Basic Principles of Lasers

To explain the process of light amplification in a laser requires an understanding of the energy transition phenomena in the atoms of its active medium. They include: spontaneous emission, stimulated emission/absorption and non-radiative decay.

The theory of quantum mechanics states that the electrons of atoms can take different energy states, E1, E2, E3, for example, with E1<E2<E3.

Spontaneous Emission

By quantum mechanics the lower energy level is more stable than higher energy levels, so electrons tend to occupy the lower level. Those electrons in higher energy levels decay into lower levels, with the emission of EM radiation. This process is called *spontaneous emission*. The radiation emitted is equal to the energy difference between the two levels.

$E2 - E1 = hn_0$

Where E2 is the upper energy level

E1 is the lower energy level

h is Plank’s constant

n_0 is frequency of the radiated EM wave.

Stimulated Emission

This is crucial if lasing is to occur. Suppose the atoms of the active medium are initially in E2. If external EM waves with frequency n_0 that is near the transition frequency between E2 and E1 is incident on the medium, then there is a finite probability that the incident waves will force the atoms to undergo a transition E2 to E1. Every E2-E1 transition gives out an EM wave in the form of a photon. We call this *stimulated emission* since the process is caused by an external excitation. The emitted photon is in phase with the incident photon, has the same wavelength as it and travels in the same direction as the incident photon.

Stimulated Absorption

If the atom is initially in the ground level E1, the atom will remain in this level until it gets excited. When an EM wave of frequency n_0 is incident on the material, there is a finite probability that the atom will absorb the incident energy and jump to energy level E2. This process is called Stimulated Absorption.

Non-Radiative Decay

Note that the energy difference between the two levels can decay by *non-radiative decay*. The energy difference can change into kinetic energy or internal energy through collisions with surrounding atoms, molecules or walls.

Population Inversion

Normally the population of the lower energy levels is larger than that of the higher levels. The processes of stimulated radiation/absorption and spontaneous emission are going on in the same time, yet even if we ignore the decay factors, stimulated absorption still dominates over stimulated radiation. This means that the incident EM wave cannot be amplified in this case.

Amplification of incident wave is only possible when the population of the upper level is greater than that of the lower level. This case is called *Population Inversion*. This is a mechanism by which we can add more atoms to the metastable level and hold them there long enough for them to store energy, thereby allowing the production of great numbers of stimulated photons.

To do this, we pump atoms into the metastable level at a rate that exceeds the rate at which they leave. A large number of atoms are therefore excited to and held in this level, leaving an almost empty level below it. The atoms stay in this metastable level without de-exciting while the population builds up, giving rise to a population inversion.

In practise laser action cannot be achieved for only two levels, as described above. Three and four level systems work however. An analysis of these systems follows, followed by a description of the pumping schemes for each system.

(Note: A metastable level is one that has a long lifetime and the for which the probability of spontaneous emission is low. This favours conditions for stimulated emission. If an atom is excited to a metastable state it can remain there long enough for a photon of the correct frequency to arrive. This photon will then stimulate the emission of a second photon.)

Amplification of Light

If population inversion exists, N2>N1, the incident signal will be amplified. The incident signal has energy equal to the number of photons times the photon energy we have

U(x) = nhn. The increase in the signal is given by

$$\frac{dU(x)}{dx} = K\left[N2(x) - N1(x)\right]U(x)$$

Where K is a proportionality constant. The solution is

$$U(x) = \exp\left[-K(N1 - N2)x\right]$$

This means that the signal will increase exponentially when there is population inversion. The exponential increase continues until the population inversion reaches a certain point, then the signal saturates, and reaches the steady state.

Pumping of the laser cavity

Optical pumping is the method used to excite the atoms from the ground state into a higher state in order to bring about the necessary population inversion needed for lasing to occur in solid state lasers. This population inversion is brought about in different ways for the 3-level (Ruby) and 4-level (Nd:YAG) laser systems. However both require atoms to be excited from the ground state into a higher energy state and this is done using optical pumps.

The three main types of optical pumping lamp used for solid-state laser are

(i) the quartz-halogen lamp (used for both Nd:YAG and Ruby)

(ii) the halogen arc lamp (used only for Nd:YAG)

(iii) the incandescent lamp (used only for Nd:YAG)

Depending on the type of laser output required there are different methods of pumping the laser cavity. If the output required is to be pulsed then the optical pump must also be pulsed (Note: there are methods of changing **C**ontimuous **W**ave (CW) laser outputs into pulsed form but these methods are not covered here. The methods described here are simply to do with the output from the gain medium without any laser accessories such as Q-switching and cavity dumping). For a pulsed laser output the laser medium is “flashed” with light rather than being continuously pumped. The optical pump mentioned above in (i) is used when a pulsed output is required and the optical pumps (ii) and (iii) are used when the laser output required is CW as these provide continuous pumping to the laser medium.

Below the absorption diagram for Nd:YAG can be seen. From this it can be seen that the two most important pumping regions for this type of laser are the 730-760nm and the 790-820nm regions since these are the wavelength values for which the Nd:YAG absorbs most photons. Since both of these regions are near the infrared region, absorption of photons of these energies wont cause much heating of the lasing medium and so there is no degradation in the amplification qualities of the medium due to overheating. There is another range of wavelengths for which the Nd:YAG shows good absorption but this range is near the ultra-violet and so would cause heating of the amplification medium. This absorption range is therefore not used for pumping the amplification medium.

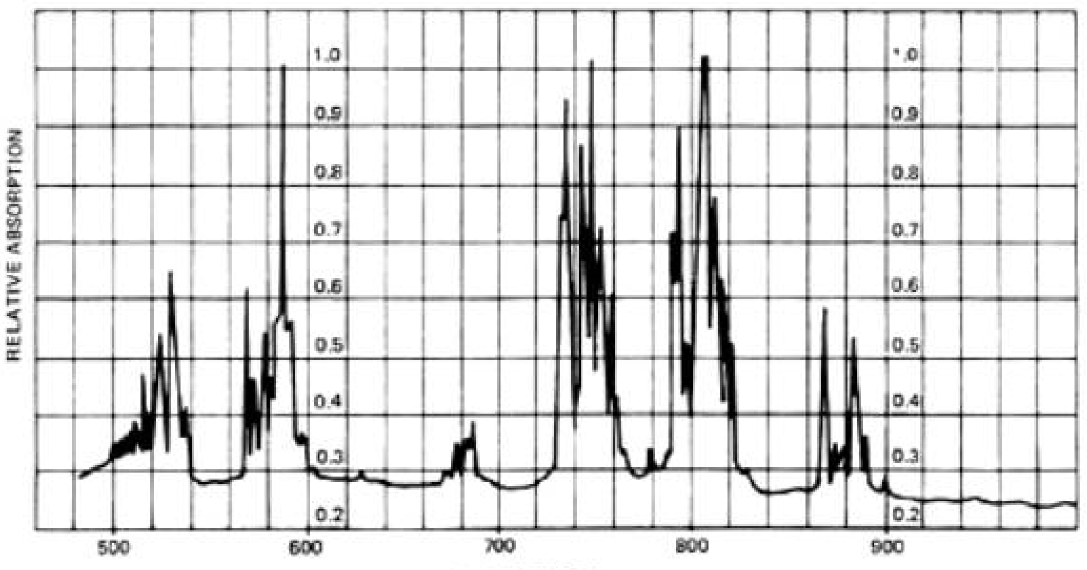


Fig 1. Absorption spectrum of Nd:YAG

Since most of the atoms are in the ground state in the Nd:YAG to begin with (and remembering that in a four level system the ground state is not the lower lasing level), it requires relatively few atoms to be excited into the upper lasing level for the population inversion required for lasing to occur. Relatively weak pumping of the medium is therefore required for lasing (assuming that the lower lasing level depopulates into the ground state rapidly, hence retaining the population inversion between upper and lower lasing levels).

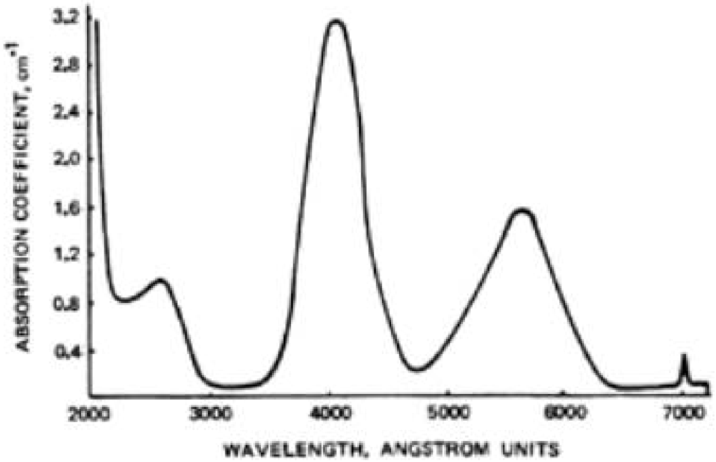


Fig 2. Absorption spectrum of Ruby

As we can see from the above absorption spectrum of the Ruby rod there are two broad absorption spectrums centered round 400nm and 550nm. Therefore light in the blue-green part of the spectrum is very effective for pumping the Ruby rod.

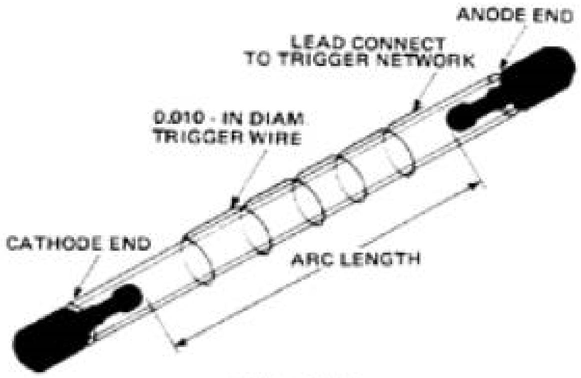
In a Ruby laser the ground state is the lower lasing level. It therefore takes an intense amount of pumping to create the required population inversion for lasing to occur. This is because most of the atoms reside in the ground state prior to pumping and these must be pumped into a higher energy level before a population inversion occurs. If these lasers were to be operated in CW it would take a large amount of pumping to maintain the population inversion. This large amount of energy causes great heating and so extremely efficient cooling systems are required for CW Ruby lasers if the rod is not to overheat and destroy the lasing action. Because of this the Ruby laser is usually operated in pulsed mode only. Although CW Ruby lasers have been built we will not discuss the pumping of such lasers here since they are not normally used.

(i) Quartz-Halogen lamp/Halogen Flashtubes

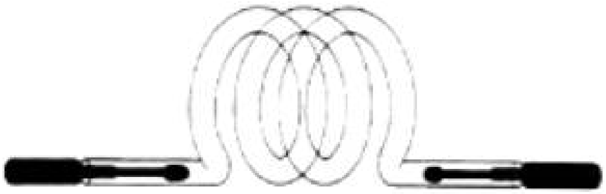
Below can be seen two common designs of flashtubes used in the optical pumping systems that are commonly used to pump the amplification medium in the solid state lasers. The first is a liner design that is “flashed” by passing a current through a noble or halogen gas. Krypton is the most effective for the Nd:YAG laser since it emits light of wavelength that corresponds with the absorption bands of the Nd:YAG but due to cost factors xenon is usually used even though it is less effective. Xenon has good emission in the blue-green spectrum of light and so is commonly used to illuminate Ruby rods for laser action to take place. The linear design is usually encased in one of the reflector setups described later. The arc length and the diameter of the flashlamp are usually chosen to be the same as that of the laser rod.

The second design for these types of flashlamps shown below is the helix design similar to that used by T.Maiman while demonstrating the first Ruby laser in 1960. The flash tube is coiled in a helix and the lasing rod is placed within this helix. For best pumping the helix is coiled tightly round the rod and immediately surrounded by a diffuse cylindrical reflector.

These two types of flashlamps are used as pulsed optical pumps with pulsed Nd:YAG lasers and with Ruby lasers. Due to the pulsed nature of the optical pumping the laser output will also be pulsed.



a. Linear flashlamp



b. Helical flashlamp

Fig 3. Two designs for flashlamp optical pumps

(ii) Halogen Arc lamps

The arc lamp shown below is used to illuminate the Nd:YAG lasing rod when continuous pumping is required (since the Ruby laser cannot be operated in CW mode, arc lamps aren't used with Ruby lasers). The lamp contains a high-pressure (2-4 atmospheres) noble gas in an inner capsule with metal electrodes at each end. This is then encased in a water envelope to cool the lamp since it is in continuous operation. The gas is ionized by a high-voltage pulse and then is maintained by a constant voltage across the electrodes. Although krypton lamps are more expensive than xenon lamps, in this case krypton arc lamps are used since they give a far superior continuous output than the xenon lamps.

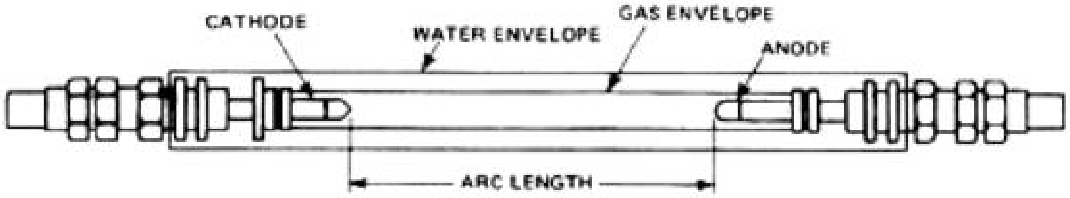


Fig 4. Arc lamp Continuous Wave Optical Pump

(iii) Incandescent Lamps

The most commonly used incandescent lamp is the tungsten filament lamp since the relatively inexpensive. These lamps provide a cheap alternative to the krypton arc lamps for pumping CW Nd:YAG lasers. Again since these lamps are used for pumping CW lasers and since the Ruby laser isn’t operated in CW these lamps aren’t used as optical pumps for Ruby lasers. These lamps have a continuous emission that is characterized as a hot blackbody emission spectrum shown below. Because of this continuous emission it is easy to see that part of the emission coincides with the absorption spectrum of the Nd:YAG laser and so can be used as an optical pump. However a lot of the light emitted by the lamp is wasted since it is not absorbed by the lasing medium. Regardless of this fact the low cost of these lamps makes it feasible to make a powerful enough lamp to provide enough illumination at the desired wavelength to make it an option as an optical pump.

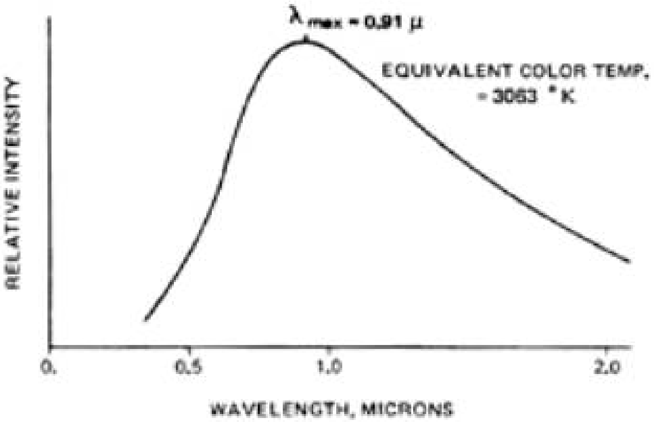


Fig 5. Emission spectrum of the Tungsten Filament lamp

Linear Flashtube Pumping Geometries

One of the more common geometries used with linear flashtubes is the elliptical setup as shown below. By placing the rod at one of the focii of the ellipse and the flashtube at the other focii of the elipse the majority of the light from the lamp is reflected onto the laser rod so the maximum amount of light from the lamp reaches the lasing rod.

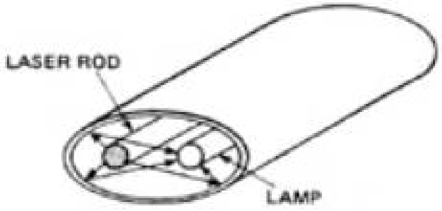


Fig 6. Elliptical Reflecting Geometry

Another common geometry used is the cylindrical layout shown below with the lamp and laser rod placed side by side in the centre of the reflecting cavity. This is less effective than the elliptical geometry shown above but is still used since the Nd:YAG doesn't require a very large amount of incident light (although it does need light whose wavelengths coincide with that of the absorption bands of the Nd:YAG) to cause a population inversion between the two lasing levels in the Nd:YAG (as explained earlier).

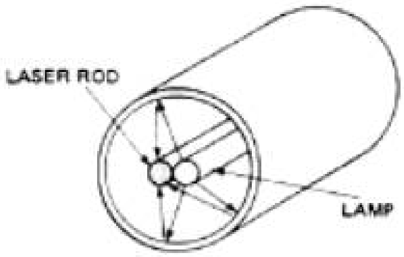


Fig 7. Cylindrical Reflecting Geometry

Other variations on the geometries used include those of the four lobe elliptical reflector and the spherical reflector as shown below.

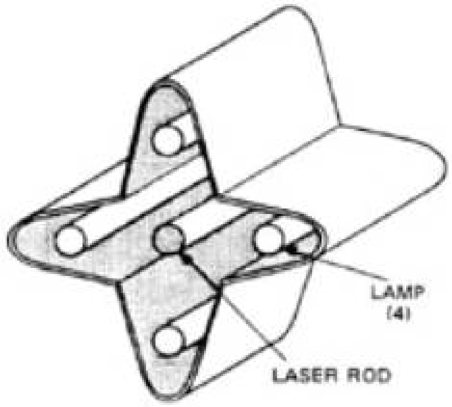


Fig 8. Four lobe elliptical Reflecting Geometry

This geometry is good for lasing rods that require quite a lot of illumination to retain the needed population in Continuous Wave mode.

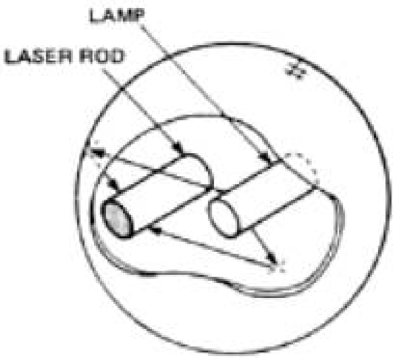


Fig 9. Spherical Reflecting Geometry

4 Level Laser System

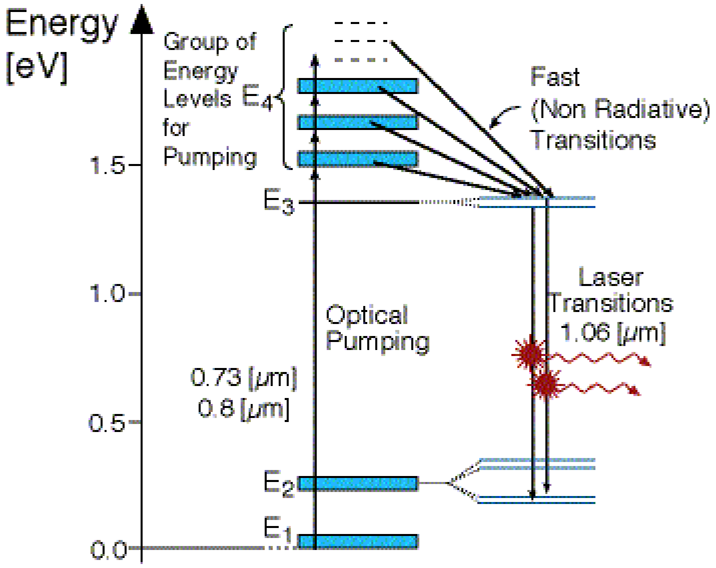


Figure 3.

As seen in Figure 3 above, there is four energy levels, with energies E1, E2, E3, E4 with populations of N1, N2, N3, N4 respectively. There energies increase for each level so that E1 < E2 < E3 < E4.

In this system, optical pumping from the ground state (E1) into the pump band (E4) excites the atoms. From this level the atoms decay by a fast, radiationless transition into the level 3 (E3). The lifetime of the laser transition from E3 – E2 is long compared to that of E4 –E3, a population accumulates in this level 3 (lasing level). Here the atoms relax and start to create laser transitions through spontaneous and stimulated emissions into level 2 (E2). At this level, like level 4 has a fast decay into the ground state. Like before this quickly de-excited atom leads to a negligible population in E2. This is significant, as the highly populated E3 level will then form a population inversion with the E2 level. Specifically as long as the population of level3 N3 is greater then 0. Therefore optical amplification and laser operation can take place.

Since only a small number of atoms need to be excited in the upper lasing level E3 to form population inversion, it proves that a 4 level laser is much more efficient and practical then the 3 level laser.

Rate Equations for 4 level laser System

$$\frac{dN_4}{dt} = W_p(N_1 - N_4) - (\gamma_{43} + \gamma_{42} + \gamma_{41})N_4$$

$$= W_p(N_1 - N_4) - \frac{N_4}{T_4}$$

$$\frac{dN_3}{dt} = \gamma_{43}*N_4 - (\gamma_{32} + \gamma_{31})N_3 = \frac{N_4}{T_{43}} - \frac{N_3}{T_{31}}$$

$$\frac{dN_2}{dt} = \gamma_{42}N_4 + \gamma_{32}N_3 + \gamma_{21}N_2 = \frac{N_4}{T_{42}} + \frac{N_3}{T_{32}} - \frac{N_3}{T_{21}}$$

Pumping into level 3 is irrelevant due to weak absorption and narrow band.

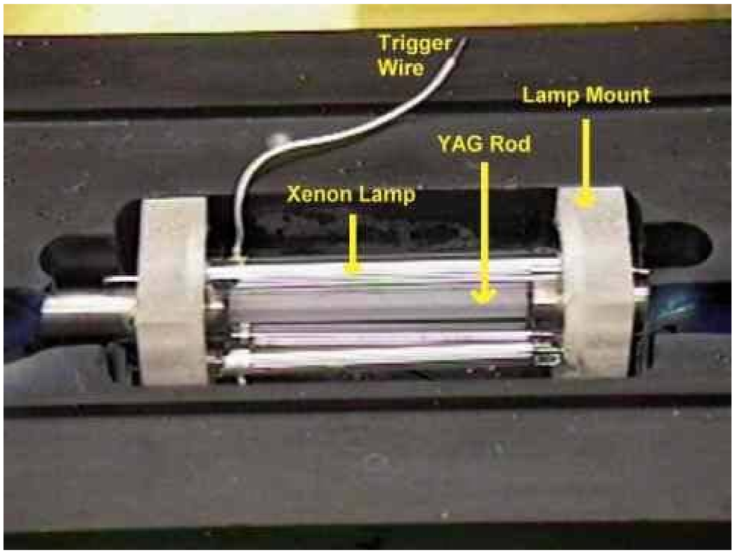
Steady-State:

$$N_3 = \frac{T_3}{T_{43}}*N_4$$

$$N_2 = \frac{T_{21}}{T_{32}} + \frac{T_{43}T_{21}}{T_{42}T_3}*N_3 = \beta N_3$$

$$\beta = \frac{N_2}{N_3} = \frac{T_{21}}{T_{32}} + \frac{T_{43}T_{21}}{T_{42}T_3}$$

Example of the four-Level System:



The Nd: YAG LASER

The Nd : YAG laser is an optically pumped laser similar to that of the Ruby laser. The rod used is a compound of Yttrium Aluminum Garnet doped with Neodymium. The YAG rod in Figure 1 is pumped optically usually with a Quartz-Halogen lamp or CW high pressure Krypton lamp. Rods used for CW operations are typically between one to four millimeters in diameter and it's length ranges from one to six inches. Using smaller diameter rods tends to create fewer cooling problems. (As open loop cooling systems can be used).The YAG rod is placed inside a quartz or glass jacket and cooled by filtered water flown directly across the surface of the rod. The ends of the rod are sealed using O-rings for protection from the pump lamplight. For systems with larger diameters a closed loop system is applied.

Operation of Nd: YAG

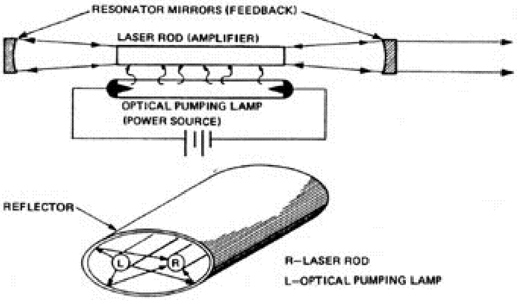


Figure 2

As shown in Figure 2. The Nd : YAG laser contains two resonator mirrors mounted separately from the rod. A range of configurations can be used for the cavity however they must contain at least one spherical mirror. Hemispherical cavities with long radii can also be used. Systems with mirrors of different Radii of curvature are common, if the shape of the beam within the cavity is desirable. The mirrors are extremely reflective and usually transparent to visible light. The rear mirror has a reflectivity of 99.9% and the front output coupler transmission ranges between ~1% to 8%

depending on how large the laser is. The output power will continue to rise until all the Neodymium atoms are excited, upon saturation the output power is at it's maximum and remain constant regardless of any increase of the input power. Therefore a high concentration of the dopant Neodymium gives cause for a higher output power.

Parameters of Nd: YAG Laser(Q-switched)

Power	250mJ
Wavelength	1.064 μm
Pulse Duration	10ns
Divergence	5mrad
Linewidth	180GHz
Spontaneous Lifetime	550μs
Refractive Index	1.82
Beam diameter	5mm

Nd:YAG Laser applications

One advantage of the Nd:YAG laser over other solid state lasers is that it can be operated in both continuous wave (CW) mode and in pulsed mode. This makes the laser more versatile than the other common solid state lasers, the Ruby laser and the Nd:glass laser, both of which can only be operated in pulsed mode. The high thermal conductivity of the Nd:YAG rod in the Nd:YAG laser coupled with its four level system make it a more energy efficient laser than the Ruby laser when operated in pulsed mode. The Nd:YAG produces the lowest energy pulses with the highest repetition rate of the three main solid state lasers, therefore if a high pulse repetition rate is required, the Nd:YAG is a good choice of laser. This high pulse repetition rate makes the Nd:YAG ideal for scribing or cutting metal sheets into intricate patterns, as well as for laser markers.

Because Nd:YAG lasers can also operated in CW mode, cooling is very important in this type of laser and so coolant systems must be built into the laser to remove any generated heat before it damages the laser or reduces the efficiency of the laser. This can add to the complexity of the lasers as they require more complex cooling systems than pulsed laser systems. However through the use of Q-switching with a CW Nd:YAG, the CW Nd:YAG laser can be operated in a pulsed mode. With this Q-switching the laser peak pulse power can be increased to 500 times that of the normally operated CW Nd:YAG laser.

Nd:YAG lasers are often used in tattoo removal. Using the double switching option with an Nd:YAG laser, a beam with wavelength of 532nm can be generated. This is a green laser light which is superior to any other laser in the removal of red ink.

Military uses of the Nd:YAG laser include use as range finders and target designators. Larger pulsed lasers are the most common solid state lasers for materials processing applications that include marking, hole drilling, scribing, and laser welding