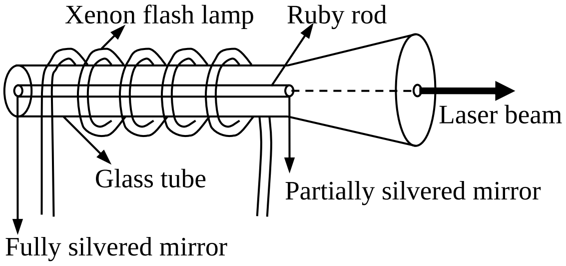
Chapter-2

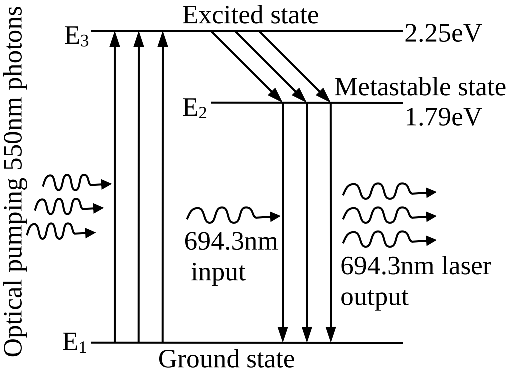
Laser Systems

2.1 Ruby laser

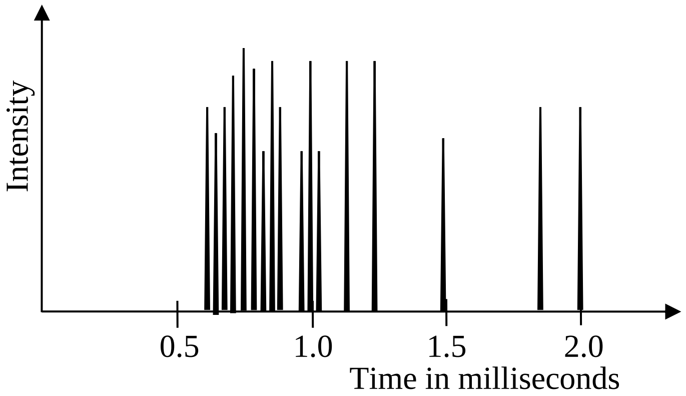
The first successful laser was fabricated by Maiman in 1960. It is a three-level solid state laser. Its main part is a ruby rod, whose ends are flat, with one of the ends is completely silvered and the other is partially silvered. Ruby is a crystal of aluminum oxide Al_2O_3 (corundum) doped with approximately 0.05 percent of chromium ions in the form of Cr_2O_3, so that some Al atoms in the crystal lattice are replaced by Cr^{3+} ions. The pink color of Ruby is due to the presence of chromium ions. The length of the ruby rod is an integral number of half wavelengths of the laser light, so that the radiation trapped in it forms an optical standing wave which will stimulate the induced emission. The ruby rod is surrounded by a glass tube. The optical pumping is achieved by a helical Xenon flash lamp surrounding glass tube containing the ruby rod.



The characteristic energy levels of Cr^{3+} ions are shown in the figure below. The lifetime of the atoms in the energy level labeled as E_3 is of the order of 10^{-8} second whereas that at the metastable state E_2 is about 0.003s. The Cr^{3+} ions are excited from the ground state E_1 to the state E_3 by absorbing light of wavelength 550 nm from the xenon flash lamp. Since the lifetime at E_3 is very small, the ions quickly undergo nonradiative transitions and fall to the metastable state. When the number of ions in the level E_2 is greater than that of E_1 the population inversion is achieved. Then photons of wavelength 694.3 nm produced by a spontaneous decay of some Cr^{3+} ions are reflected back and forth between the silvered ends of the ruby rod and stimulated other ions to radiate. As a result a large pulse of monochromatic coherent red light is emerged out through the partially silvered end of the rod. Once all the chromium ions in the metastable state have returned to the ground state the laser action stops. It is then necessary to send one more flash of pumping radiation from the xenon tube. Thus the ruby laser operates in pulses.



Spiking of a ruby laser: The output of a pulsed ruby laser is found to consist of a series of pulses of duration of a microsecond or less. Duration of an individual spike is of the order of 0.1 to 1 μs and the time interval between two adjacent spikes is about 1 to 10 μs. The power of each spike is of the order of 10^4 to 10^5 watt.

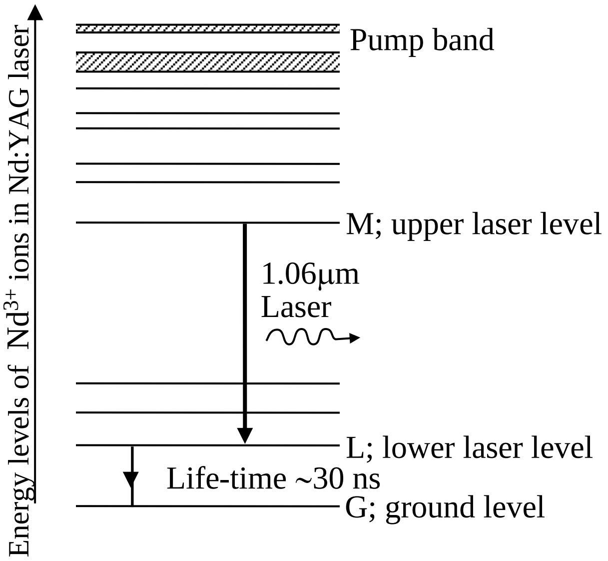


2.2 Nd:YAG Laser

There are many four level solid state lasers using rare-earth ions such as neodymium, erbium, dysprosium etc. in various crystals. An example of it is the laser using the energy levels of neodymium ion. The trivalent neodymium Nd^{3+} ions may be incorporated in various host materials like glass, yttrium aluminium garnet (YAG). Here we consider only the Nd:YAG laser.

Nd:YAG laser is a solid state laser using one of the rare-earth elements neodymium ion in a crystal of Yttrium Aluminium Garnet. The neodymium Nd^{3+} ions is incorporated in the $Y_3Al_5O_{12}$ abbreviated as YAG) crystal lattice. It is a four-level laser.

The Nd:YAG crystal has good optical quality and high thermal conductivity. The crystal size is limited to lengths of approximately 0.1 m and diameter of 12 mm. Doping concentration for Nd:YAG crystals are typically of the order of 0.725% by weight. The Nd ion concentration is $\sim 1.38\times10^{26}$ per m^3.



The energy level diagram of neodymium ions in the crystal is shown in the figure. Using a flash lamp or a continuous wave (cw) lamp the ions are excited to the levels above M. The pump threshold is much lower than that for ruby. These ions then relax down to the metastable level marked as M. The lifetime at the metastable level (upper laser level) is about 230 μs. L is an intermediate level (lower laser level) between the ground state G and the metastable state M. Since the energy difference between the lower laser level and the ground state is of the order of 0.26 eV, the ratio of the population of the lower laser level to that of the ground state at room temperature (T = 300 K) is given by $e^{-\frac{\Delta E}{k_B T}} \approx e^{-9} \ll 1$. This shows that the lifetime of lower laser level is very short ~30 ns. Thus, the lower laser level is almost unpopulated and hence the population inversion is easy to achieve. The main pump bands for the excitation of Nd ions are in the 0.81 μm and 0.75 μm wavelength region. The laser transition is between the levels M and L producing laser beam of wavelength about 1.06 μm, which lies in the infrared region. The emission line corresponds to the homogeneous broadening and has a width $\Delta\nu \approx 1.2\times10^{11}$ Hz ($\Delta\lambda \approx 4.5$ Å).

Neodymium doped lasers range from small diode-pumped version with outputs of a few milliwatts up to high average power lasers with average powers up to several kilowatts. The Nd:YAG lasers are categorized as

1. **Flaslamp-pumped Q-Switched Nd:YAG laser**

   One of the most useful types of Nd:YAG lasers is the flashlamp-pumped Q-switched oscillator-amplifier system. It consists of two linear flashlamps and a Nd:YAG laser rod of length 0.1 m and 6 mm diameter with its ends coated with antireflection coatings. The laser rod assembly is placed inside an unstable resonator laser cavity along with a Pockels cell Q-switching device.

2. **Flashlamp-pumped continuous wave (cw) Nd:YAG laser**

   The heading is really a misnomer due to two reasons. First reason is that the lamp is operated to produce continuous wave rather than pulsed waves. It is generally referred to as an arc lamp rather than flashlamp. Second reason is that, although the laser gain medium is pumped by a continuous wave arc lamp, the laser output is not actually a true continuous wave (cw) laser but instead a 200-300 ns pulses with an average power of as much as 15 watts. This type of laser is very effective for frequency doubling the 1.06 µm light to the green at 0.53 µm.

3. **Diode-pumped Nd:YAG laser**

A number of laser manufacturers are currently developing compact diode pumped Nd:YAG lasers. This laser produces single frequency output of greater than 10 mW and a linewidth less than 2 MHz with a consequently large longitudinal coherence length of greater than 150 m.

2.3 Argon ion Laser

The Argon ion laser is one of a class of noble-gas ion lasers, which typically generate multiple watts of optical power in a green or blue output beam with high beam quality. This laser is primarily continuous wave (cw) laser, although a few of these are commercially available as pulsed lasers.

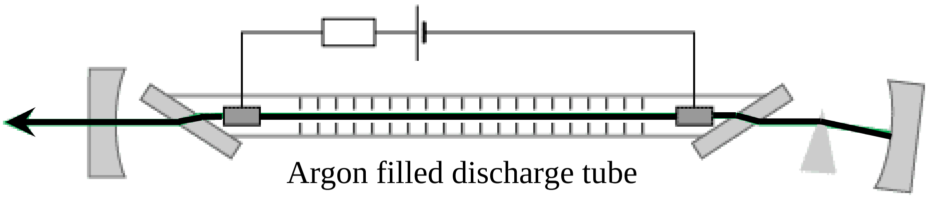


Fig.a

The core component of an argon ion laser is an argon-filled tube, made e.g. of beryllium oxide ceramics, in which an intense electrical discharge between two hollow electrodes generates a plasma with a high density of argon (Ar^+) ions. A solenoid around the tube (not shown in the figure) can be used for generating a magnetic field, which increases the output power by better confining the plasma. The lasers incorporate electron excitation resulting when the plasma electrons within the gas discharge collide with the argon ions.

The argon ion lasers operate in the high temperature plasma tubes with bores up to 1 to 2 mm diameter and with lengths ranging from 0.1 m to approximately 1.8 m. Excitation is done by a current discharge (with voltage drop across the tube may be 100 V or a few hundred volts, and the current can be several tens of amperes, so that the electric power is of the order of several tens of kilowatts) that passes along the length of the tube, concentrated in the small bore. The high current density in the centre of the tube ionises the gas and provides the energy to excite the ions to the lasing energy levels. The dissipated heat must be removed with a water flow around the tube. There are smaller air-cooled argon ion lasers, generating some tens or hundreds of milliwatts of output power from several hundred watts of electric power.

The Argon ion laser can provide approximately 25 visible wavelengths ranging from 408.9 nm to 686.1 nm and more than 10 ultraviolet wavelengths ranging from 275 nm to 363.8 nm. By frequency doubling wavelengths as short as 229 nm can also be produced. In the visible spectral region cw powers up to 100 watt are available, with the output concentrated on a few strong lines mainly 488 nm and 514.5 nm. The emission and gain bandwidth of these lasers is determined primarily by Doppler broadening with a width on each laser transition is of the order of 2.5 GHz.

Commercial argon ion lasers are generally manufactured in three sizes. They are,

1. High power large-frame water cooled.
2. Medium power small-frame water cooled.
3. Low power air cooled.

Excitation mechanism and energy level diagram:

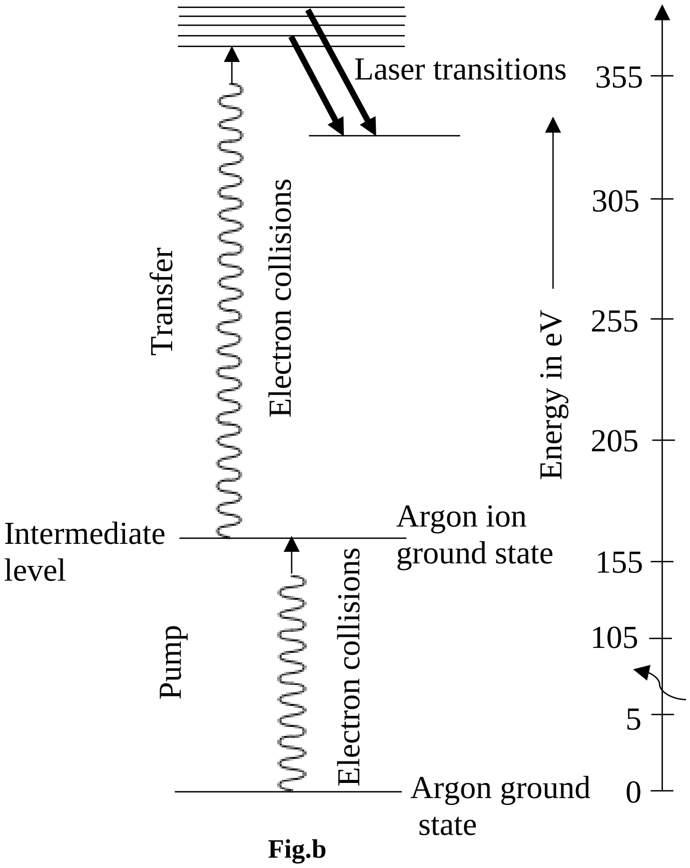


Fig.b

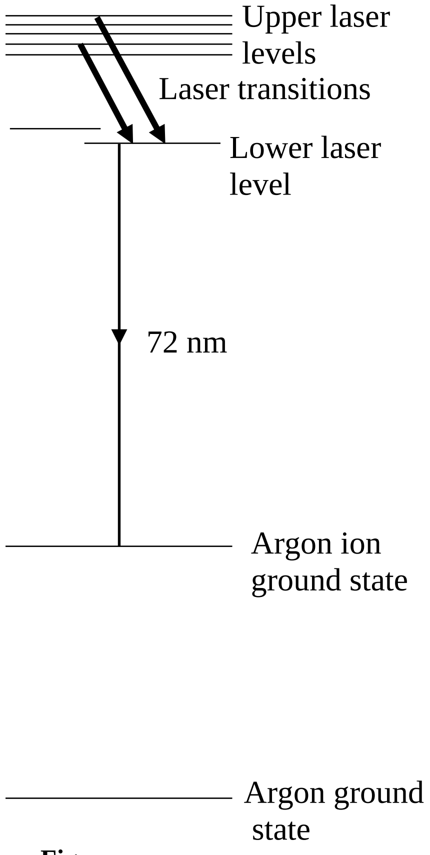


Fig.c

Excitation occurs in a different way for the pulsed argon laser and the cw argon laser.

(a) **Pulsed visible laser transitions**: The pulsed laser transition occurs via a single step process. In this process the electrons collide with argon atoms in the $3p^6$ ground state and excite them directly to the set of $3p^4 4p$ upper laser levels in the Ar^+ ions.

(b) **Continuous wave (cw) argon laser**: In this case the excitation is a two-step process as shown in fig.b, where the electrons first collide with the ground state neutral argon atoms to produce ground state argon single ions. The second step involves the electron collisional excitation from the argon ion ground state to the upper laser levels. The population inversion is established between the upper laser levels involving $3p^4 4p$ configurations and the lower laser levels of $3p^4 4s$ electronic configuration. The population inversion is produced on transitions between all of these upper levels and lower levels owing to the rapid decay of the lower laser levels (72 nm transitions) as indicated in the fig.b.

The two-step excitation process leads to a laser power output that is proportional to the square of the discharge current. Thus, it is most desirable to operate these lasers at extremely high discharge currents.

2.4 Helium-Neon laser

The helium-neon laser, which was first fabricated by Ali Javan and his co-workers at Bell Telephone Laboratories in U S A, is the first gas laser operated successfully.

The He-Ne laser consists of a mixture of helium and neon in the ratio of about 10:1 enclosed in a tube of about 0.5 m in length and 5 mm in diameter at a low pressure of about 1mm of mercury (1 torr). The two mirrors, one is 100% reflecting and the other is partly transparent, kept inside at the ends of the tube act as the resonator. The distance between the mirrors is equal to an integral number of half the wavelength of the laser light. The gas inside the tube is excited by an electric discharge produced in the gas by means of two electrodes connected to a source of high frequency alternating current.

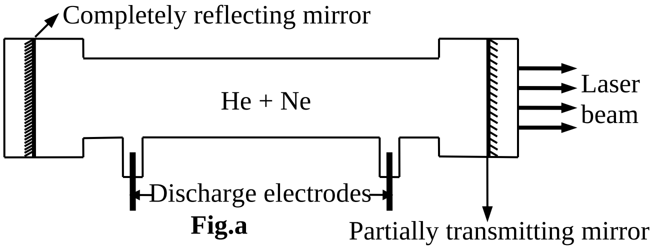


Fig.a

When the electric discharge is passed through the gas mixture the electrons collide with the helium atoms. Thus the helium atoms are excited to the 2s level as shown in fig.b, while the neon atoms are much less readily excited by the electron collision. The excited state 2s of He is relatively long lived. The energy 20.61 eV of this level is almost same as the energy 20.66eV of the 5s level of neon atoms. Hence the energy of the helium atom is easily transferred to neon atoms when they collide. The additional energy is being provided by the kinetic energy of the atoms. The population inversion in He-Ne laser is between the 5s and 3p (18.70eV) states of neon. The purpose of the He atoms is to help to achieve a population inversion in the neon atoms. A spontaneous transition from 5s to 3p state emits a photon of wavelength 632.8 nm which triggers the stimulated transitions resulting in the emission of narrow red laser beam through the partly transmitting mirror. The transitions from 3p to 3s are spontaneous but not coherent. Finally, the neon atoms undergo radiationless transitions to the ground state.

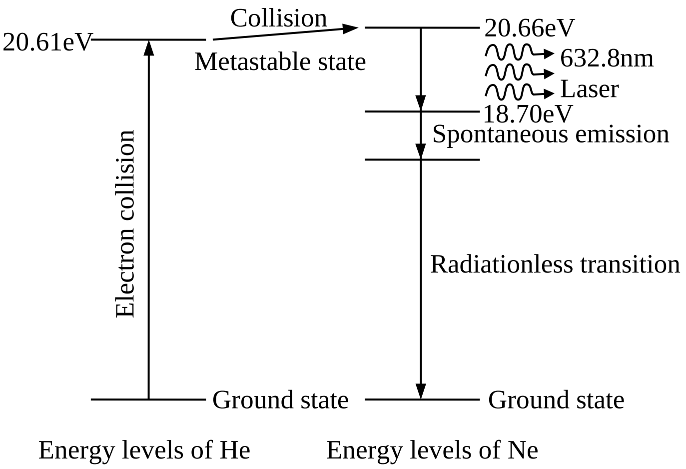


Fig.b

Typical power outputs of helium-neon lasers lie between 1 and 50 mW of continuous wave for inputs of about 5 to 10 W.

Unlike the ruby laser, the He-Ne laser operates continuously. This is because the electron collisions that excite the He and Ne atoms occur at all times. The laser light from the gas lasers is found to be more directional and much more monochromatic than that of the solid state lasers because of the disadvantage such as various imperfections in the solids and the heating caused by the flash lamp are absent here. The gas lasers are also capable of supplying a continuous laser beam without the need for elaborate cooling arrangements.

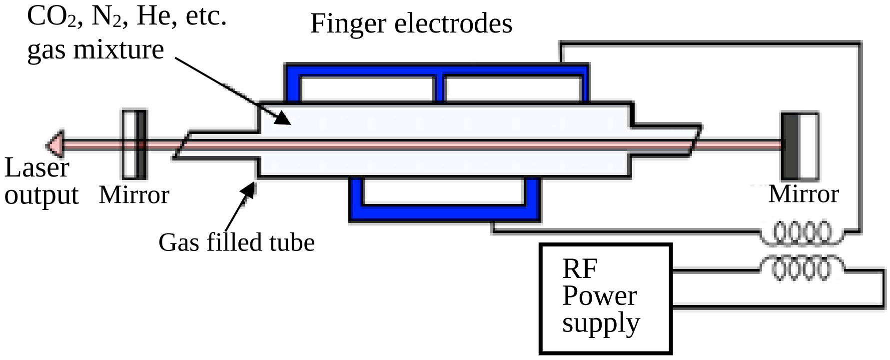
One disadvantage of using the internal mirrors is their erosion due to the gas discharge. Even though having the resonator mirrors outside the cavity provides greater flexibility, then the ends of the discharge tube causes a loss due to reflection.

He-Ne laser is used in supermarkets to read bar codes.

2.5 The Carbon dioxide laser

The carbon dioxide laser (CO2 laser) was one of the earliest gas lasers to be developed (invented by Kumar Patel of Bell Labs in 1964), and is still one of the most useful. Carbon dioxide lasers are the highest-power continuous wave lasers that are currently available. They are also quite efficient: the ratio of output power to pump power can be as large as 20%. The

CO2 laser produces a beam of infrared light with the principal wavelength bands centering on 9.6 and 10.6 micrometers.



The active laser medium (laser gain/amplification medium) is a gas discharge which is air-cooled (water-cooled in higher power applications). The filling gas within the discharge tube consists of around 10–20% carbon dioxide (CO_2), around 10–20% nitrogen (N_2), a few percent hydrogen (H_2) and/or xenon (Xe) (usually only used in a sealed tube), and the remainder of the gas mixture helium (He). The specific proportions vary according to the particular laser.

The population inversion in the laser is achieved by the following sequence: electron impact excites vibrational motion of the nitrogen. Because nitrogen is a homonuclear molecule, it cannot lose this energy by photon emission, and its excited vibrational levels are therefore metastable and live for a long time. Collisional energy transfer between the nitrogen and the carbon dioxide molecule causes vibrational excitation of the carbon dioxide, with sufficient efficiency to lead to the desired population inversion necessary for laser operation. There are three modes of vibration the symmetric stretching as shown in fig.a, bending mode shown in fig.b and asymmetric stretching as shown in fig.c. Each vibrational level is further divided into rotational sublevels. The nitrogen molecules are left in a lower excited state. Their transition to ground state takes place by collision with cold helium atoms. The resulting hot helium atoms must be cooled in order to sustain the ability to produce a population inversion in the carbon dioxide molecules. In sealed lasers, this takes place as the helium atoms strike the walls of the container. In flow-through lasers, a continuous stream of CO2 and nitrogen is excited by the plasma discharge and the hot gas mixture is exhausted from the resonator by pumps.

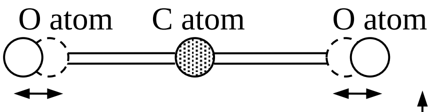


Fig.a
Symmetric stretching

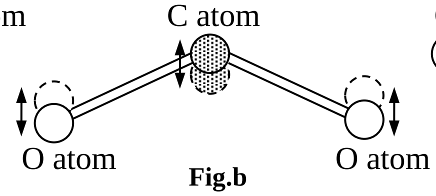


Fig.b
Bending mode

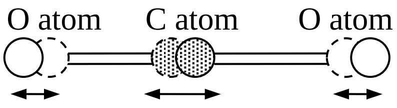
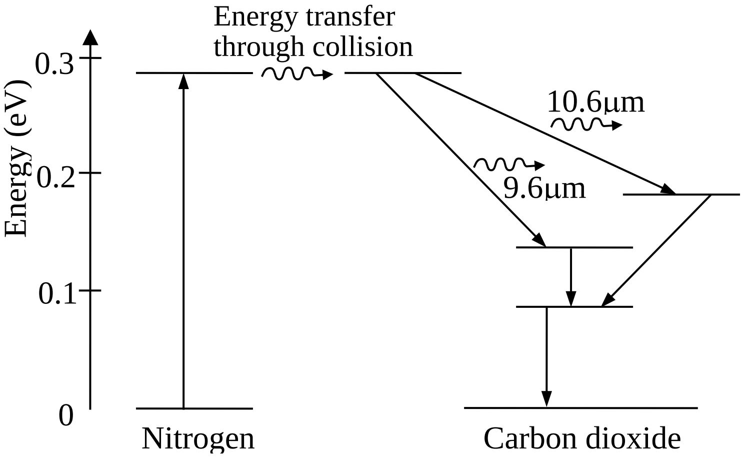


Fig.c
Asymmetric stretching

Because CO_2 lasers operate in the infrared, special materials are necessary for their construction. Typically, the mirrors are silvered, while windows and lenses are made of either germanium or zinc selenide. For high power applications, gold mirrors and zinc selenide windows and lenses are preferred. There are also diamond windows and lenses in use. Diamond windows are extremely expensive, but their high thermal conductivity and hardness make them useful in high-power applications and in dirty environments. Optical elements made of diamond can even be sand blasted without losing their optical properties. Historically, lenses and windows were made out of salt (either sodium chloride or potassium chloride). While the material was inexpensive, the lenses and windows degraded slowly with exposure to atmospheric moisture.



The most basic form of a CO_2 laser consists of a gas discharge (with a mix close to that specified above) with a total reflector at one end, and an output coupler (a partially reflecting mirror) at the output end.

The CO_2 laser can be constructed to have continuous wave (CW) powers between milliwatts (mW) and hundreds of kilowatts (kW). It is also very easy to actively Q-switch a CO_2 laser by means of a rotating mirror or an electro-optic switch, giving rise to Q-switched peak powers of up to gigawatts (GW).

Applications of CO_2 laser

Industrial (cutting and welding): Because of the high power levels available (combined with reasonable cost for the laser), CO_2 lasers are frequently used in industrial applications for cutting and welding, while lower power level lasers are used for engraving.

Medical (soft-tissue surgery): They are also very useful in surgical procedures because water (which makes up most biological tissue) absorbs this frequency of light very well. Some examples of medical uses are laser surgery and skin resurfacing ("laser facelifts", which essentially consist of vaporizing the skin to promote collagen formation). Also, it could be used to treat certain skin conditions such as hirsuties, papillaris, genitalis by removing embarrassing or annoying bumps, podules, etc. Researchers in Israel are experimenting with using CO_2 lasers to weld human tissue, as an alternative to traditional sutures. The CO_2 laser remains the best surgical laser for the soft tissue where both cutting and haemostasis is achieved photo-thermally (radiantly). CO_2 lasers can be used in place of a scalpel for most procedures, and are even used in places a scalpel would not be used, in delicate areas where mechanical trauma could damage the surgical site. CO_2 lasers are the best suited for soft tissue procedures in human and animal specialties, as compared to other laser wavelengths. Advantages include less bleeding, shorter surgery time, less risk of infection, and less post-op swelling. Applications include gynaecology, dentistry, oral and maxillofacial surgery, and many others.

Other applications: The common plastic poly (methyl methacrylate) (PMMA) absorbs IR light in the 2.8–25 μm wavelength band, so CO_2 lasers have been used in recent years for fabricating microfluidic devices from it, with channel widths of a few hundred micrometers. Because the atmosphere is quite transparent to infrared light, CO_2 lasers are also used for military range finding using LIDAR techniques. CO_2 lasers are used in the Silex process to enrich uranium. The Soviet Polyus was designed to use a megawatt carbon-dioxide laser as an orbit to orbit weapon to destroy SDI satellites.

2.6 Fiber Laser

The first fiber laser was operated in Nd-doped glass fiber. Here we discuss only the erbium-doped fiber amplifier. Its operating wavelength is 1.53 μm, a wavelength that is very close to the optimum wavelength 1.55 μm for fiber communication.

Laser structure: Fig.a shows a diagram of an erbium-doped fiber amplifier incorporated into a section of a long distance optical fiber transmission line. It consists of

1. A diode pump laser.
2. A wavelength selective coupler, that allows the pump wavelength to enter the fiber transmission system without disturbing the signal.
3. An erbium-doped fiber amplifier spliced into the optical fiber transmission system.
4. An optical isolator.

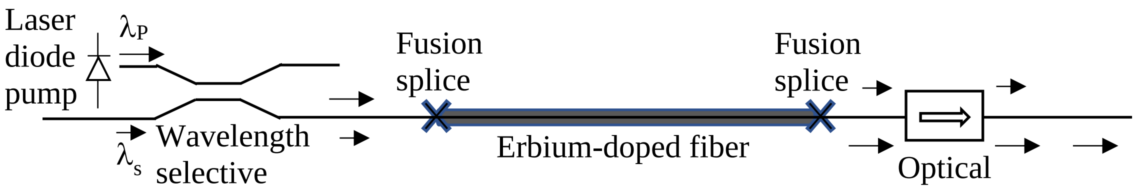


Fig.a

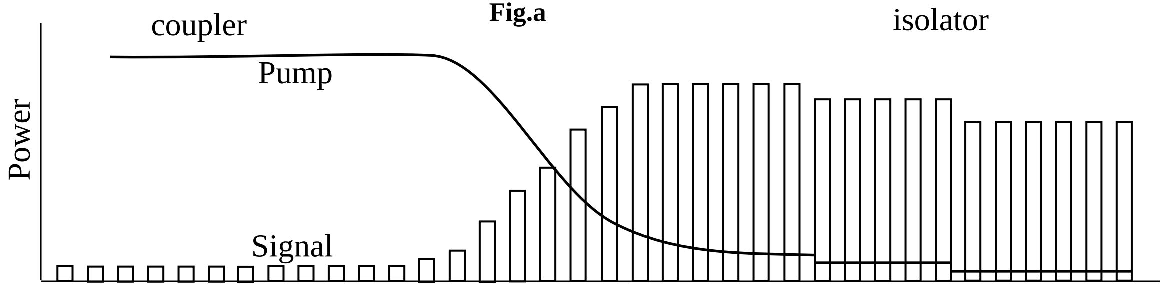


Fig.b

The diode laser continually pumps the fiber and as the signal pulses pass through the system they are amplified, while the pump beam is depleted as shown in the fig.b.

Excitation mechanism: Fig.c shows the energy level diagram for the erbium-doped fiber laser. Optical pumping can take place in two ways.

1. From the ground state ${}^4I_{15/2}$ to the excited states ${}^4I_{11/2}$ at a wavelength of 0.98 µm.
2. From the ground state ${}^4I_{15/2}$ to the upper laser states at 1.48 µm.

When the pumping occurs to the excited states ${}^4I_{11/2}$ as mentioned in the first case, there is rapid relaxation from this state to the upper laser states. If the pumping is direct to the upper laser state as mentioned in the second case, rapid relaxation occurs from the higher-lying levels to the lowest lying levels of the upper laser levels and the laser transition occurs from this low-lying upper laser states to the ground state. The laser output then occurs in the region of 1.53– 1.56 µm. Consequently, the higher-lying levels of the upper laser states are not significantly populated and rapidly decays non-radiatively to the lower levels of the upper laser state.

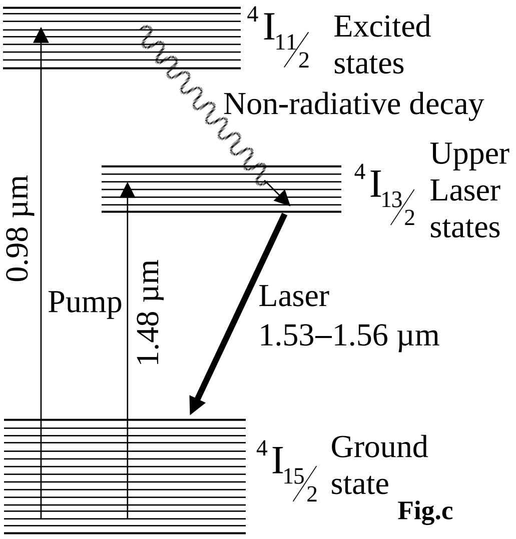


Fig.c

Applications

1. Primary application of the erbium-doped fiber laser is in long-distance communication over fiber optic networks.
2. It is especially useful in undersea communication links through which amplification of the optical signal can be accomplished directly by inserting pieces of erbium-doped fiber at the appropriate locations in the fiber network. The optically transmitted signal will thus obtain a direct boost (amplification) as it travels from one continent to another.

3. They are used to produce ultra-short pulses with pulse widths as short as 100 fs (femto second) and pulse repetition frequencies of up to 10 GHz.
4. Because of their simplicity they are under consideration as possible replacements for distributed-feedback semiconductor lasers.

2.7 Semiconductor Lasers

Most semiconductor lasers are laser diodes, which are pumped with an electrical current in a region where an n-doped and a p-doped semiconductor material meet. For example, if the level of current flowing through a Gallium Arsenide p-n junction is increased beyond a certain threshold, a lasing action takes place in which the spontaneous emission stimulates an increase in the radiant power. However, there are also optically pumped semiconductor lasers, where carriers are generated by absorbed pump light, and quantum cascade lasers, where intra-band transitions are utilized.

Semiconductor lasers are unique when compared to other types of lasers by the following reasons.

1. They are very small
2. They operate with relatively low power input.
3. They are very efficient.

Semiconductor lasers operate in a different way from other lasers. They require the merging of two different materials, n-type material and p-type material. The laser action occurs in the interface between these two materials.

Types of semiconductor laser devices: There are two types of semiconductor laser devices. They are,

1. **Edge emitting laser**: These type of semiconductor lasers has the laser beam parallel to the surface of the p-n junction region as shown in fig.a. A pair of parallel faces perpendicular to the plane of the junction is polished optically flat. The other two faces are roughened to avoid lasing in the directions other than the main one. The structure is called a Fabry-Perot cavity. Typically, the mirrors are produced by using the cleaved surfaces at the ends of the laser crystal, or, by distributed feedback (DFB) within the crystal, or, distributed Bragg reflecting structures at the ends of the crystal.

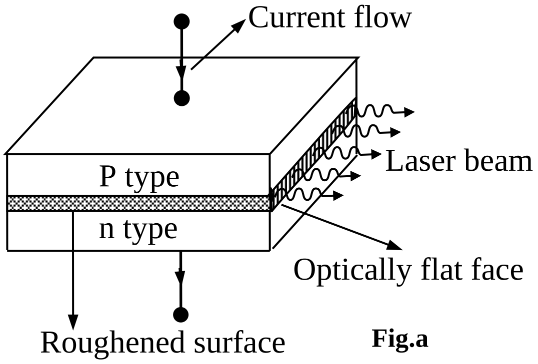


Fig.a

2. **Surface emitting lasers**: They have laser beam emitting in a direction perpendicular to the junction region with multilayer Bragg reflecting mirrors incorporated into the crystal as shown in fig.b.

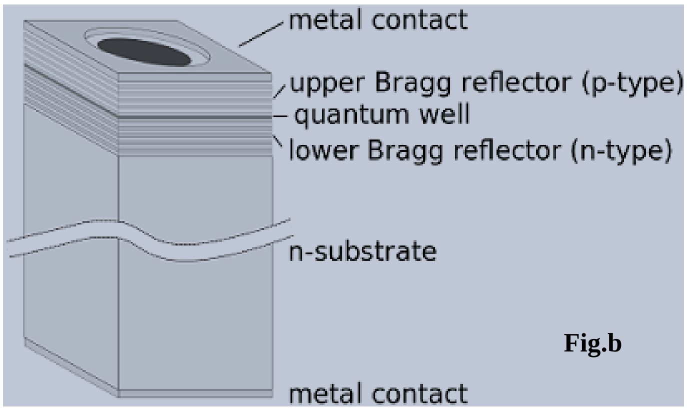
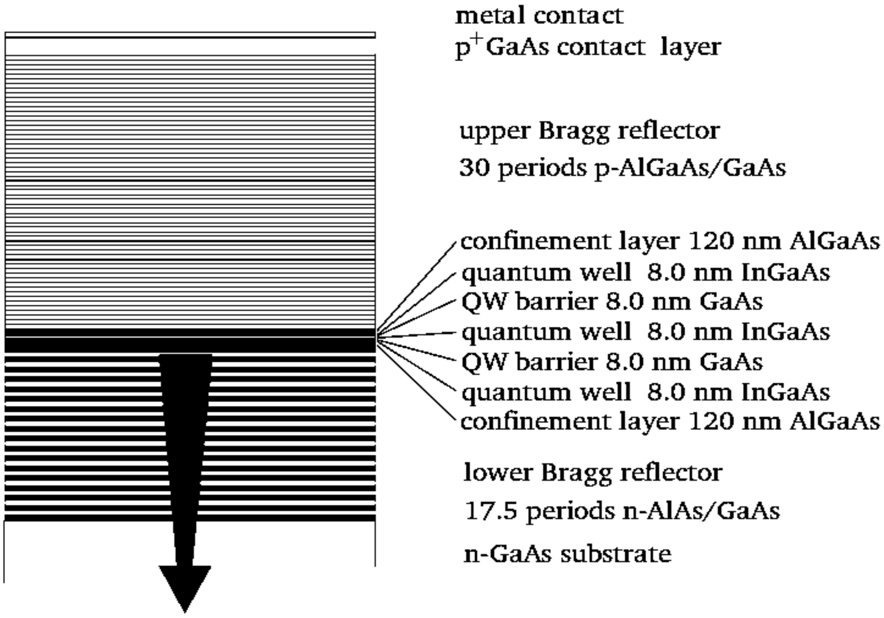


Fig.b



Semiconductor laser materials

Depending upon the wavelength region of interest semiconductor lasers are based upon one of the four different types of materials.

Three of them are referred to as III−V semiconductors. They consist of the materials in column III and V of the periodic table. Column III elements include A*l*, Ga, In and T*l*. These materials are trivalent and lack one electron in the crystalline matrix (covalent bond). The column V materials are N, P, As and Sb are pentavalent and one electron excess during the bond formation.

The fourth type of materials are referred to as II−VI compounds. The column II atoms lack two electrons and column VI atoms have two extra electrons available for a binary compound. The column II materials are Zn and Cd. The column VI atoms are S, Se and Te. Column II materials can combine to column VI materials to form binary compounds. An example is ZnSe, which has a bandgap of 2.71 eV and forms the basis for blue-green semiconductor lasers.

The semiconductor laser crystals are grown by the process of epitaxial growth.

Group	Material	Abbreviation	Bandgap in eV
III−V	Alumimum arsenide	A*l*As	2.16
	Alumimum phosphide	A*l*P	2.45
	Alumimum antimonide	A*l*Sb	1.58
	Boron nitride	BN	7.5
	Boron phosphide	BP	2.0
	Gallium arsenide	GaAs	1.42
	Gallium nitride	GaN	3.36
	Gallium phosphide	GaP	2.26
	Gallium antimonide	GaSb	0.72
	Indium arsenide	InAs	0.36
	Indium phosphide	InP	1.35
	Indium antimonide	InSb	0.17

II–VI	Cadmium sulphide	CdS	2.42
	Cadmium selenide	CdSe	1.70
	Cadmium telluride	CdTe	1.56
	Zinc sulphide	ZnS	3.68
	Zinc selenide	ZnSe	2.71
	Zinc telluride	ZnTe	2.393

Other common materials (alloys) for semiconductor lasers are

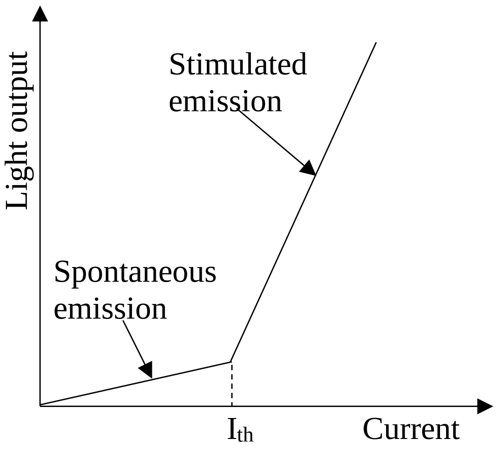
- AlGaAs (aluminum gallium arsenide)
- InGaP (indium gallium phosphide)
- InGaAs (indium gallium arsenide)
- GaInNAs (indium gallium arsenide nitride)
- GaInP (gallium indium phosphide)

Four basic types of laser materials

1. Gallium-Arsenide based lasers: Laser output lies in the red and near infra-red region with the wavelength range 635 nm – 870 nm.
2. Indium-phosphide based lasers: 1.55 µm (1550 nm)
3. Zinc-selenide based lasers: Blue and green portion of the spectrum; 460 nm – 520 nm.
4. Gallium-Nitride based laser: The most recently developed class of semiconductor laser are those based upon GaN compound and related alloys. Laser produced lies in the blue and the ultraviolet wavelengths.

Operation of semiconductor laser: When the diode is forward biased current flows across the junction due to electrons and holes. As the bias increases, the current also increases. Figure shows the typical output of a semiconductor laser versus the current flowing the semiconductor laser. Two cases may arise.

1. Current is low: For low currents (below the threshold current), incoherent light (due to the spontaneous emission) is emitted from the junction when the recombination process occurs. This is the light associated with the light-emitting diodes (LED).
2. High currents: If the current is high enough (above the threshold current) there are more electrons in the conduction band at a given energy than in the valance band and thus the population inversion is achieved. When the current reaches the threshold value the stimulated emission occurs and the laser beam is emitted from the junction.



Semiconductor lasers may be operated on a pulsed basis by applying pulses of voltage across the junction. Semiconductor lasers can also be produced by optical pumping, i.e. electrons are excited to the conduction band by absorbing photons.

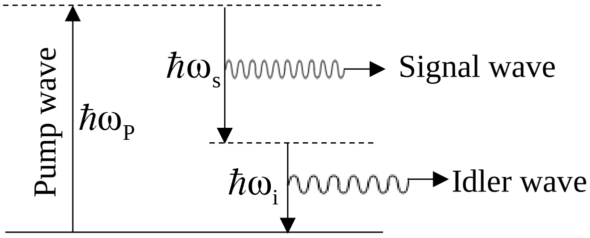
Commercial laser diodes emit at wavelengths from 375 nm to 1800 nm, and wavelengths of over 3 µm have been demonstrated. Low power laser diodes are used in laser printers and CD/DVD players. More powerful laser diodes are frequently used to optically pump other lasers with high efficiency. The highest power industrial laser diodes, with power up to 10 kW (70 dBm), are used in industry for cutting and welding.

The advantages of semiconductor lasers are that they are compact, efficient and can be fabricated with ease. However, their monochromaticity, coherence and directionality are inferior to those of other lasers.

2.8 Optical parametric Oscillator

Till now we have discussed the production of laser (coherent light) by light amplification by stimulated emission. Now we discuss another method of producing the coherent light. An *optical parametric oscillator* (OPO) is a coherent source of light like a laser but it uses the process of light amplification brought about by the phenomenon of nonlinear (second order) interaction in a crystal. We will discuss the nonlinear interaction and the phenomenon of frequency mixing in detail in the third chapter, *nonlinear optics*. The first OPO was first demonstrated by Giordmaine and Miller in 1965.

Nonlinear crystals are used as parametric media for the parametric generation of light (similar to nonlinear capacitors shows a parametric phenomenon in electronics), which is based on optical mixing.



Solid line: Real energy level
Dashed line: Virtual energy level

Fig.a

OPO converts an input laser wave (called "pump") with frequency ω_P into two output waves of frequencies ω_s and ω_i by means of second-order nonlinear optical interaction such that,

$$\hbar\omega_P = \hbar\omega_s + \hbar\omega_i$$

i.e. $$\omega_P = \omega_s + \omega_i$$

For historical reasons, the two output waves are called "signal" and "idler", where the output wave with higher frequency is the "signal" and the other "idler". Or, the desired amplified output wave is the signal and the unwanted output wave is the idler.

To obtain a high power by parametric amplification we use a uniaxial crystal with a relatively high nonlinear susceptibility, which is cut according to the requirement of the wave synchronism and is placed inside an optical resonator. A laser with output beam of frequency ω_P is used for pumping the parametric amplifier. The intensity of the pump beam must be high enough to activate the nonlinear properties of the crystal so as to compensate the losses that may occur. The mirrors of the resonator must have high reflectances for the resonant frequencies ω_s and ω_i (for doubly resonant OPOs and for singly resonant OPOs high reflectances for the selected frequency ω_s) and high transmittance for the pump frequency ω_P (and the frequency to be rejected). The parametric amplifier, under these conditions, goes into oscillations at both the frequencies ω_s and ω_i. The process is known as *parametric oscillation* and the device used for this purpose is called the *optical parametric oscillator*.

Most OPOs are singly resonant, i.e., they have a resonator which is resonant at either the signal or the idler wavelength, but not for both. However, there are also doubly resonant OPOs, where both signal and idler are resonant. The latter makes sense only with a single-frequency pump laser. We now consider only the single resonant oscillator which is resonant at the signal wave.

Singly resonant oscillator: Fig.b sows the schematic diagram of singly resonant oscillator. It consists of a nonlinear crystal placed inside an optical resonator. The crystal is pumped by a pump laser operating at the frequency ω_P. The resonator mirrors are such that both of them have high transmittivity at the pump and the idler wavelengths (all wavelengths we want to reject from the resonator) while the mirrors have high reflectivity at the signal wavelength (selected wavelength). Thus, the resonator provides for feedback only at the signal wavelength and it is the signal wavelength which can oscillate in the cavity, provided the loss in signal wave is compensated by the gain in the signal wave due to nonlinear interaction (second order nonlinearity).

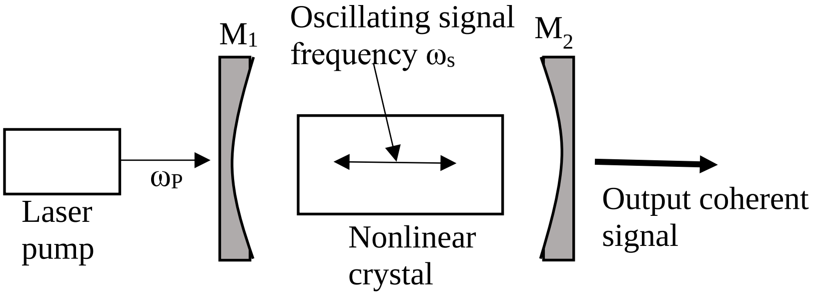


Fig.b

Now when the crystal is pumped by the external laser, then initially spontaneous parametric fluorescence (generation of signal and idler waves from pump photons) takes place and if the phase matching condition is satisfied, then this leads to the spontaneous generation of the frequencies ω_s and ω_i. This is similar to spontaneous emission in a laser cavity that initiates the laser oscillation. This spontaneously emitted signal and idler propagates through the crystal and their amplitude change. When these waves reach one of the mirrors, say M_2, only signal gets reflected and the pump and idler waves are transmitted and escaped from the resonator. Thus, only the signal propagates in the reverse direction. Since the phase matching condition is not satisfied in the reverse direction the signal suffers loss and hence no gain. When the signal reaches the first mirror it undergoes partial reflection and transmission. The reflected wave again undergoes nonlinear interaction and its amplitude increases. In such a cavity only oscillations with signal frequency is built up within the cavity and since the idler wave does not build up its amplitude can be neglected.

In the case of doubly resonant oscillator, both the mirrors have high reflectivity at the signal and idler wavelengths and thus both the waves are resonant within the cavity.

The most promising use of a parametric oscillator is that it can be used to generate tuneable laser light. Tuning of a parametric oscillator can be achieved by controlling the frequency of the secondary waves (signal and idler) generated.

There are several methods to control the frequency. One of these is to rotate the crystal in such a way that different frequencies are phase matched. The other method is to vary the crystal temperature, whose refractive index is a function of temperature.

Comparison OPO with Lasers

Although parametric oscillators are in many respects similar to lasers, there are also a couple of important differences:

- Whereas many lasers can be operated with spatially incoherent pump sources, a parametric oscillator requires relatively high spatial coherence of its pump. In most cases, a diode-pumped solid-state laser is used.
- Whereas the emission wavelength of most lasers can be tuned only in a narrow range, many parametric oscillators offer the potential for wavelength tuning with extremely wide tuning ranges. These may span regions in the visible, near or mid-infrared part of the electromagnetic spectrum. Particularly in the mid-infrared region, OPOs are very commonly used, because there is little competition from mid-IR lasers.
- The parametric amplification process requires phase matching to be efficient. The phase-matching details also determine the oscillation wavelength. Wavelength tuning is in most cases achieved by influencing the phase-matching conditions, e.g. by changing the crystal temperature, the angular orientation of the crystal (for critical phase matching), or the poling period (for quasi-phase matching in periodically poled

crystals). Within the phase-matching bandwidth, tuning is also possible with an intracavity optical filter. The tuning range can be limited either by restrictions of phase matching (see below), or by the transparency region of the nonlinear material or by the spectral region with high reflectivity of the resonator mirrors.

- The parametric amplification occurs only in the direction of the pump beam (as another consequence of phase matching), which means that a unidirectional operation in a ring resonator is automatically obtained. (In fact, ring resonators are often used, due to various advantages.)
- No heat is deposited in the nonlinear crystal, unless there is some parasitic absorption at the pump, signal or idler wavelength. As OPOs are mostly operated with all wavelengths involved lying well within the transparency region, there is normally not much heating. Only at fairly high power levels may a disturbance of the phase-matching conditions occur. Thermal lensing is usually not significant.
- An idler wave is generated, which carries away the difference between the generated signal power and the absorbed pump power. (Only in the rarely used case of *degenerate parametric oscillation*, is there no idler wave.) More precisely, the photon energy of the idler wave is the difference in the photon energies of the pump and signal. The idler wave plays an essential role in the nonlinear conversion process; when an OPO is operated in a spectral region with strong idler absorption in the crystal, the threshold pump power can be much higher, and the efficiency lower.
- No energy is stored in the nonlinear crystal. Therefore, the gain is present only as long as the pump wave is there, and pump fluctuations directly affect the signal power. The dynamics are therefore different to laser dynamics.
- Other than the fluorescence of a laser gain medium, parametric fluorescence occurs only in the direction of the pump beam. More precisely, it is observed in those modes which experience parametric gain.

Types of Optical Parametric Oscillators

Q-switched Pump: The majority of OPOs are pumped with a Q-switched laser. The pulses from the laser emit on the order of nanoseconds, allowing the system to easily overcome the threshold for oscillation. This threshold is the excitation level where the laser’s output is driven by stimulated emission; at this point the system is “lasing.” Oscillators with Q-switched pumps typically produce a shorter output pulse with a larger linewidth. These systems are typically singly-resonant and pumped with an actively Q-switched Nd:YAG laser. The short-produced pulses have energies in the microjoule to millijoule range and frequencies in near- to mid-infrared region.

Continuous Wave Pump: Continuous wave lasers can also pump OPOs. This pump works best with a highly nonlinear crystal gain medium such as the LiNbO3. Continuous wave pumps are best for single-frequency applications.

Mode-Locked Pump: Researchers can use mode-locked lasers to pump OPOs and produce ultrashort pulses of light. The frequency within the resonator of these oscillators matches the pulse repetition rate of the pump. This provides output pulses with high energy while requiring significantly less than 1 Watt of power for the pump.