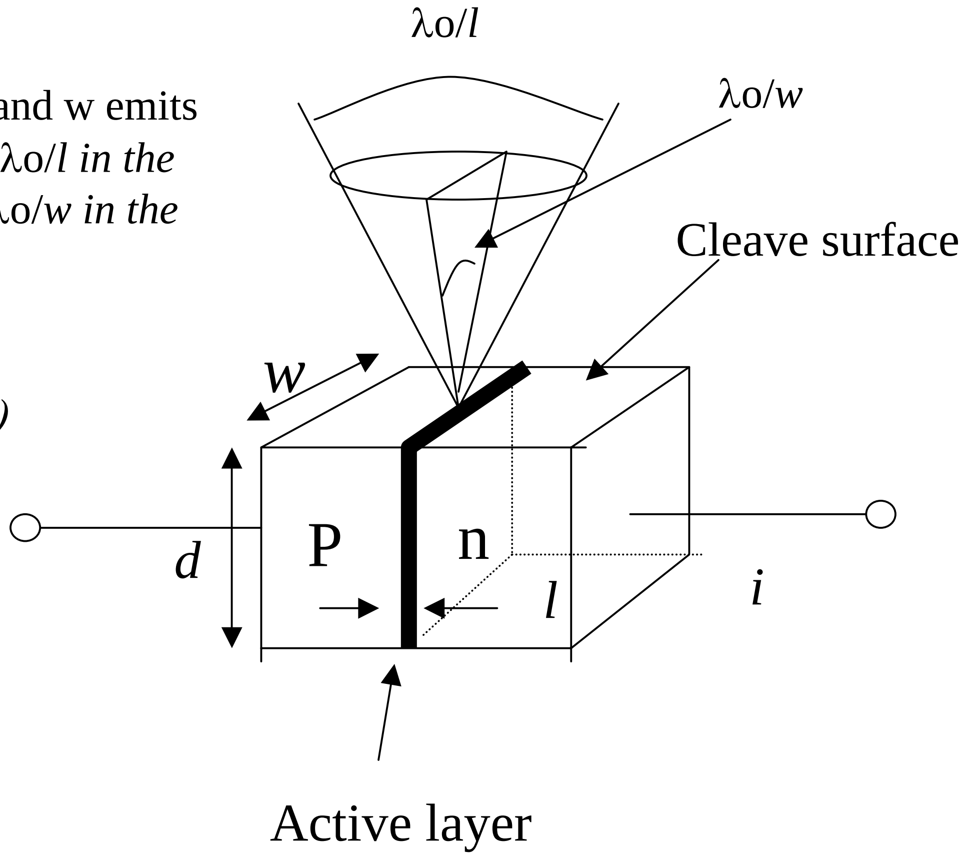
The emission spectrum is relatively complex and typically contains a number of longitudinal modes of the optical cavity. The spacing between longitudinal modes is relatively large, because of the short length of the optical cavity. However, the relatively large spectral width of the GaAs laser allows several modes to be present.



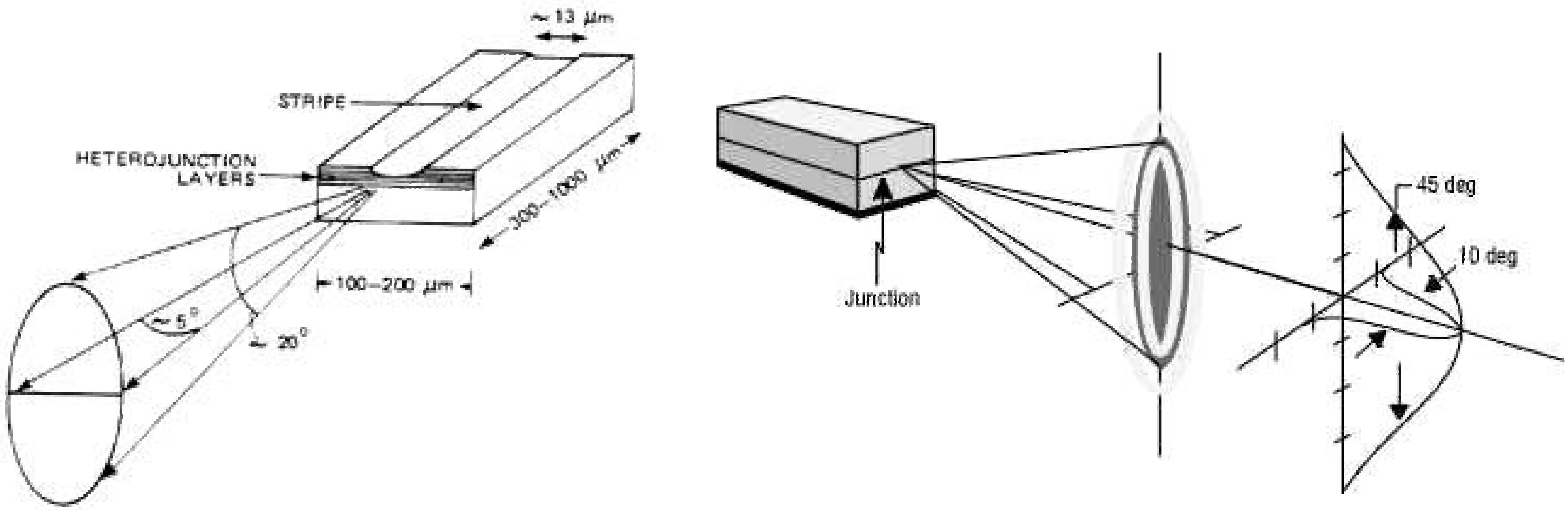
Far-Field Radiation Pattern

A laser diode with an active dimnesion l and w emits Light with far field angular divergence ~ λo/*l in the Plane perpendicular to the junction and* λo/*w in the Plane parallel to the junction.*

Assume Gassian beam of diameter 2Wo, the divergence angle is $\theta = (2\pi)(\lambda o/2Wo)$



Spatial Characteristics



A semiconductor laser typically has an elliptical spatial profile

The profile is caused by diffraction. Light is emitted through the aperture defined by the small junction. Diffraction through the narrow dimensions of the junction causes the beam to spread into a broader angle than is observed with other types of lasers.

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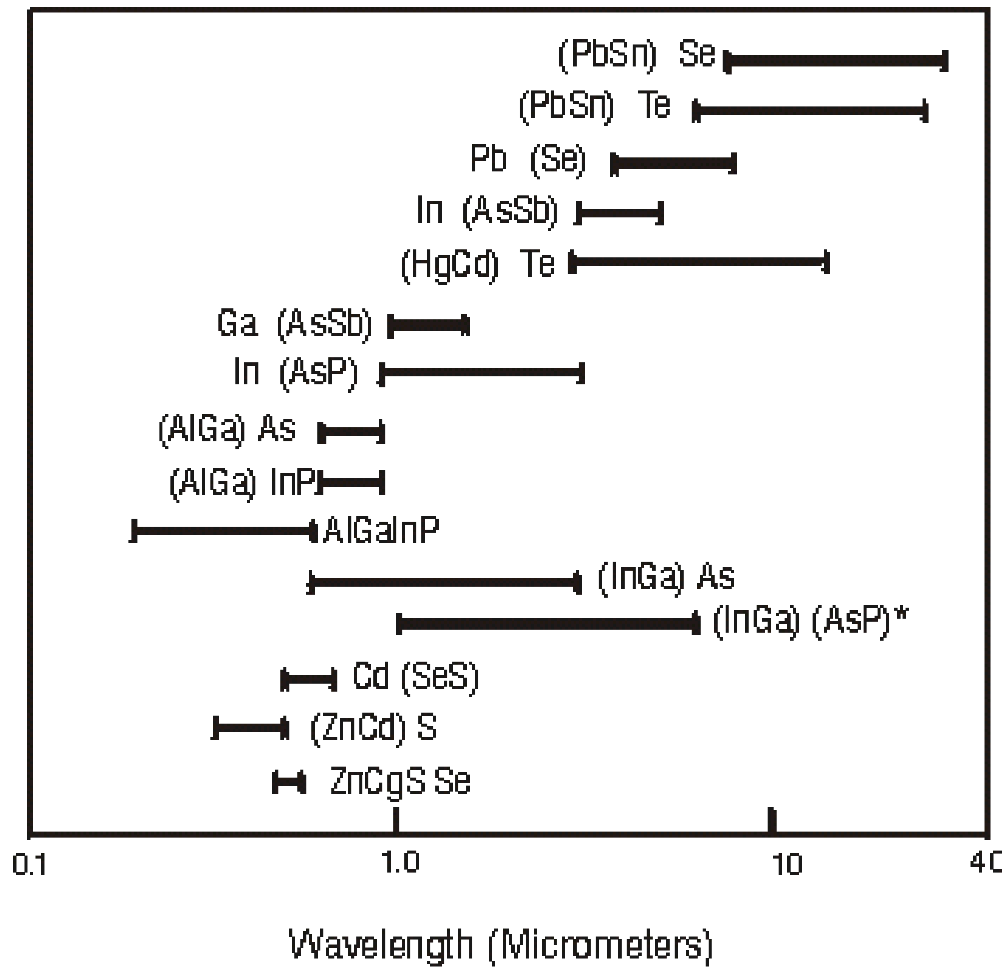
Laser Lifetime

Two different types of failure mechanisms have been identified in gallium arsenide lasers. One is a catastrophic decrease in the power output. This catastrophic damage may occur within a single pulse of the laser, and it is associated with damage of the end surfaces of the laser. The damage is produced by the light output of the laser itself. Tiny cracks or grooves in the junction are produced. To avoid this type of damage, peak power output of the laser must be limited.

There is also a gradual increase in power, which is manifested by increasing threshold current. This damage is produced by the current flowing through the junction. This is a complex phenomenon that is complicated by random variations in the laser life. To extend the life of the laser diode, current density through the junction should be limited.

Other Types of Semiconductor Lasers

Material	Wavelength (μm)	Material	Wavelength (μm)
ZnS	0.33	GaAs	0.84-0.95
ZnO	0.37	InP	0.91
Gan	0.40	GaSb	1.55
ZnSe	0.46	InAs	3.1
CdS	0.49	Te	3.72
ZnTe	0.53	PbS	4.3
GaSe	0.59	InSb	5.2
CdSe	0.675	PbTe	6.5
CdTe	0.785	PbSe	8.5



Wavelength ranges covered by a number of semiconductor lasers of mixed composition

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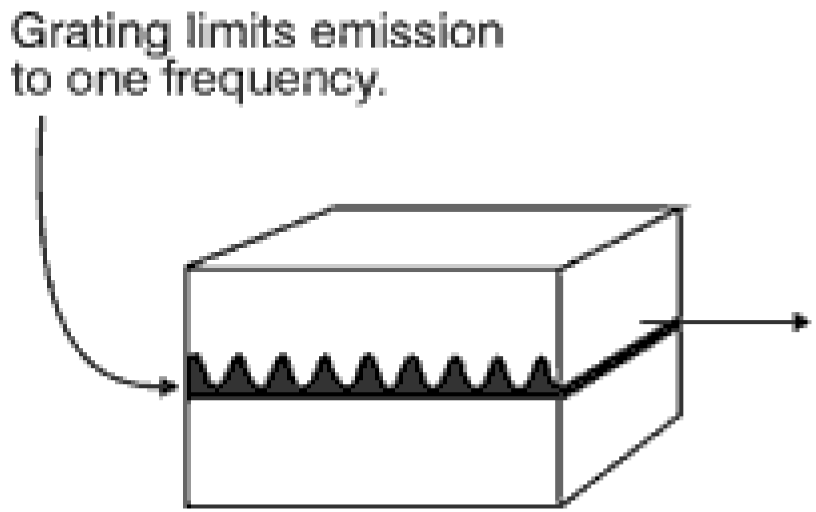
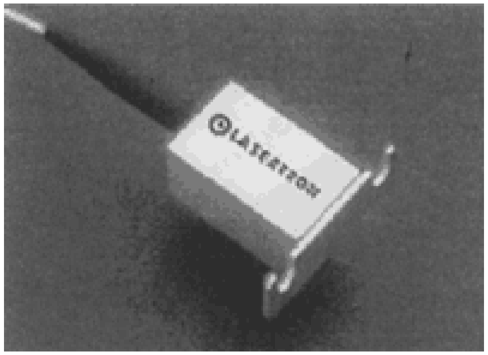
Distributed-feedback (DFB) laser

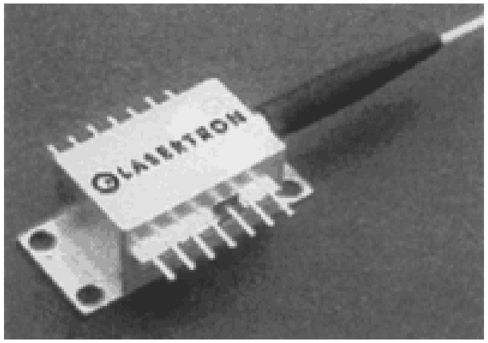


With introduction of a corrugated structure into the cavity of the laser, only light of a very specific wavelength is diffracted and allowed to oscillate.

Packaging

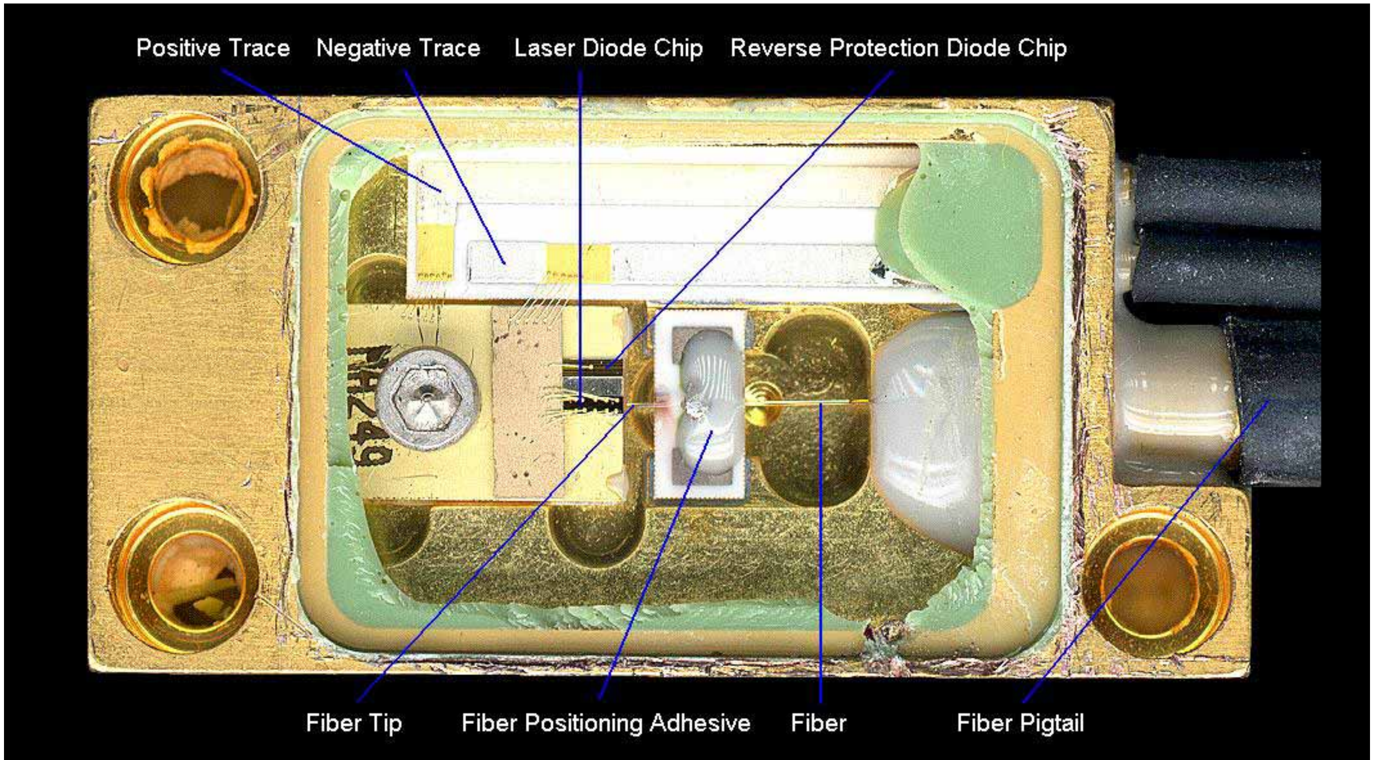


14-pin DIL package (Courtesy of Lasertron)



1550-nm DFB laser in butterfly package (Courtesy of Lasertron)

Laser fiber coupling



Typical 1 Watt Fiber-Coupled Diode Laser Showing Interior Construction

Laser applications

Industrial applications:engraving, cutting, scribing, drilling, tooling, welding, etc.

Medical applications: cutting, soldering, correct vision **diagnostics of cancer cells using fluorescence, and photo dynamic therapy , remove unwanted tissue, photothermal, etc.**

Micromachining: 3-D micromaching, etching, engraving, etc.

Characteristics of Several Industrial Lasers

LASER	POWER RANGE (W)	WAVE-LENGTH (m)	TYPICAL INDUSTRIAL APPLICATIONS
CO_2 – Flowing Gas (Continuous Wave and Pulsed)	500 – 45,000	10.6	Cutting, welding, cladding, free forming, and hardening
CO_2 – Sealed (Pulsed)	10 – 1,000	10.6	Micro-welding, cutting, scribing, and drilling
Nd:YAG (Continuous Wave)	1,000 – 5,000	1.06	Welding, cutting, cladding, and hardening
Nd:YAG (Pulsed)	10 – 2,000	0.53 - 1.06	Micro-welding, cutting, drilling, scribing, and marking
Nd:YAG –Diode Pumped (Pulsed)	10 - 500	1.06	Cutting, drilling, scribing, marking, and micro-machining.
Excimer (Pulsed)	0.001 - 400	0.157 – 0.351	Micro-machining, marking, and photolithography

"Laser Applications and Processing in Precision Manufacturing" was help at the EOC on December 7, 2000

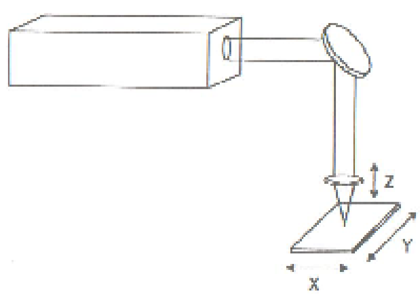
Laser Wavelengths

- Each type of laser has a characteristic wavelength of the output beam
- The particular wavelength of the laser has several ramifications on processing:
  - lower wavelengths, typically, have better absorption in metallic materials
  - however, lower wavelengths also allow the transmission through fiber optics
  - lower wavelengths also provide smaller focused spots

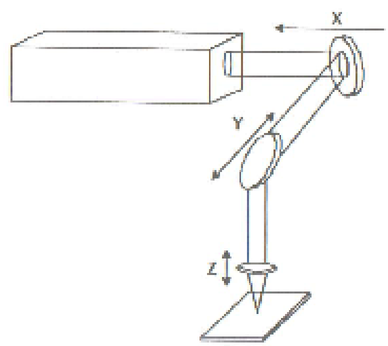
Beam Delivery Systems for Laser Processing

Hard Optic Delivery (CO2, Nd:YAG, and Excimer Lasers)

Moving workpiece

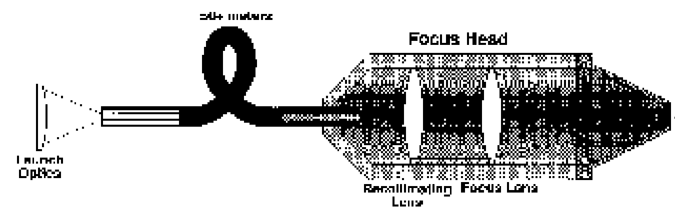


Moving Optics



- Mirrors must be properly aligned and clean
- Can be used with practically any wavelength
- Hard optical systems are fairly reliable

Fiber Optic Delivery (Primarily Nd:YAG Lasers)



- Versatile delivery to workstation
- No practical fiber materials for use with CO_2 lasers (10.6 µm radiation)
- Requires high fiber bend radius (approx. 0.2 m) to prevent leakage
- Destroys coherency of beam, resulting in larger focal spot

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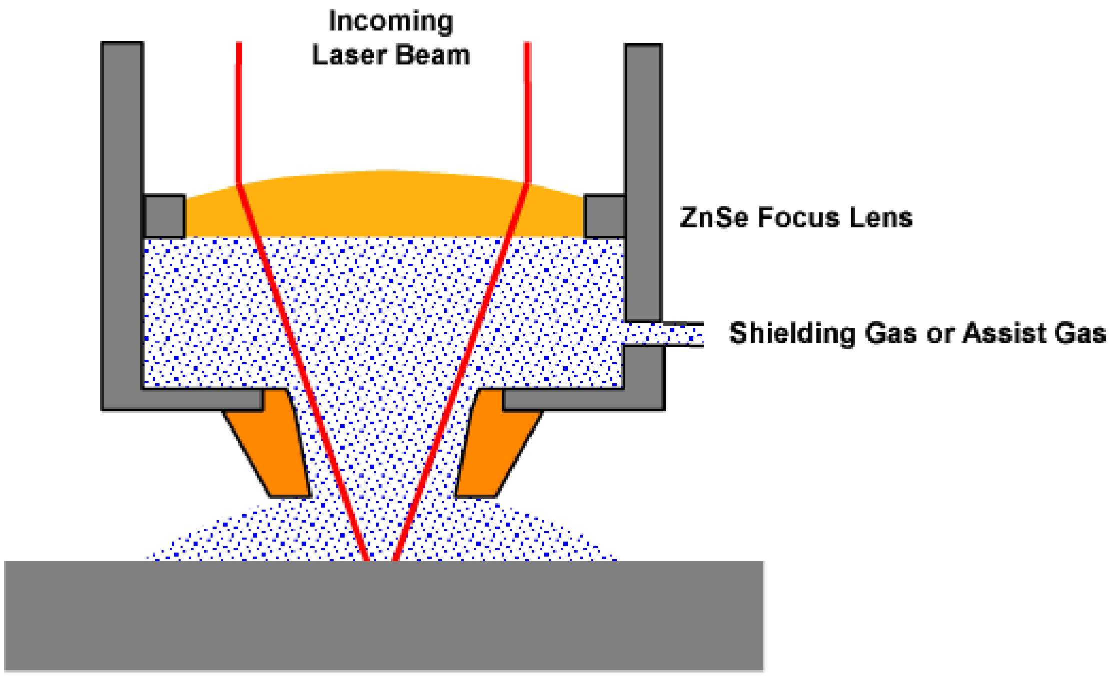
There are major performance differences between Nd:YAG and CO_2 lasers. One reason is that Nd:YAG light is emitted at a wavelength of 1.06 microns in the near infrared, while CO_2 light is emitted at 10.6 microns. The material interactions at these wavelengths differ. Most organics don't absorb 1 micron light very well, while they absorb 10 micron light. So, non-metal processing is generally a CO_2 application. Metals are more reflective at 10 microns than at 1 micron, so CO_2 lasers only weld effectively in the "keyhole" mode, where the irradiance is high enough to generate a vapor channel in the workpiece. Once you get into keyhole mode, the high average power of CO_2 lasers makes high speed welding possible. For small spot welds, Nd:YAG lasers are far more controllable.

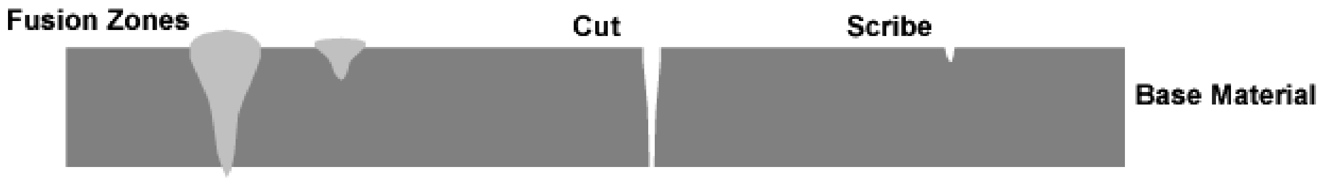
Also, since there are a lot more Nd atoms in a YAG rod than there are CO_2 atoms in laser gas, Nd:YAG lasers can deliver much higher peak powers than CO_2 lasers. This makes them better for drilling. Conversely, since it's hard to cool a solid rod, Nd:YAG lasers have problems with high average powers. You can build a CO_2 laser with very high power; Convergent has commercial 45 kW units, and much bigger ones have been built.

Components of a Laser Processing System



- The application of lasers in industry cover a wide range of processes (to name a few):
  - welding, brazing, and soldering,
  - cutting and drilling
  - scribing and marking
  - micro-maching
  - near net shape processing

- Typically, a particular laser is chosen to optimize the process



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Examples of Laser Cutting with a Pulsed CO_2 Laser

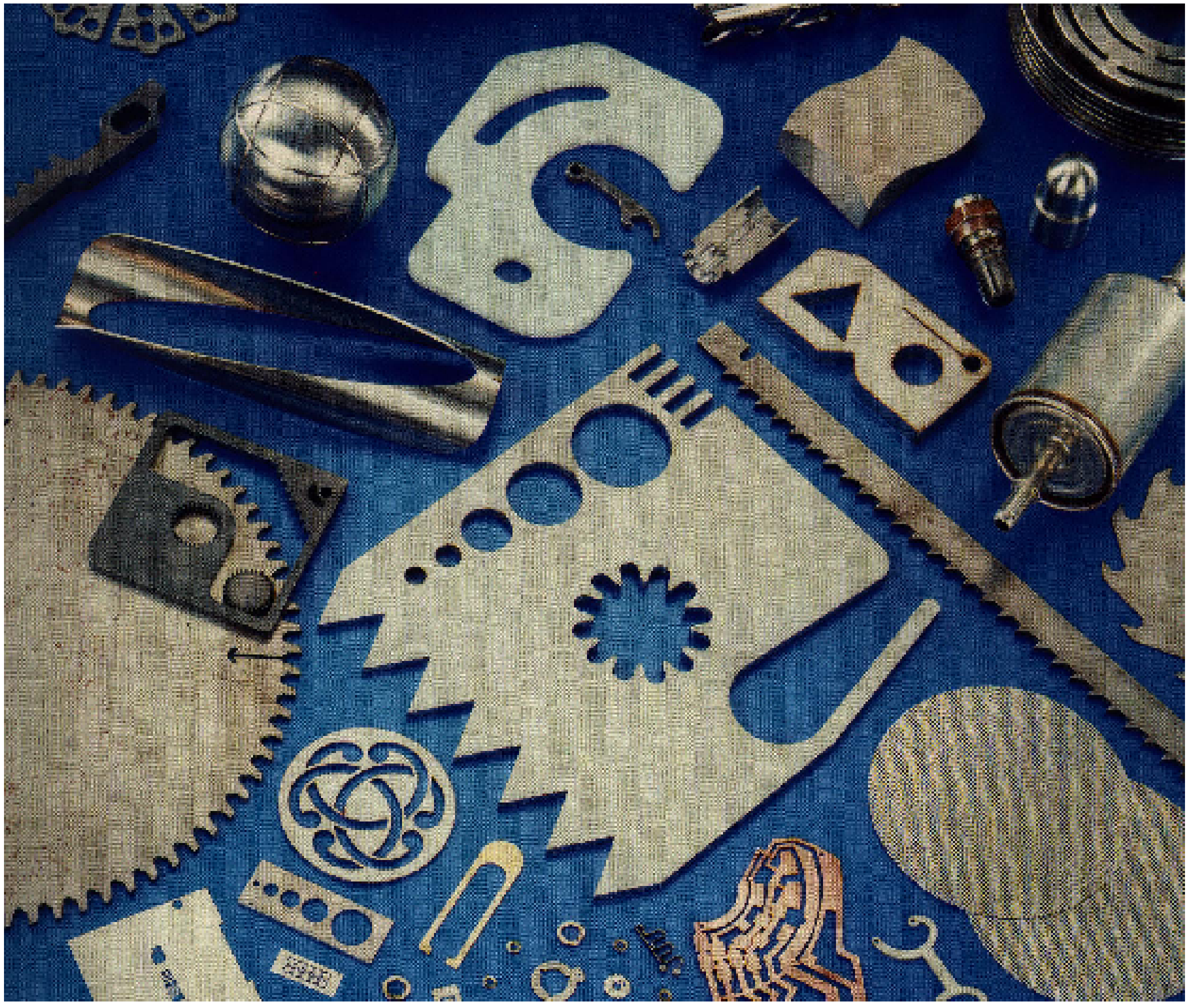

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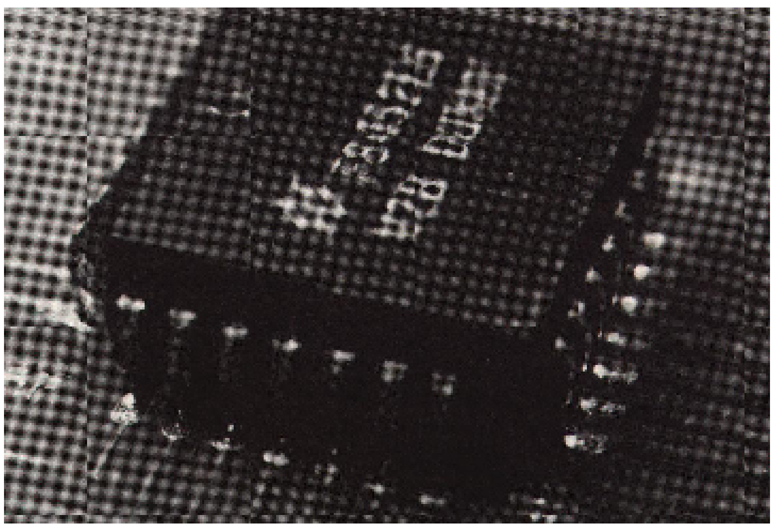
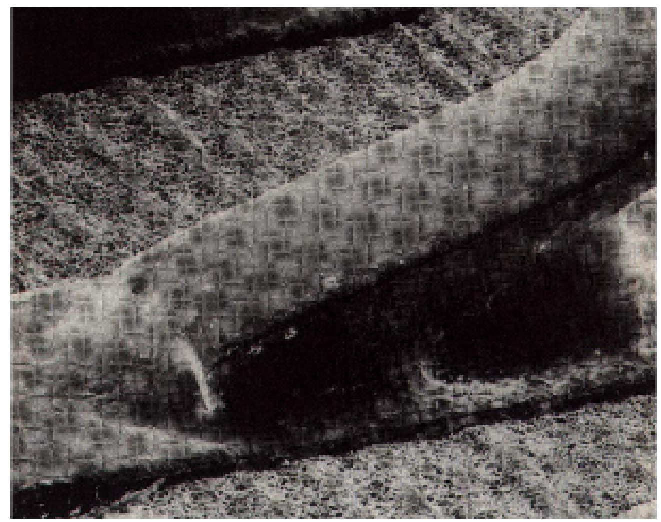
Photo courtesy of PRC Laser

Precision Soldering of Electronic Components Using a Nd:YAG Laser

Laser Soldered Component



Laser Soldered Joint Showing Wetting



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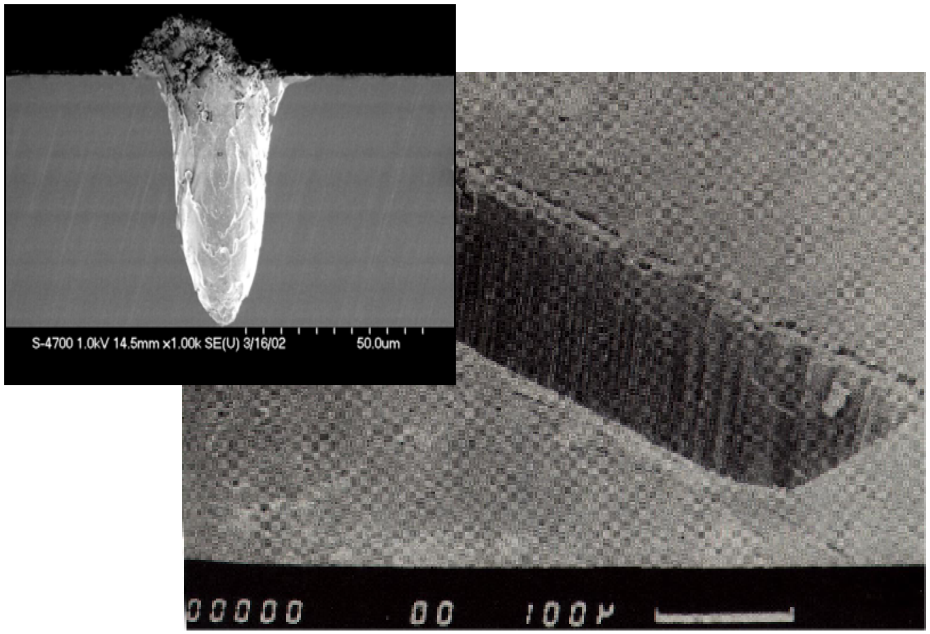
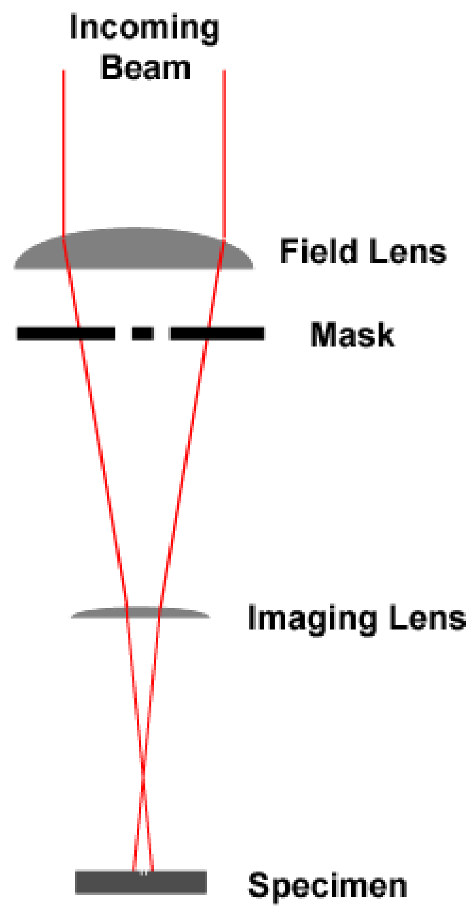
Micro-machining with Excimer Laser and Image Projection



100   m wide slot in borosilicate glass using image projection and 20X demagnification and excimer laser (ArF at 193 nm)



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Lasers in General Surgery

Almost every medical surgery in which a removal of tissue is required, or a cut needs to be made, can be done with a laser.
In general, the results using lasers are better than the results using a surgical knife.

- When a **bleeding need to be stopped**, a Nd-YAG laser can be used. Its radiation enters deep into the tissue, and heats and coagulates a large area.
- When a **clean cut** need to be done, an Excimer laser is used.
- A more **general cutting tool** is the CO_2 laser.

Lasers in Dentistry

Dental soft tissue treatment applications are similar to those of other soft tissue in the body, and are common for many years.

- In case of **gum surgery**, with the laser most of the patients suffer less postoperative pain.
- Almost no bleeding.
- No stitches required.

Dental hard tissue treatment is new, and only in May 1997 the **FDA** **(Federal Drug Administration)** approved the Er-YAG laser for use on the hard tissue (teeth) in humans.

Rami Arieli: "The Laser Adventure" Chapter 9.2.1 page 11

Examples of Laser used in Dentistry

Argon: laser teeth whitening
Dual Wavelength Surgical Argon: teeth whitening; soft tissue surgeries, such as gingivoplasty, frenectomy and biopsy; composite curing, which reinforces and strengthens the tooth
Nd:YAG: soft tissue surgery, such as gingivoplasty, frenectomy, gingivectomy, bacteria reduction when treating gum disease
Er:YAG: removal of tooth decay/cavities while also decontaminating the area, frenectomy, crown lengthening
Perio Diode: gum treatment and soft tissue surgery, such as gingivoplasty
Low Level Laser Therapy (LLLT): biophotomodulation, treats canker sores, herpes, sore jaws, helps relieve post-op discomfort and promotes post-op healing
Diagnodent Laser: early detection of cavities

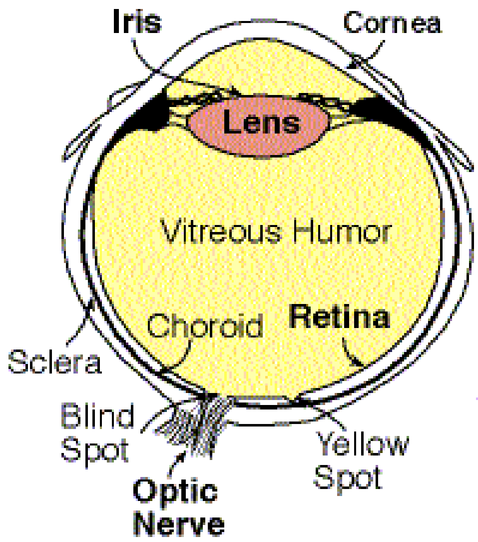
Lasers for eye treatment

Soldering Detached Retina

As a result of mechanical shock, the retina inside the eye can be torn, and detached from the tissue it is connected to

The electromagnetic radiation from the laser heats the detached retina, and as a result the damaged blood vessels around the retina are closed and solder to place.

Because of the **focusing effect of the eye**, small amount of laser power is needed to solder the detached retina.
Excimer laser



Rami Arieli: "The Laser Adventure" Chapter 9.2.1 Eye page 1

Lasers in Diagnostic Medicine, and in combination with Drugs

Diagnostics of cancer cells using Fluorescence, and Photo Dynamic Therapy (PDT)

One of the biggest problems in medicine today is to find a **cure for cancer**.

There are **many treatments for cancer to destroy the cancer cells**, such as:

- Disectomy of the infected organ.
- Radioactive irradiation.
- Heat treatment.

Types of Lasers

Although there are several different kinds of lasers, only three kinds have gained wide use in medicine:

Carbon dioxide (CO_2) laser—This type of laser can remove thin layers from the skin's surface without penetrating the deeper layers. This technique is particularly useful in treating tumors that have not spread deep into the skin and certain precancerous conditions. As an alternative to traditional scalpel surgery, the CO_2 laser is also able to cut the skin. The laser is used in this way to remove skin cancers.

Neodymium:yttrium-aluminum-garnet (Nd:YAG) laser—Light from this laser can penetrate deeper into tissue than light from the other types of lasers, and it can cause blood to clot quickly. It can be carried through optical fibers to less accessible parts of the body. This type of laser is sometimes used to treat throat cancers.

Argon laser—This laser can pass through only superficial layers of tissue and is therefore useful in dermatology and in eye surgery. It also is used with light-sensitive dyes to treat tumors in a procedure known as photodynamic therapy (PDT).

Soft lasers

Most of the medical laser applications were until recently based on the **thermal effects** caused by the electromagnetic radiation which was absorbed in the biological tissue.

In the last few years, some new applications are using low power **lasers with output power less than 1 Watt**.

Some of the effects of these low power levels on the biological tissue is not thermal, and in effect **the mechanism of interaction is not yet clear**.

It is sometimes referred to as **Biostimulation**, which does not explain a lot.

Lasers in Dermatology

Among these defects are:

- **Pigmented skin**, **Abnormal skin growth**, **Blemishes**.
- **Tattoos**. Today, with the wide variety of lasers in use, tattoos can almost completely be erased from the skin. Different wavelengths are used to remove different ink colors from the skin. The specific laser wavelength is **selectively absorbed by the specific color, without damage to surrounding cells**. Usually the treatment is made in a number of treatments. After each treatment checking what was left in the damaged skin. (Ruby and Nd: YAG laser)

  A nice Web site about the laser tattoo removal is at **Beckman Laser Institute and Medical Clinic**:

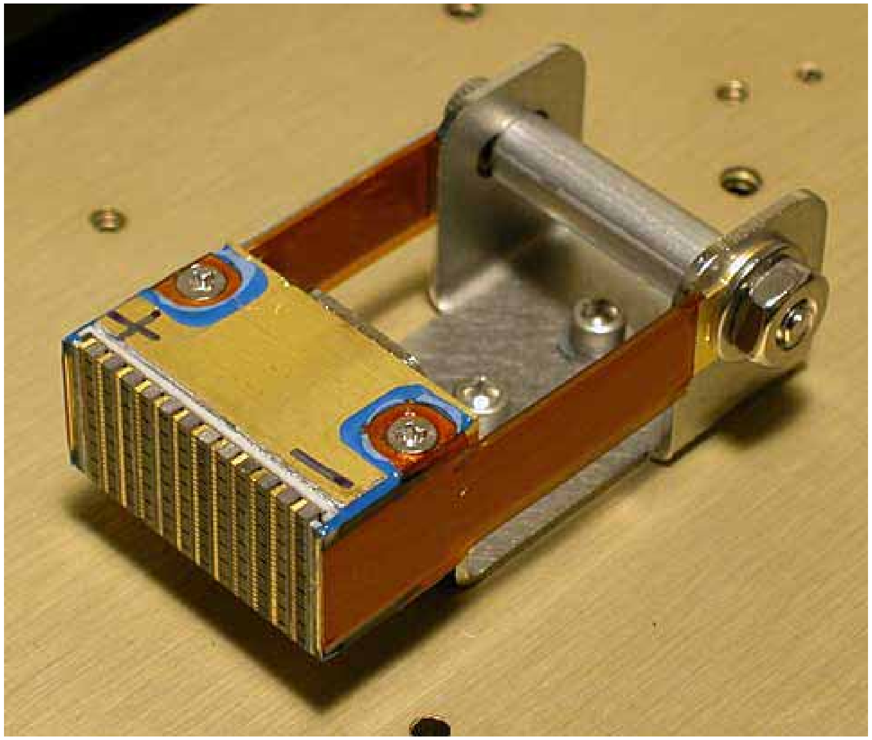
  http://www.bli.uci.edu/clinic/tattoos.html

- **Carcinomas and malignancies**.

This is an example of a laser system for hair removal procedures.

Emitting wavelength	*(810 ± 10) nm*	Classification: IIIb
Output power	*User-adjustable 0 to 15 Joules*	Designation: OEM
Generation modes	*CW*	Manufacturer: LaserTec, UK
Beam characteristic	*Semiconductor Diode*	Warranty: 1 Year
Pulse duration	*Manual Adjust*	Emission Indicator: Yes
Weight	*1.2 kg max*	Key Lock: Yes
Optics	*Pinpoint 2mm*	Beam Shutter: No
Dimensions	*10 x 19 x 7.5 inches*	21CFR 1040, IEC 825-1:1993: No

Diode laser arrays



Courtesy E-Bay

Specifications

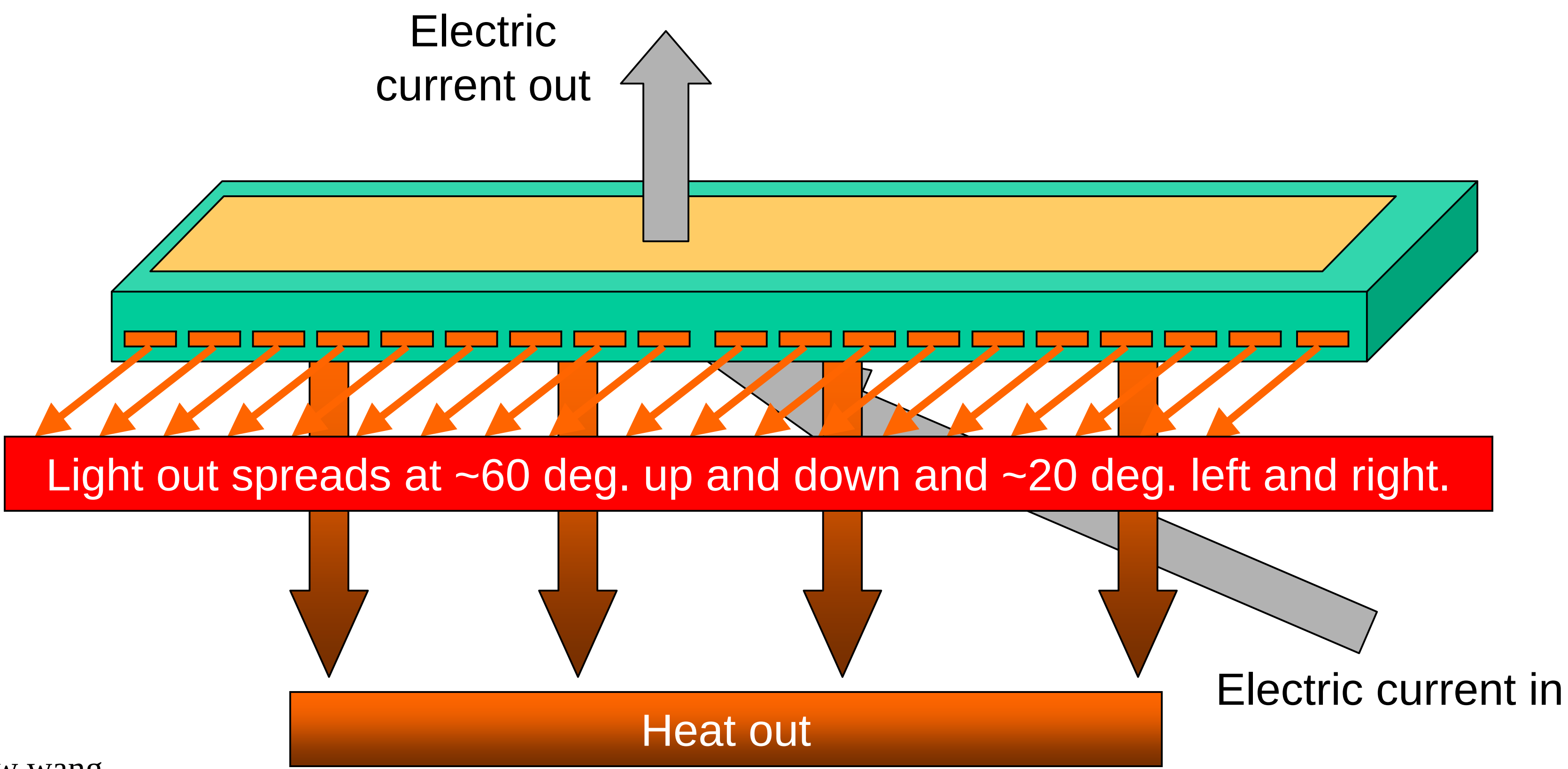
- Emitting Dimensions: 10 x 17.2mm
- CW Output Power: 240W
- Threshold Current: 7A
- Operating Current: 25A typ, 30A max
- Operating Voltage: 22.8V typ, 25.8V max
- Series Resistance: 0.19 ohm
- Beam Divergence: 35 x 10 degrees
- Peak Wavelength: 803nm
- Spectral Width: 3nm typ, 4nm max

Cooling Requirements

- Flow: 1.5 LPM
- Pressure: 15 PSI
- Water Temperature: 25C
- DI Water not required
- <20um particle filter required

laser diode bar array made by Spectra Diode Labs (SDL). This is model 3474-MB. It consists of 12 20W diode bars in a 10 x 20mm G stack package producing an amazing 240W with an energy density of 120W/cm^2.

A diode laser bar



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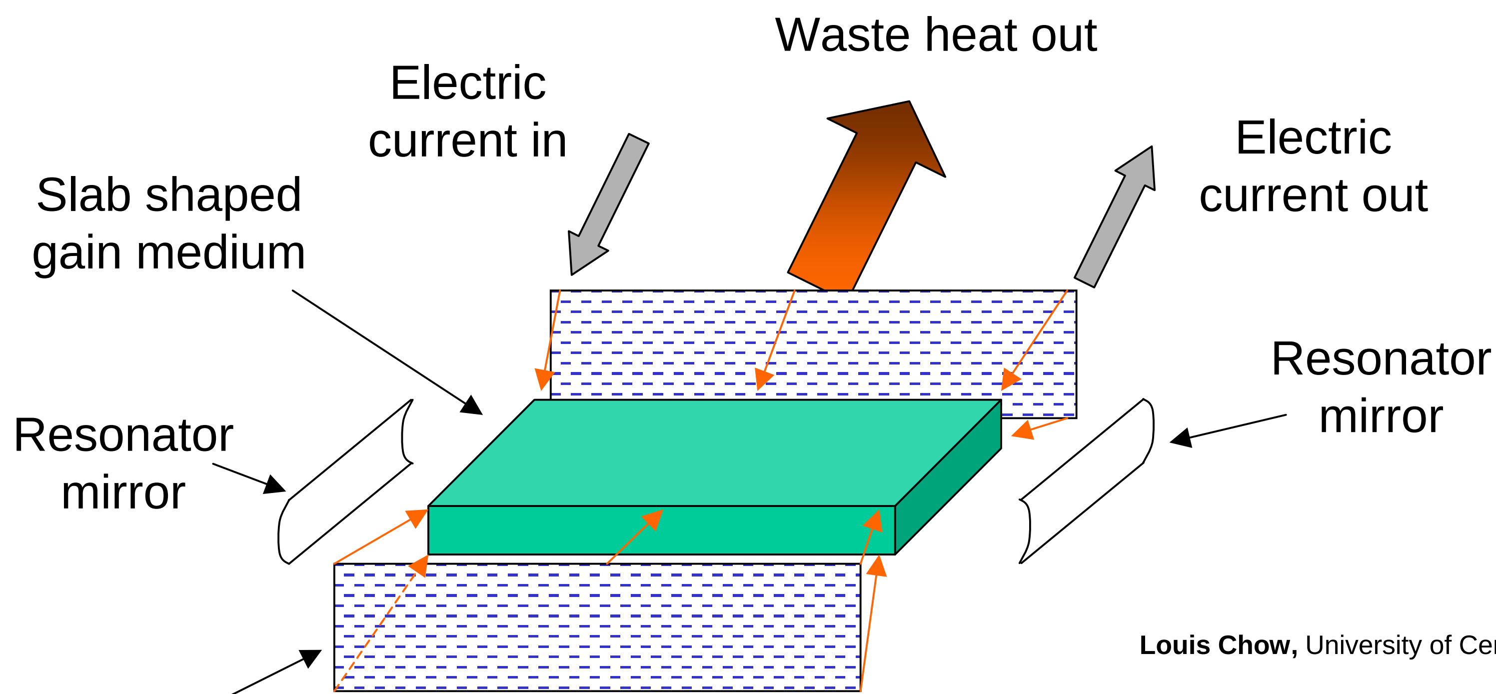
Louis Chow, University of Central Florida

A diode laser array pumped solid state laser



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Diode laser arrays (2) with beam control prisms pumping a slab laser through both mid sized edges

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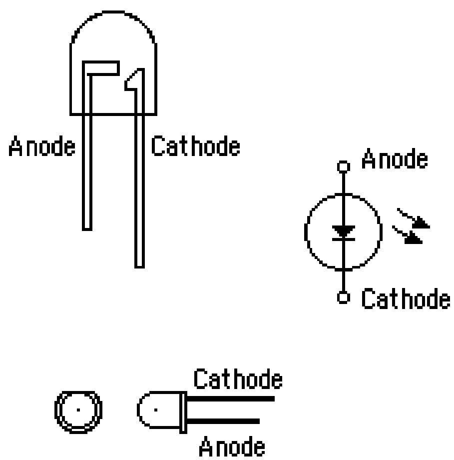
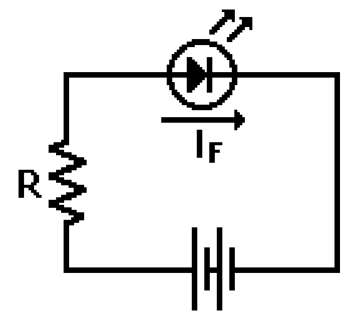
Light Emitting Diode (LED)

The electroluminescent process of LED is to covert input electrical energy into output optical radiation in the visible or infrared (heat) portion of the spectrum, depending on the semiconductor material.

LEDs and laser diodes are very similar devices. In fact, when operating below their threshold current, all laser diodes act as LEDs.



Flat side and long
lead indicate cathode.



LEDs are generally more reliable than lasers, but both sources will degrade over time. This degradation can be caused by heat generated by the source and uneven current densities. In addition, LEDs are easier to use than lasers.

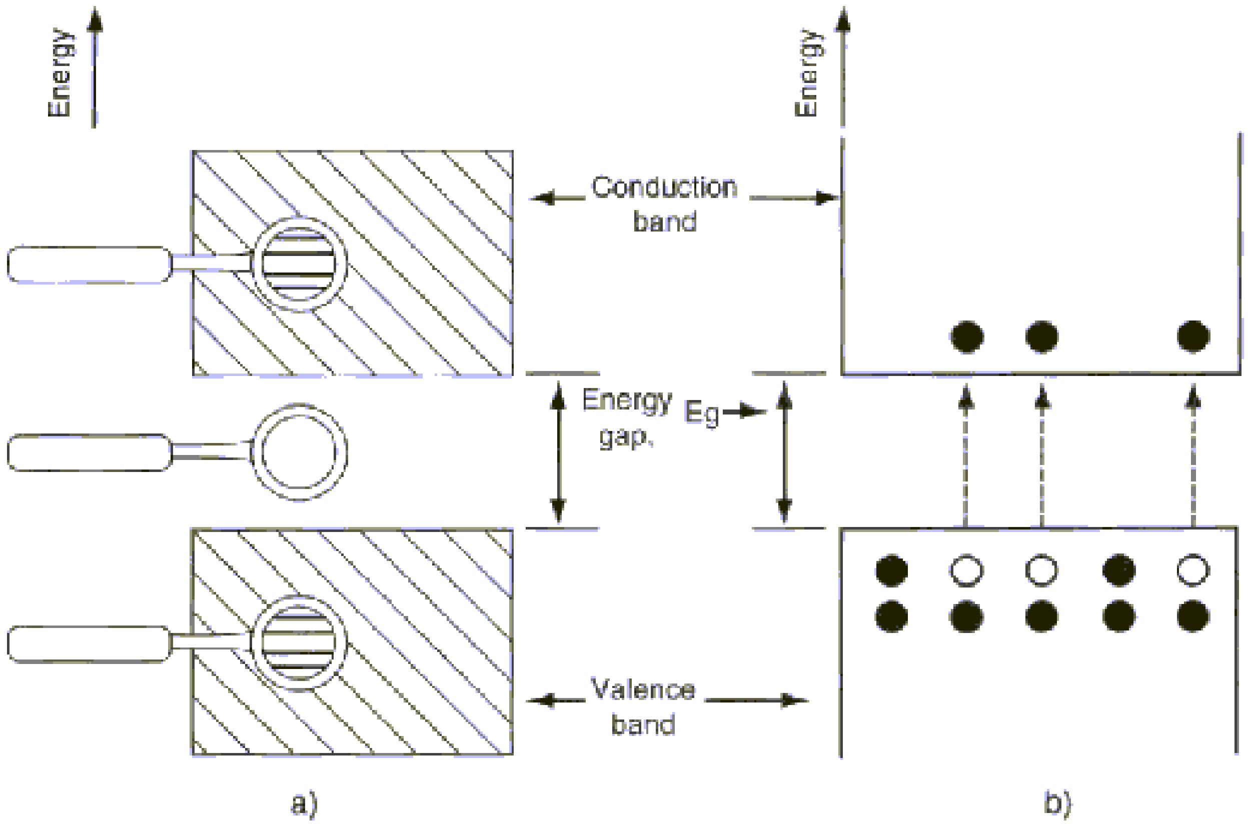
LEDs are found in a wide variety of consumer electronics products. LEDs are used as visible indicators in most electronics equipment, and laser diodes are most widely used in compact disk (CD) players. The LEDs used in fiber optics differ from the more common indicator LEDs in two ways:

1. The wavelength is generally in the near infrared (because the optical loss of fiber is lowest at these wavelengths).
2. The LED emitting area is generally much smaller in order to allow the highest possible modulation bandwidth and improve the coupling efficiency with small core optical fibers.

The effective emitting area of an LED is perhaps .25 x .25 mm. To focus an incoherent source like this to a 2 um spot with imaging optics would require a ratio of distances of roughly 125:1 for the LED-to-lens compared to the lens-to-image plane.

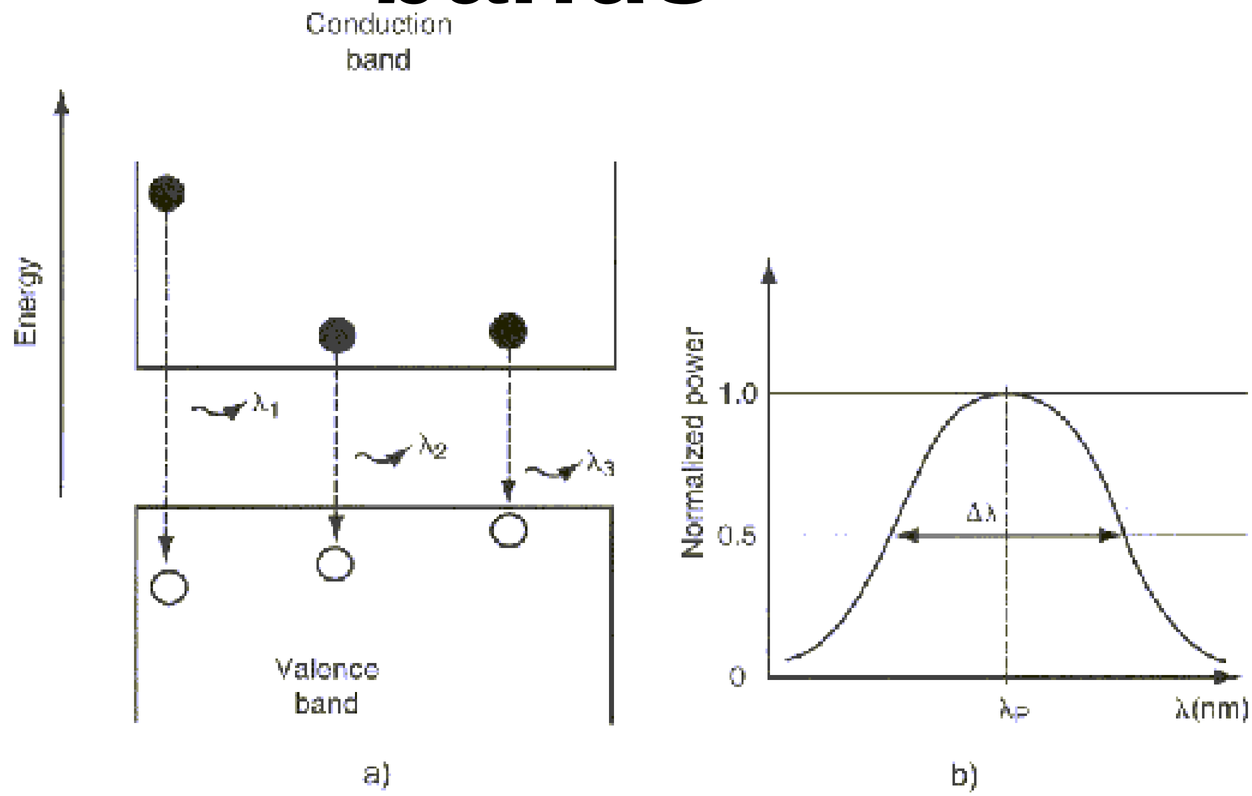
Simple optics don't focus all wavelengths at the same focal length. So the wide bandwidth of the LED causes a little trouble. There is another effect having to do with the size of the lens (diffraction limit) and the wavelength, but this is also secondary to an understanding of the *primary* reason why an LED can't be focused.

Light radiation—energy bands



a) General representation; (b) for finite temperature

Light radiation—energy bands



a) Radiation process *An electron-hole recombination releases a quantum of energy—a photon*
; (b) spectral width of radiated light.

Energy Gaps in LEDs

the bandgap energy E_g of the LED

$$E_g=hc/\lambda$$

Where:
h = Plank's Constant = 4.13×10^{-15} eV•s
c = speed of light = 2.998×10^{8} m/s
λ = wavelength in nm

Common Light Emitter Materials & Characteristics

Material	Formula	Energy Gap	Wavelength
Gallium Phosphide	GaP	2.24 eV	550 nm
Aluminum Arsenide	AlAs	2.09 eV	590 nm
Gallium Arsenide	GaAs	1.42 eV	870 nm
Indium Phosphide	InP	1.33 eV	930 nm
Aluminum-Gallium Arsenide	AlGaAs	1.42-1.61 eV	770-870 nm
Indium-Gallium-Arsenide-Phosphide	InGaAsP	0.74-1.13 eV	1100-1670 nm

Light-emitting diodes use GaAlAs (gallium aluminum arsenide) for short-wavelength devices. Long-wavelength devices generally incorporate InGaAsP (indium gallium arsenide phosphide).

Type	Peak (nm)	Dominant (nm)	Efficacy (lm/W)
GaAsP on GaAs substrate red	660	650	~55
GaP/ZnO (low current red, varies with current)	697 (nom) 660-697	600-640	~10-30
GaAsP on GaP substrate red	630	615	180-200+
GaAsP on GaP substate yellow	590	588	400
GaAlAsP (ultrabright red)	660 have seen 635-650	645 typ.	80
"T.S." AlGaAs (HP)	646-655	637-644	80-95
InGaAsP (bright red-orange)	620-625	608-615	~200
InGaAsP bright yellow	590	588	400
GaP green	565	upper 560s-570	? 620 (Brighter greens are simil
"Pure green" GaP (There is an InGaP with similar color)	near 550	near 555	670
Nichia InGaN green	522 (?)	525	very roughly 450
Toyoda Gosei InGaN green	516	520	very roughly 425
InGaN blue (Nichia and Toyoda Gosie)	466	470	very roughly 75
GaN blue (Panasonic 450 nm) (This is a broader band blue)	450	470	very roughly 100
SiC ("Cree type") blue	466-470	around 480	very roughly 130
GaN on SiC substrate blue (Radio Shack 276-311)	430	around 450	maybe 50

Blue LED

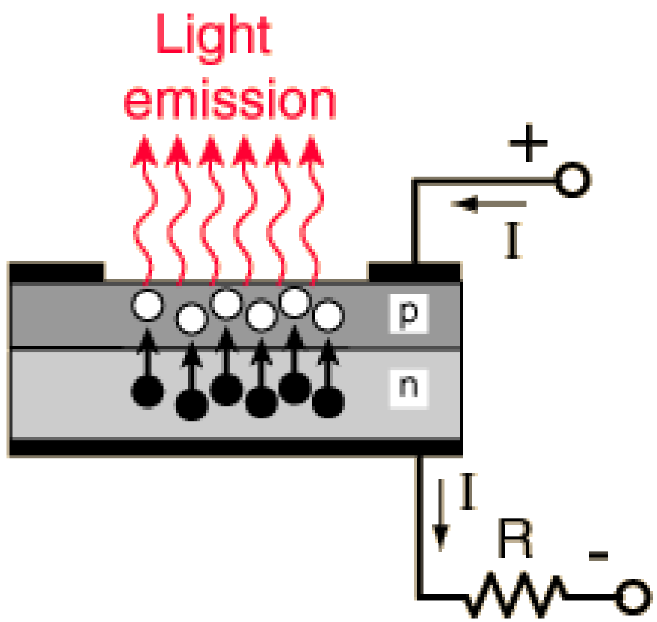
After a decade of intense research, a bright blue LED was successfully produced by Nichia Chemical of Japan in 1994. The material used for the diode was gallium nitride GaN. Nichia has also produced an InGaN laser diode which lases in the blue-violet region of the spectrum.

Blue LEDs are important for the development of high-information-density storage on optical disks, as well as a host of other applications such as high-resolution television and computer displays, image scanners and color printers, biomedical diagnostic instruments, and remote sensing.

Other ways of producing blue light from solid state sources involve doubling the frequency of red or infrared laser diodes. Hitachi and Matsushita have taken this approach to producing blue light for optical disks and digital versatile disks (DVD).

Reference: The Elusive Blue Laser, The Industrial Physicist, 3, September 1997, p16

LEDs are p-n junction devices constructed of gallium arsenide (GaAs), gallium arsenide phosphide (GaAsP), or gallium phosphide (GaP). Silicon and germanium are not suitable because those junctions produce heat and no appreciable IR or visible light. The junction in an LED is forward biased and when electrons cross the junction from the n- to the p-type material, the electron-hole recombination process produces some photons in the IR or visible in a process called electroluminescence. An exposed semiconductor surface can then emit light.



hyperPhysics

Current-Voltage

The current-voltage relation of a diode is derived based on the Boltzman's and Maxwell's equations. The equation of voltage and current is given:

$$I_{diode} = I_{do}(e^{\frac{qV}{kT}} - 1) \qquad \text{(dark current)}$$

where k=Boltzman's constant= 8.62e-5 eV/^{o}K, T= temperature (^{o}K) and q = single electron charge =1.6e-19 coulombs and I_{do} is reverse saturated current.

Light Power

Light power, P, is energy per second, that is, the number of photons times the energy of an individual photon, hv. The number of photons is equal to the number of excited (injected) electrons, N, times the esternal quantum efficiency, η_{ex}. Thus,

$$P = (N\,\eta_{ex}\,hv)/t$$

The forward current injects electrons into the depletion region, where they recombine with holes in radiative and nonradiative ways. Thus, nonradiative recombinations take excited electrons from useful, radiative recombinations and decrease the efficiency of the process. We characterize this by the *internal quantum efficiency*, η_{int}, which shows what fraction of the total number of excited (injected) electrons produces photons. The transmission efficeincy with which the internal photons can be extracted from the LED structure η_e . Therefore, the external quantum efficiency $\eta_{ex} = \eta_{int}\eta_e$

On the other hand, the number of electrons (N) times the electron charge (e) per second constitutes current (I):

$$I = Ne/t$$

and $N = It/e$. Hence, the radiated light power is:

$$P = (It/e)(\eta_{ex}\, hv)/t = [(\eta_{ex}\, hv)/e]I$$

Another measure of performance is the overall quantum efficiency, η which is defined at the ration of the radiated power P to the applied electrical power

$$\eta = P/IV = \eta_{ex}\, hv/eV$$

Where V is voltage drop across the device, for $hv \sim eV$, as is the case for commonly encountered LEDs, it follows that $\eta = \eta_{ex}$

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Responsivity

The responsivity *R* of an LED is deifined as the ratio of the radiatted light power *P* to the injected current *I*

$$R = P/I = \eta_{ex}\, h\nu/e$$

Lifetime

Lifetime, τ, of the charge carriers is the time between the moment they are excited (injected into a depletion region) and the moment they are recombined. It is sometimes called *recombination lifetime* and it ranges from nanoseconds to milliseconds. We distinguish between radiative, τ_r and nonradiative, τ_{nr} combination lifetimes so that the total carrier lifetime, τ, is equal to :

$$1/\tau = 1/\tau_r + 1/\tau_{nr}$$

Incidentally, internal quantum efficiency, η_{int}, which shows how many photons are radiated with respect to a specific number of injected electrons, can be quantified by the following formula:

$$\eta_{int} = \tau / \tau_r$$

Rise/Fall time

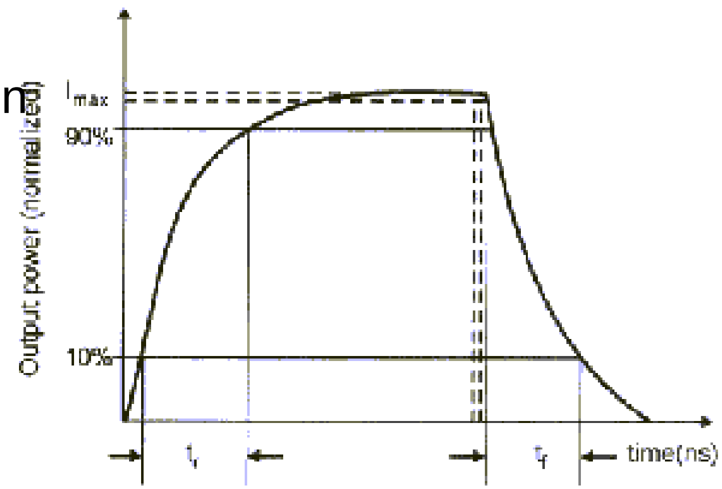
Rise/fall time, t_r, is defined as 10 to 90% of the maximum value of the pulse, Rise/fall time is determined by an LED's capacitance (*C*), input step current with amplitude(I_p), and the total recombination lifetime ( ) so that:

$$t_r = 2.2[\ \ + (1.7 \text{ x } 10^{-4} \text{ x } T\,°K \text{ x } C\,)/I_p],$$

where T °K is absolute temperature in kelvin (0°C = 273°K).

This formula is important because it discloses the parameters on which rise time depends. With a high I_p, the second term on the right side of Formula becomes negligible and *rise time is ultimately determined by the recombination lifetime*.

Manufacturers prefer to measure, not calculate, rise time, and typical values that can be found in data sheets range from 2 to 4 ns.



b)

Spectral Distribution

Under a weak pumping, such that quasi-Fermi levels lie within the bandgap and are at least a few $k_B T$ away from the band edges, the spectral density achieves its peak value at the frequency $v_p = (Eg + k_b T/2)/h$, *the FWHM of the spectral density is* $\Delta v \sim 1.8\, k_B T/h$. *The width express in terms of the wavelength* λ,

$$\Delta\lambda \sim 1.45 \lambda_p^2\, k_b T$$

Modulation bandwidth

Modulation bandwidth, *BW*, is the range of modulating frequencies within which detected electric power declines at –3 dB. In electronics, the general relationship between bandwidth and rise time is given by the well-known formula

$$BW = 0.35/t_r$$

Modulation bandwidth is limited by the recombination lifetime

This discrepancy occurs because if the forward current is modulated at angular frequency ω, an LED's output light intensity, $I(\omega)$, will vary as follows [5]:

$$I(\omega) = I(0) / \sqrt{[1+(\omega\tau)^2]}$$

where $I(0)$ is the LED's light intensity at constant current and τ is a carrier lifetime, as before. Detected electric power is proportional to I^2. Taking $I^2(\omega)/I^2(0) = ½$, which is a –3 dB decline, one can find from above formula that

$$BW = \Delta\omega = 1/\tau$$

This yields a very important principle: *An LED's modulation bandwidth is limited by the recombination lifetime of the charge carriers*. The physics governing this result is as follows: Suppose you excite an electron at the conduction band. It takes τ ns for this electron to fall to the valence band and recombine. During this interval you cannot change its status, so that if you turn off the forward current, you must wait τ ns until radiation will actually cease. This τ ns interval is necessary to allow a charge carrier to reach its destination. In other words, you cannot stop an excited electron that is on its way from the conduction band to the valence band. Thus, *lifetime τ puts a fundamental limit on the modulation bandwidth of an LED*. (You can repeat this reasoning using a *p-n* junction model: While an electron is moving through an active region, you cannot stop it; that is, you cannot change its status until this electron recombines.)

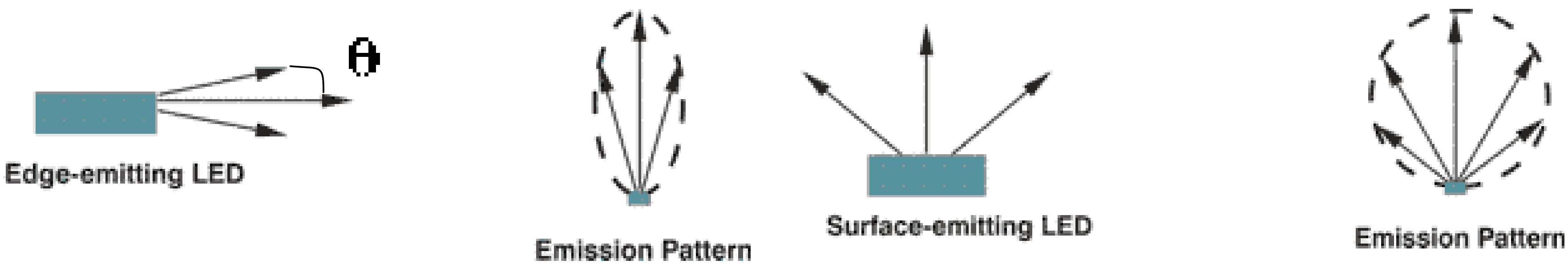
Active Material	Type	Radiating wavelength λ (nm)	Spectral width $\Delta\lambda$ (nm)	Output power into fiber (μW)	Forward current (mA)	Rise/fall time (ns)
AlGaAs	SLED	660	20	190–1350	20(min)	13/10
	ELED	850	35–65	10–80	60–100	2/2–6.5/6.5
GaAs	SLED	850	40	80–140	100	—
	ELED	850	35	10–32	100	6.5/6.5
InGaAsP	SLED	1300	110	10–50	100	3/3
	ELED	1300	25	10–150	30–100	1.5/2.5
	ELED	1550	40–70	1000–7500	200–500	0.4/0.4–12/12

Source: *Lightwave 1999 Worldwide Directory of Fiber-Optic Communications Products and Services*, March 31, 1999, pp. 58-61.

LED

There are two basic types of LED structures: edge emitters and surface emitters.

$$P = P_0 \cos\theta$$



output power is high (emitting spot is very small, typically 30-50 μm)

narrow emission spectra (FWHM is typically about 7% of the central wavelength)

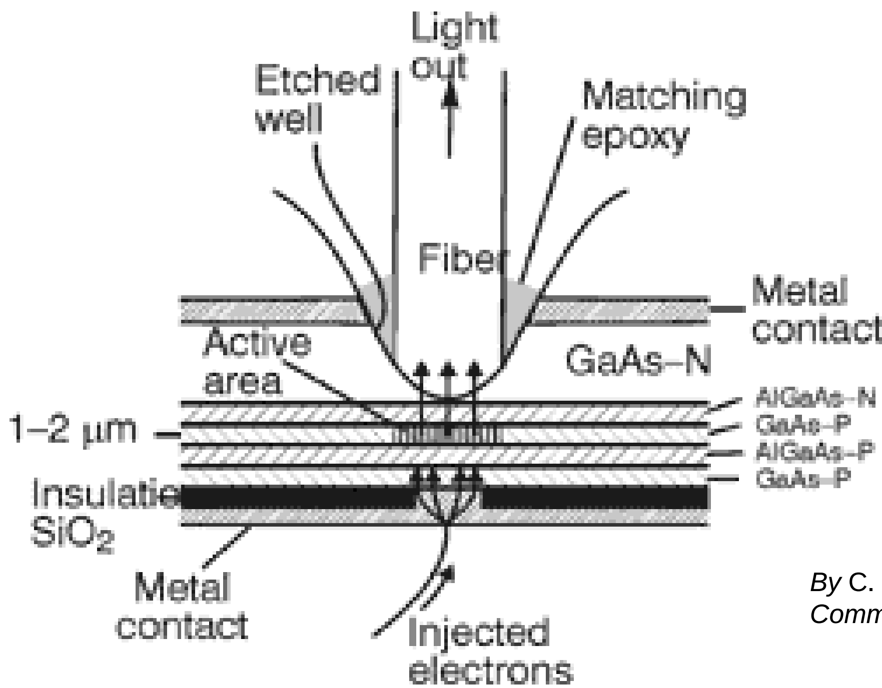
Narrow beam pattern

simple structure, are relatively inexpensive, offer low-to-moderate output power levels, and are capable of low-to-moderate operating speeds

output power is as high or higher than the edge-emitting LED, but the emitting area is large, causing poor coupling efficiency to the optical fiber

emit light in all directions

Surface-emitting LEDs



By C. A. Burrus and B. I. Miller, *Optical Communications* 4:307-69 (1971).

In surface-emitting LEDs (SLED) the radiation emanates from the surface. Example is a Burrus diode