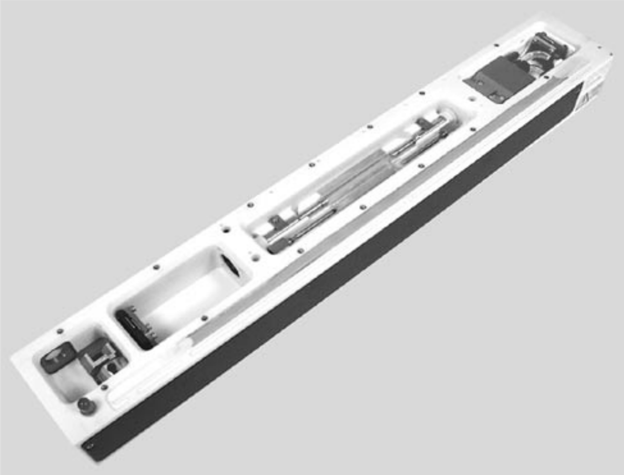
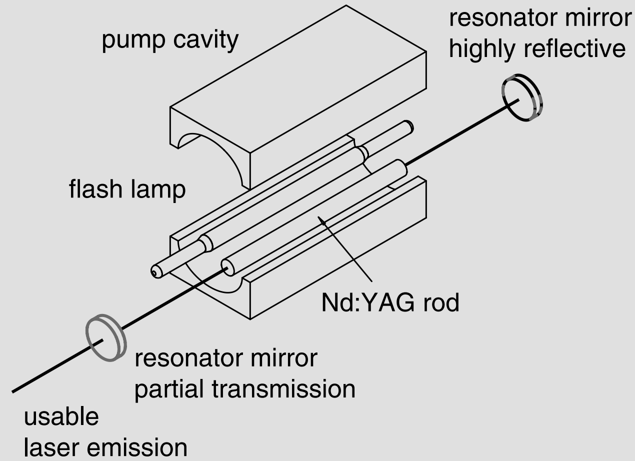
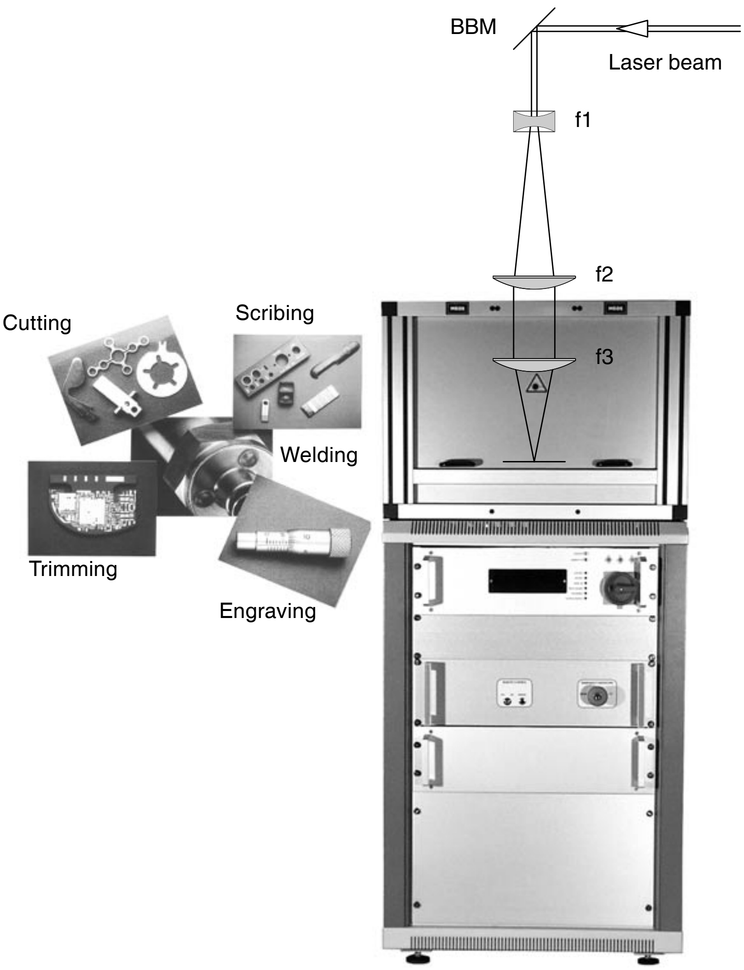
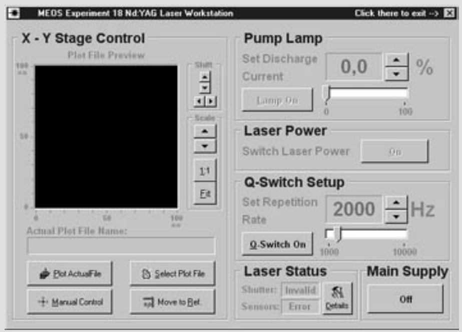




EXPERIMENT 18

ND:YAG LASER WORKSTATION





MEOS

Table of Contents

A. First Installation

Before the system can be operated it must be prepared as described in the following chapters. Follow these instruction carefully to avoid damage to the system.
Important Note:
Do not connect the system to the mains unless it is stated in this proceedings to do so.

A.1 Requirements

Electrical	**3 phase 440 Volts AC / 16 A**
Water cooling	**max. 18° C, 4 bar**
consumption	**0.25 cbm/h**
Ambience	**5° - 32° C**

A.2 Removing transportation securings

Open the side doors of the electronics cabinet and remove the transportation securings TS1 and TS2.

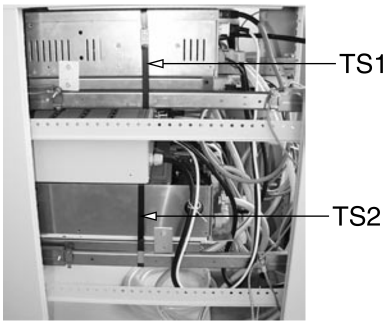


Fig. A2.1 Transportation securings

A3. Filling the Cooling System

Fig. A3.1: Drawn Cooling Unit

The secondary, closed loop cooling circuit contains de-ionised water as cooling agent. It is transported by the pump (CP) from the water reservoir (WR), passing parts of the resonator, the heat exchanger, the particle filter and the main de-ionisation filter (DF, fig. A3.2), the power supply and back to the water reservoir.
Before shipment the secondary cooling system has been emptied and must refilled again. For this purpose the front fixing screws of the cooling unit are removed and drawn out of the electronics cabinet. In the next step the red cover of the water reservoir (WR) is removed. Now the provided de-ionised water is filled into the reservoir until the level reaches 1 cm from the upper edge of it.

Important:

! Before the system can be switched on, it must be checked if the sense of rotation of the cooling pump is the same as indicated on the housing of the motor. Due to not unified regulations for three phase mains supplies it may happen that the motor does not rotate in the required direction.

A4. Checking the sense of rotation of the cooling pump

Connect the inlet hose for the external cooling to the water tab and the outlet hose to an aprobiate downpipe. Open the tab for a small ow rate, but note that the water starts only to ow when the temperature inside the systems rises and the temperature control valve opens.

The following tasks are only allowed to be performed by an experienced and certified electrical engineer.

Fig. A4.1: Cooling pump marked with the right sense of rotation

Open if not done before the rear door of the system. To check the sense of rotation the connector CT (fig. A4.2) is removed from the laser supply unit and substituted by the connector CP (fig. A4.3).

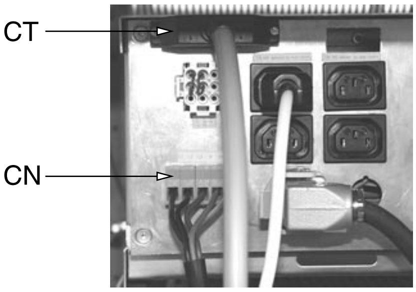


Fig. A4.2: Rear of laser power supply

Connect the jack CJ of the remote push button to the connector CP and the connector CP. Replace connector CT by the connector CP.

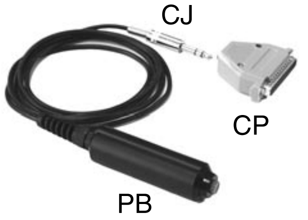


Fig. A4.3: Connector CP and remote push-button PB to be used for checking the sense of rotation of the cooling pump

Do not press the remote push button unless it is stated to do so!

Never press the push button while switching on the main power switch, since this may destroy the laser power supply!

Connect the mains supply cable to the mains supply and switch on the main switch located on the front panel of the laser power supply.

Important Note:

Before connecting to the mains make sure that the local mains connection fulfils all safety requirements in accordance with VDE 0100 or equivalent local regulations. Declare the area as safety region and make sure that you or other persons do not touch inner parts of the system.

Observe the rotating shaft of the cooling pump and press the button of the remote control.

Notice the sense of rotation and release the push button.

Switch off the main switch located on the front panel of the and remove the system mains connector from the mains supply.

If the motor does not turn in the right direction, exchange the connection wire L1 of the junction box CN (fig. A4.2) against L2 and repeat the procedure.
If the motor now turns with the right sense of rotation, remove the connector CP and connect the original CT back to the laser power supply.

Observe the level of water inside the reservoir and add if necessary. Connect the system to the mains supply and switch on the main power switch at the front panel of the laser power supply. The cooling system starts to operate. Add more water if required until the level stays constant at 1 cm below the upper edge of the reservoir.
Switch of the system and disconnect the mains power cable from the local mains power supply.
Fix the cover of the reservoir and move the drawer of the cooling unit back to the electronics rack. It may happen that it cannot pushed completely into the rack. In this case push the main blue de-ionisation shlightly into the direction as shown in fig. A4.3.

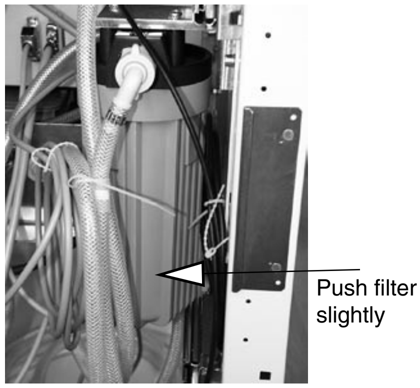


Fig. A3.2 Pushing the de-ionisation filter

Connect the parallel printer port of the control computer with the provide cable to the rear of the control unit and close all doors of the electronics cabinet.

A5. Starting the system

Befor starting the system it is recommended to read in minimum the chapters 5 to 8 and follow the start instructions of chapter 5.4.

A6. Checking the Laser Output Power

This procedure should only be carried out from an experienced and in Laser Safety trained person.

The laser beam coming from the laser head is bended by means of an adjustable mirror towards the laser nozzle where it will be focused and passes the nozzle.
To obtain the maximum on laser power, the beam has to be aligned in such a way that it passes all components without hindrance.
For this purpose two apertures are used.
The first one (A1) is already built into the top of the laser nozzle assembly, wheras the second (A2) is built into a click holder which can be inserted into the laser nozzle instead of the focusing lens.
For this procedure a laser power meter is required for a maximum of 100 W.

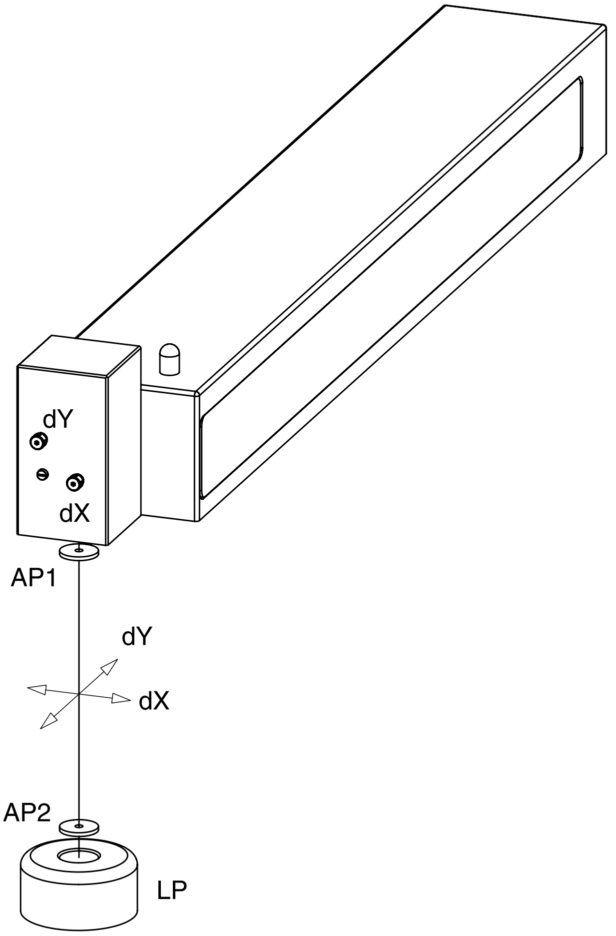


Fig. A7.1: Checking Laser power

Proceed as follows:

1.) The system is switched off
2.) Connect the remote push-button to the front panel of the control unit and insert the safety key to enable the remote operation.
3.) Lift the door of the processing chamber and remove the cap of the laser noozle with the gas inlet.
4.) Remove the focusing lens
5.) Place the laser power meter head centred to the laser head
6.) Move down the door of the processing chamber as far as the connection cable of the meter head it will allow. The possibilty that laser radiation will leave the chamber is nearly zero, however, the system now is a class 4 laser
7.) Prepare the area as laser safety region for a class 4 laser and use laser safety goggles.
8.) Start the system
9.) Set the pump lamp current to 20%
10.) Switch on by software command the pump lamp
11.) Observe the power meter while pressing the push-button of the remote control.
12.) Release the push-button and switch off the lamps by software command. Compare the reading of the power meter with the curve of fig. A7.2. However, one should be aware that a tolerance of 10 % is acceptable due to different calibration states of optical power meter.
13.) Insert the click mount with the aperture and repeat step 10.) to 12.). If necessary tweak the adjustment screws dY an dX of the beam bending mirror (fig. A7.1).
14.) If it turns out, that the adjustment range of the beam bender is not sufficient to reach the output power, the laser head may have lost its pre-aligned position during transportation. In this case proceed as follows, otherwise proceed with step 19.)
15.) The laser head is mounted to the supporting base plate by means of three screws. Two screws are located towards the front and one towards the rear of the laser head.
16.) Switch off the system.

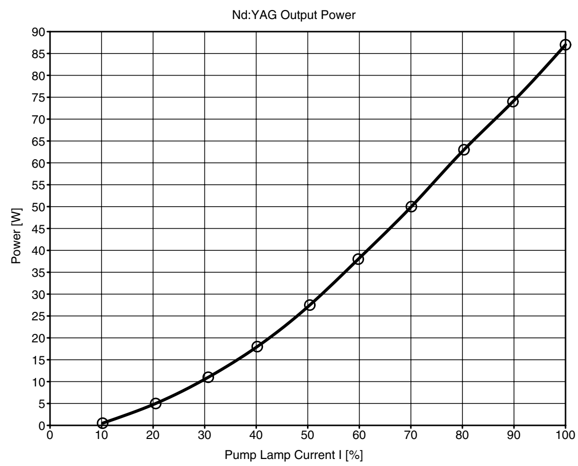


Fig. A7.2: Laser output power versus pump lamp current

17.) Lift the door of the processing chamber to get access to the screws. Slightly loose the screws in such a way that the laser head can be moved smoothly.
18.) Start the system and align the position of the laser head as well as the adjustment screws for maximum output power. Fix the screws of the laserhead. The single screw towards the rear should not be fastened too tight since this screw shall allow the laser head to move due to thermal expansion. For this reason the screw is provided with a shim and spring washer.
19.) Set the lamp power to 100%.
20.) The output power should be 80W minimum
21.) If required tweak again the adjustment screws.
22.) Switch off the system and exchange the aperture AP2 against the click holder with the lense of 50 mm focal length.
23.) Attach the noozle assembly with the cutting gas inlet to the laser noozle. The laser beam has to pass without hinderance the brass aperture. If not, tweak again the adjustment screws.
24.) Switch off the system, disable the remote control and disconnect the the push-button. The system is now again a class 1 laser.

In the most unlikely case that the output power does not reach 80 W read chapter 6 for basic alignment of the laser head.

1 The Nd:YAG-Laser

1.1 Optical pumping

Optical pumping is a process in which light is radiated into a specimen under investigation and the effect of the light on the specimen is examined. It was in this way that the strange physical phenomenon was observed of atoms only being able to accept or release energy in well defined quantities. This observation led to the conclusion that atoms only have discrete energy states or energy levels. When light is absorbed or emitted, a transfer takes place between the energy levels (Fig. 1.1). A transition from the level with the energy E_1 to a level with the energy E_2 can occur if an incoming photon is absorbed with the energy $E_{Ph} = E_2 - E_1$. In the reverse case, a photon with the energy $E_{Ph} = E_2 - E_1$ is emitted if a transition of the atom takes place from a state with energy E_2 to one with energy E_1. The two processes of absorption and emission differ in that an external field with the energy E_{Ph} must be present for absorption, whereas no field is present for emission. This emission occurs spontaneously from the system itself without external fields. It can be compared to the radioactive decay of an excited nucleus. The analogous inverse process to absorption, i.e. emission under the application of external fields is termed induced emission.

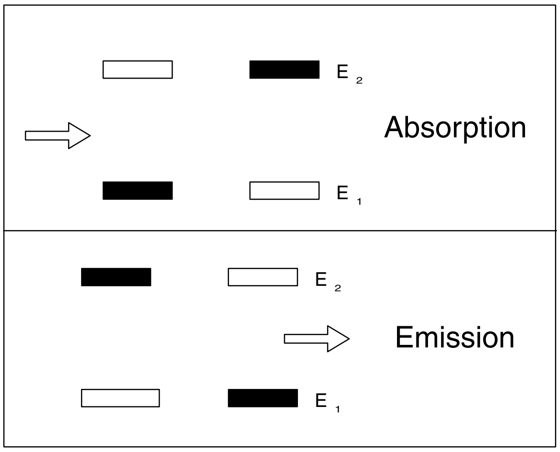


Fig. 1.1: Absorption and emission

For each of the processes the number of atoms can be stated which absorb or emit a photon per unit of time and per unit of volume.

$$\frac{dn_1}{dt} = -B_{12} \cdot n_1 \cdot u_{ph} \qquad \text{Absorption}$$

$$\frac{dn_2}{dt} = -B_{21} \cdot n_2 \cdot u_{ph} \qquad \text{Induced emission}$$

$$\frac{dn_2}{dt} = -A_{21} \cdot n_2 \qquad \text{Spontaneous emission}$$

B_{12} denotes the Einstein coefficient of absorption,
B_{21} the Einstein coefficient of induced emission and
A_{21} the Einstein coefficient of spontaneous emission,
n_1 and n_2 are the densities of the atoms in the states 1 and 2 respectively,
u_{ph} is the energy density of the external field.

By integration of the equation for spontaneous emission, information is obtained on the variation of this type of emission with respect to time:

$$n_2(t) = n_2(t_0) \cdot e^{-A_{21} \cdot t}$$

A decay probability and a mean life-time can be given completely analogous to radioactive decay. The Einstein coefficient A_{21} represents this probability and

$$\tau = \frac{1}{A_{21}}$$

the mean life-time.
This states the time which passes before the number of excited atoms has reduced to 1/e or before $n_2(t)$ has reached the value

$$n_2(t) = n_2(t_0) \cdot \frac{1}{e}$$

For normal optical transitions, this value is between 10^{-8} and 10^{-9} sec. This life-time which is determined by the spontaneous transitions alone is relevant for the natural half width of a spectral line. According to the Heisenberg uncertainty principle, there is a relationship between the width and the life-time:

$$2\pi \cdot d\nu = \frac{1}{\tau} = A_{21}$$

where $d\nu$ is the half-width of the spectral line.
According to the above requirements transitions will only take place if the energy of the absorbed or emitted photon is sharply defined, i.e.

$$E_{ph} = E_2 - E_1$$

In actual fact nature is not that critical and it is seen that photons with a slightly different energy also take part in these processes. The reason for this is that the energy levels are broadened due to various mechanisms.

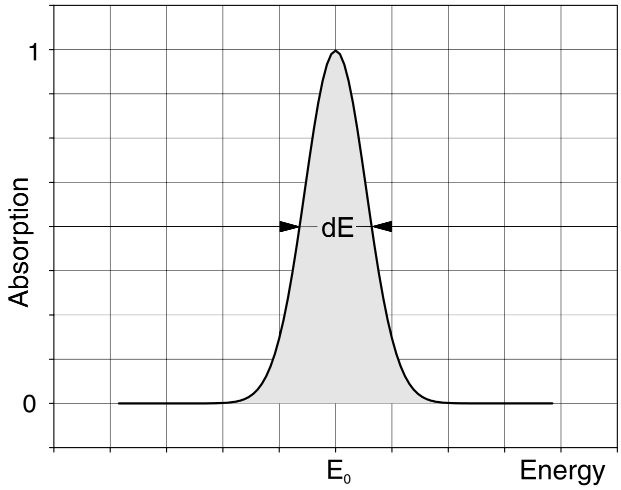


Fig. 1.2: Broadened absorption transition.

Depending on how mobile the atoms are due to their temperature and how they are affected by interactions with their environment, there is a broadening dE which means that photons within this region are accepted. The width of the transition is given by the half width dE for the relevant transition (Fig. 1.2). The same theory is valid for emission.

E_0 is the energy at which the absorption is the highest. It corresponds to the value E_2- E_1. For the sake of completeness it should be mentioned that there are also situations in which this value can be displaced. The shape of the absorption curve corresponds to a Gaussian distribution. By definition dE is the width of the curve at which the absorption has fallen to one half of the maximum value. This is known as the full width at half maximum (FWHM). If there are other transitions within the vicinity of this transition, they may overlap, producing a substantially wider absorption curve (Fig. 1.3). This is particularly important in the case of the absorption of laser diode radiation in Nd:YAG which is discussed later.

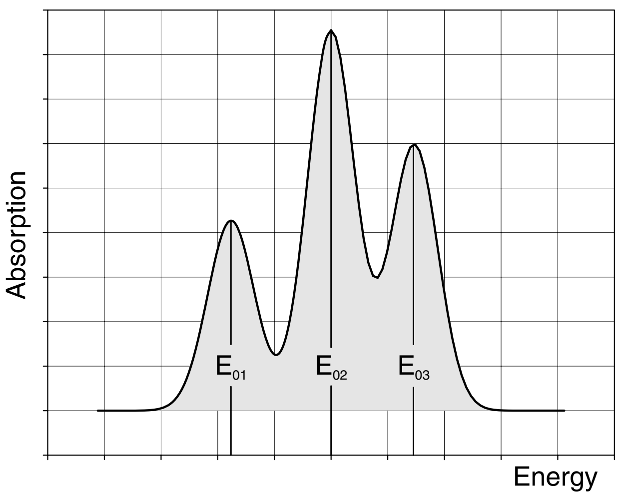


Fig. 1.3: Absorption for three neighbouring transitions with different absorption strengths

In principle an atom may have any number of energy levels, but they must be discrete. The transitions between the individual levels take place according to defined selection criteria. When the atom is excited with a defined energy, an emission spectrum is observed with characteristic energies and this spectrum gives precise information about the energy levels involved. Excitation by optical pumping has therefore developed as a very important method used in spectroscopy. It is also an indispensable technique for the excitation of a number of different types of lasers. Optical pumping in conjunction with Nd-YAG lasers is of particular interest, because these have become widely accepted for industrial use, along with the CO_2 laser. The laser-active material which, in the case of the Nd-YAG laser, is excited by optical pumping, consists of Neodymium atoms that are accommodated in a transparent host crystal (YAG = Yttrium Aluminium Garnet). Whereas up to a few years ago Nd-YAG lasers were almost excited using discharge lamps, optical pumping with laser diodes is becoming more significant. This is because laser diodes are available economically and they emit narrow band light at high optical powers, which matches the energy levels of the Nd-YAG crystal (Fig. 1.4). The advantage over the discharge lamp is that the emission of laser diodes is nearly completely absorbed by the Nd-YAG, whereas the very wide spectral emission of discharge lamps is absorbed to only a small extent. The efficiency of optical pumping with discharge lamps is about 3%, but figures of up to 50% can be achieved using laser diodes! But nevertheless pumping with discharge lamps is still very common especially for high power laser systems.

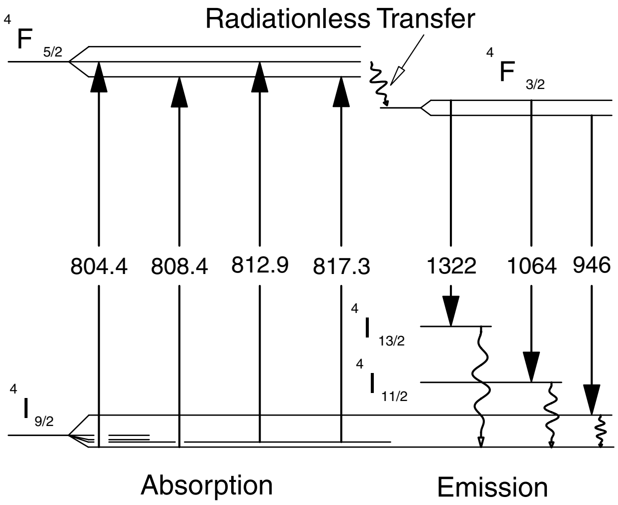


Fig. 1.4: Relevant energy levels of Nd-YAG for optical pumping around 805 nm

Some energy levels of the Nd atom are illustrated in Fig. 1.4. Here, only those are shown which are significant for optical pumping around the main absorption band at 800 nm. The levels are labelled with their spectroscopic notations. Since the Nd atoms are situated within the YAG host crystal, the otherwise degenerated energy levels of the isolated Nd atom split into a number of states. This gives rise to the ground state $^4I_{9/2}$ from 5 sub states and the state $^4F_{5/2}$, which can be pumped from 5 sub states. When optically pumped the Nd atoms of the $^4F_{5/2}$ state pass very quickly into the $^4F_{3/2}$. The laser transition which is technically most interesting takes place between the $^4F_{3/2}$ state as starting level and terminates in the $^4I_{11/2}$ state with an emitted wavelength of 1064 nm. From here the Nd atoms relax again into the ground state $^4I_{9/2}$ where the pumping process starts from the beginning again. The Neodymium therefore has an ideal four level system.

1.2 Four-level system of the Nd:YAG laser.

The principle is shown in Fig. 1.5. Under the radiation of a light field (optical pumping), transitions from ground state 1 to the upper level 4 occur. The reverse processes from state 4 to state 1 are prevented by very fast transitions from state 4 to state 3 without radiation. he laser transition takes place from level 3 into level 2 which is thermally not populated. From here the Nd atoms relax again back to ground state 1. The irradiation by light, which leads to the population of an otherwise empty state, is termed optical pumping. The emptying of a level occurs either with the emission of photons or without radiation. Transitions without radiation take place due to mechanical interactions such as collisions or vibrations and they are also designated as relaxation. The number of transitions without radiation per second is termed the relaxation rate. Transitions in which photons are emitted occur spontaneously or are induced. Spontaneous transitions also occur without pumping processes. However, induced emissions only occur if a pumping process takes place. Rates are also stated here, one rate for spontaneous emission and another one for induced emission. Each state which can interact with one or more other states is labelled with this type of rates.

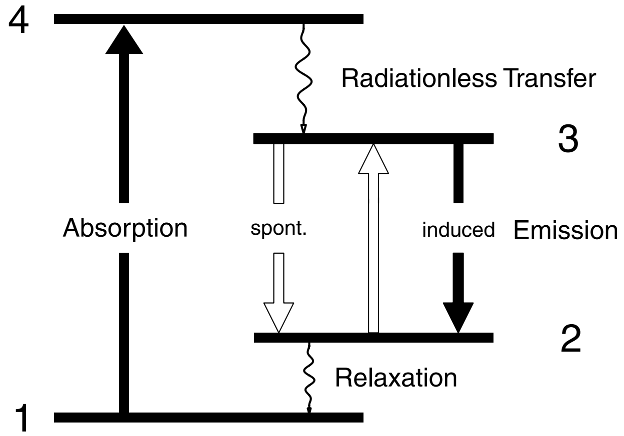


Fig. 1.5: **Principle of the four-level laser**

W_{14} probability of absorbing a pump photon.
S_{43} probability of relaxation from state 4 to 3 .
S_{32} probability of spontaneous emission of a photon.
W_{32} probability of induced emission of a photon.

W_{23} probability of induced absorption of a photon.
S_{21} probability of relaxation from state 2 to state 1.

However, in Fig. 1.5 showing the principle, only the transition probabilities that are significant for the pump and laser processes are indicated.

All the designated levels are populated to some extent due to pumping. The extent to which each state is populated is given by the number N_i of Nd atoms which are in the relevant state i of excitation:

State 1 N_1
State 2 N_2
State 3 N_3
State 4 N_4

Under the realistic assumption made in this example that the Nd atoms only pass through the labelled excitation steps, the sum of the population densities gives the Nd atoms which are available.

The desired laser oscillation will, however, only be achieved if an adequate population inversion can be established between states 3 and 2.

The conditions under which laser emission occurs, together with how the laser behaves, can be predicted by a model of the so called rate equation model. Initially, the main interest will be focused on continuous laser operation.

1.3 Rate equation model for four levels

The model describes the situation in a simple but exact manner. Each of the levels involved is regarded as a reservoir to which or from which “particles” ow. The particles used in this picture represent the Nd YAG atoms related to their corresponding state. Particle streams owing to the level are given a positive sign, those owing away are given a negative sign. This is carried out for each of the involved states. The number of excited atoms per unit of time in state 3 is:

$$\left.\frac{dN_3}{dt}\right|_p = \eta \cdot W_{14} \cdot N_1 = W_p \cdot N_1 \quad \textbf{pump rate}$$

where η is the pumping efficiency. The transition from state 4 occurs so fast that the level 3 is pumped immediately and the population N_4 density of state 4 is therefore $N_4 \sim 0$.

Spontaneous process

Another process affecting state 3 is spontaneous emission:

$$\left.\frac{dN_3}{dt}\right|_s = -\Gamma \cdot N_3 \quad \textbf{spontaneous rate}$$

where $\Gamma = 1/\tau_s$ and τ_s is the mean life-time of a photon before it is spontaneously emitted.

Induced processes

Finally, the induced processes occurring between states 3 and 2 under the in uence of the laser field must also be considered. The relevant rates are proportional to the difference in the population numbers N_2 and N_3 and to the photon density p of the laser field. The effective cross-section σ for the emission or absorption of a photon arises as a constant of proportionality:

$$\frac{dN_3}{dt} = \sigma \cdot c \cdot p \cdot (N_2 - N_3) \quad \textbf{induced rate}$$

Therefore the variation in the population density of level 3 with respect to time can be written as the sum of the separate rates:

$$\frac{dN_3}{dt} = \sigma \cdot c \cdot p \cdot (N_2 - N_3) - \Gamma \cdot N_3 + W_p \cdot N_1$$

Furthermore, the assumption is made that the transition from state 2 to state 1 is also so fast that only very few of the particles accumulate in state N_2 that means $N_2 = 0$ and the total number N_0 of Nd atoms is therefore:

$$N_0 = N_1 + N_3$$

Since N_0 is constant, also $dN_0/dt = 0$ and dN_1/dt becomes $-dN_3/dt$. Therefore the variation of the population density N_1 with respect to time is:

$$\frac{dN_1}{dt} = -\sigma \cdot c \cdot p \cdot (N_2 - N_3) + \Gamma \cdot N_3 - W_p \cdot N_1$$

It is important for the later laser process to know how the photon density on the laser transition 3 to 2 varies with respect to time. With each „induced“ absorption process a photon is annihilated and a photon is created with each induced emission process.

$$\left.\frac{dp}{dt}\right|_i = -\sigma \cdot c \cdot p \cdot (N_2 - N_3) \quad \textbf{induced}$$

Once created, the photon density does not remain in a resonator, instead it reduces with the time constant τ_{ph}, because photons are leaving at the mirrors of the resonators or are lost in other ways.

$$\left.\frac{dp}{dt}\right|_l = -\frac{p}{\tau_{ph}} \qquad \textbf{losses}$$

The complete variation of the photon density with respect to time is:

$$\frac{dp}{dt} = \sigma \cdot c \cdot p \cdot (N_3 - N_2) - \frac{p}{\tau_{ph}}$$

For simplification the population inversion N_3-N_2 is designated as n . The variation of the population inversion with respect to time is obtained by the following relations:

$$\frac{dn}{dt} = -\sigma \cdot c \cdot p - \Gamma \cdot n + W_p \cdot (N_0 - n) \quad \textbf{(1.1)}$$

and for the photon density:

$$\frac{dp}{dt} = p \cdot (\sigma \cdot c \cdot n - \frac{1}{\tau_{ph}}) \quad \textbf{(1.2)}$$

1.3.1 Solution of the rate equations

The differential equations (1.1) and (1.2) form a pair of coupled conditional equations for the two unknown functions n(t) and p(t). The equations are non-linear because they both contain the term pn. Analytical solutions are not known and one has to rely on computerised solutions.

1.3.2 Steady-state solution

When the system is in the state of equilibrium, i.e. for steady-state laser operation, the values for dn/dt and dp/dt are equal to zero. In this case an expression for the population inversion is obtained immediately:

$$n = \frac{N \cdot W_p}{\sigma \cdot c \cdot p + W_p + \Gamma}$$

When the laser is operated below or just at the threshold, no photon field is formed (p=0). In this case Wp << Γ and the threshold inversion is given by:

$$n(p = 0) = n_0 = N \cdot \frac{W_p}{\Gamma}$$

This equation states that in a four-level laser an inversion immediately is produced when it is pumped. This is a particular advantage as opposed to other laser systems. Unfortunately, neither the photon density nor the pumping rate are directly accessible by measurement.

However, the photon density is coupled to an easily measured quantity, i.e. the power applied in the pumping process. If the relationships between the photon density p and the corresponding intensity, as well as the resonator output and loss characteristics are considered, the output power P_a of a four-level laser can be obtained as:

$$P_a = \eta \cdot \frac{E_{32}}{E_{41}} \cdot (P_p - P_{th}) \cdot \frac{T}{T + L} \qquad \textbf{(1.3)}$$

In this equation E_{32} signifies the energy difference between states 3 and 2 (laser wavelength). E_{41} is the energy difference between states 4 and 1 (pump wavelength), T is the transmission of the output coupling mirror, L is the loss in the resonator due to dispersion, absorption or refraction. P_p is the pump power and P_{th} is the threshold pump power. Above the threshold pump power P_{th} the output power of the laser increases linearly with the pump power.

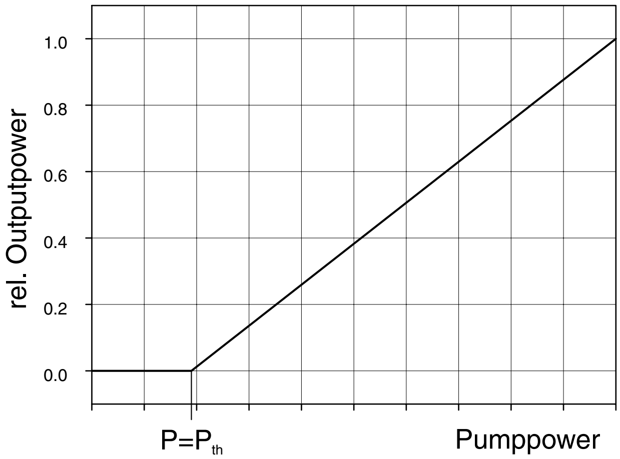


Fig. 1.6: Laser output power as a function of the pump power

The slope α_s of the straight line (Fig. 1.6) is one of the most important parameters of a laser and is termed the slope efficiency.

$$\alpha_S = \eta \cdot \frac{E_{32}}{E_{41}} \cdot \frac{T}{T + L} \qquad \textbf{(1.4)}$$

The quantity E_{32} / E_{42} is also known as the quantum efficiency. It gives the energy ratio of a laser photon to the pump photon. For the Nd-YAG laser pumped for example at 810 nm, this value is 810 nm / 1064 nm = 0,76.

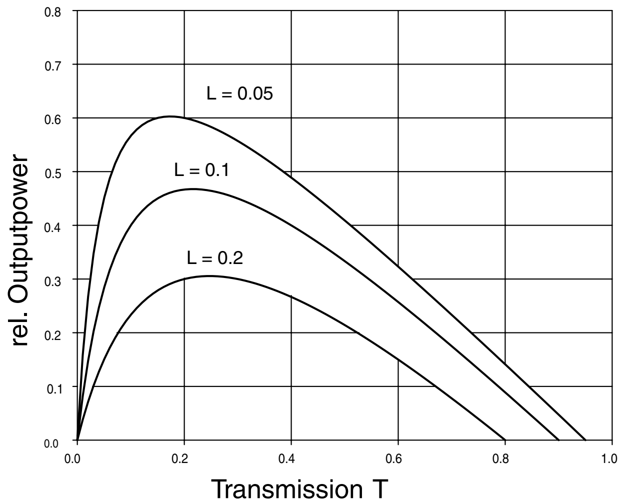


Fig. 1.7: Laser output power in dependence of the transmission T of the output mirror and the losses L.

The value η is the quantum yield, but unfortunately sometimes both quantities are commonly named as the quantum efficiency. For the laser designer it is important to obtain the highest possible output at the highest possible efficiency. Another important feature is that the transmission T for the resonator output mirror must be selected as large as possible according to equation (1.4). However, this has the consequence that the threshold pump power P_{th} increases and the output power decreases according to equation (1.3). A compromise between both equations must therefore be found. In practice the losses L depend on various parameters of the resonator including the quality of the laser rod, the absorption losses of the laser mirror etc., so that a mathematical formula covering all effects would be too complicated. It has proven useful to measure the curve of Fig. 1.7 directly at the laser to find the degree of output coupling. A series of output mirrors with various transmission values is used for this purpose.

1.3.3 Time-varying solution

The previous solutions described the situation where the laser operates in a steady state. However, for practical operation of the laser, conditions in disturbed equilibrium must also be considered. These kinds of disturbances occur when the intensity of the pump-light source change or the laser resonator is slightly disturbed mechanically. Large deviations from the steady state are particularly important when they cause problems (e.g. spiking and hot spots), but also when they lead to useful operating modes (Q switching). Small deviations of the steady state with $\delta n \ll n$ or $\delta p \ll p$ lead to damped harmonic oscillations of n and p. Larger deviations produce undamped non-harmonic oscillations. In this case, power peaks (spiking) of such a intensity may occur that the laser mirrors or the Nd-YAG materials can be destroyed. However, if disturbances are carried out in a controlled manner, these types of power peaks, which extend up into the gigawatt region (!), can be used to advantage. Computerised solutions must be used in calculating the solutions to the rate equations for these cases. In the following, these cases are therefore only qualitatively described.

1.3.4 Spiking

A large deviation from the steady state undoubtedly occurs when the laser is switched on or when the pump-light source is switched on. Until the threshold pump power P_{th} is reached, there are practically no photons present in the resonator.

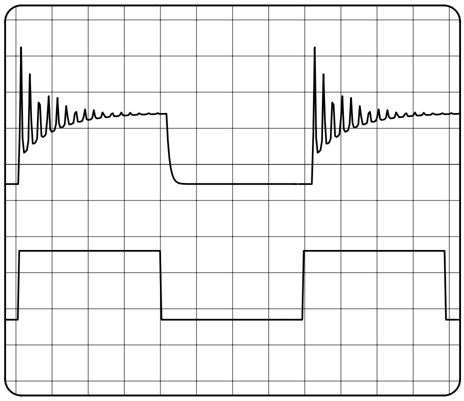


Fig. 1.8: Spiking of the Nd-YAG laser

When the population inversion reaches the threshold, a photon field is formed. However, due to the resonator propagation time, it takes a while until the photon density reaches the steady state value. During this period the inversion, which rises linearly with time, increases above the value of the threshold inversion. This in turn means a more rapid increase in the photon density. This rise is so rapid that the inversion falls to a value slightly below the threshold and the laser oscillation stops (Fig. 1.8). The process starts again, but this time the laser is only slightly below the threshold and the expected inversion overshoot is not so large as before. In this manner the system approaches the steady state. The first power spike (initial spike) can reach a peak power of a factor 100 to 1000 higher than the steady state power value. Spiking therefore can cause serious problems and it can lead to the destruction of the optical surfaces so that the laser might destroy itself during switch-on. This behaviour which will be observed in the latter experiments indicates, that the Nd YAG crystal can store energy.

1.3.5 Q-switching

The quality of a resonator is the quotient of the resonance frequency and the half width of the resonance curve. The definition is the same as for oscillator circuits known from electronics. A low Q figure for a resonator signifies high losses and vice versa. In a laser resonator with low Q, a high inversion can be produced without laser oscillation, because the threshold is high. If the resonator Q is then suddenly switched to a higher value, a high photon density is formed and a large part of the inversion stored in the laser-active material transfers into the photon field. This is a similar process as discussed with the occurrence of spiking. In contrast to spiking, here the laser threshold is controlled by the insertion and removal of resonator losses. The losses can be switched with an electro or acousto - optical switch. The energy level from which the laser emission of 1064 nm starts is the $^4F_{3/2}$ state (Fig. 1.4) which has a mean lifetime of app. 250 µsec. This means that it takes 250 µsec before the intensity of the spontaneous emission decreases to 1/e of its starting value, when the pumping field is switched of suddenly. For a laser system, this behaviour can be exploited for the generation of short pulses with high peak powers. Although the time dependent solution of the rate equations can not be derived by analytical expressions one can obtain some simple derivations under the following assumptions. Because of the very fast increase of the photon density the terms in Eq. (1.1) of the pumping rate the rate of spontaneous emission can be neglected. The development in time of the population density Eq.(1.1) simplifies with

$$n_{th} = \frac{1}{\sigma \cdot c \cdot \tau_{ph}}$$

in this case to:

$$\frac{dn}{dt} = -\frac{n}{n_{th}} \cdot \frac{p}{\tau_{ph}} \qquad \textbf{(1.5)}$$

and the photon density to:

$$\frac{dp}{dt} = (\frac{n}{n_{th}} - 1) \cdot \frac{p}{\tau_{ph}} \qquad \textbf{(1.6)}$$

The above equations can be solved for the build up of the giant pulse when the population density n is nearly constant and corresponds appr. to the starting population n_i. Then Eq. (1.6) becomes:

$$\frac{dp}{p} = \frac{1}{\tau_{ph}} \cdot (\frac{n_i}{n_{th}} - 1) \cdot dt$$

with the solution for the photon density:

$$p(t) = e^{(\frac{n_i}{n_{th}} - 1) \cdot \frac{t}{\tau_{ph}}}$$

In accordance to the above solution the density of the photons rises exponential with a time constant τ, which is due $n_i/n_{th} >> 1$ considerably lower than the life time τ_{ph} of the photons inside the resonator. An additional remarkable aspect in the development in time of the photon density is the point where the inversion n(t) is decreased to n_{th}. At this moment dp/dt becomes 0 and therefore p = const. = p_{max}. Eq. (1.6) can now be written as:

$$\frac{dn}{dt} = -\frac{p_{max}}{\tau_{ph}}$$

The negative sign indicates that the inversion is decreasing further. No additional laser photons will be produced. The photon density reaches its maximum and decays now with the time constant

$$\tau_{ph} = \frac{L}{c \cdot (1 - R)}$$

related to the lifetime of the photons inside the resonator.

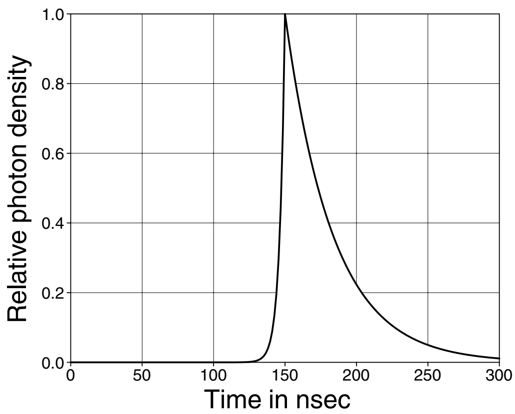


Fig. 1.9 : Calculated photon density for n_i / n_{th} = 10, a resonator length L of 100 mm and resonator losses of 1%. The rising part of the curve corresponds to the surplus inversion and the falling one to the photon life time inside the resonator

The peak value of the photon density is given by:

$$p_{max} = n_{th} \cdot \ln\left(\frac{n_{th}}{n_i}\right) - (n_{th} - n_i)$$

and the peak value of the intensity I_{max} by:

$$I_{max} = \frac{1 - R}{2} \cdot h \cdot \nu \cdot c \cdot p_{max}$$

The cross section of the stimulated emission σ for the transition 3-2 (Fig. 1.5) amounts σ = 8.8 10^{-19} cm^{-2} and the photon energy $h\nu_{1064\,nm}$ = 2 10^{-19} Joule.

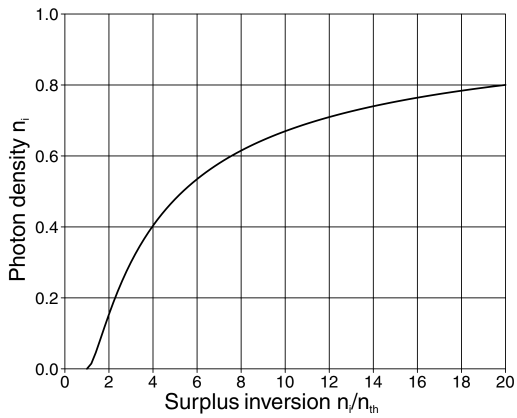


Fig. 1.10: Attainable peak value of the photon density relative to the initial inversion n_i versus the surplus inversion n_i / n_{th}

At this point of the discussion it becomes clear why lasers, who's starting energy level for the laser process has a low lifetime, do not exhibit a considerable increase of the output power under Q-switch operation. These lasers can only achieve a small value of a surplus inversion n_i / n_{th}.

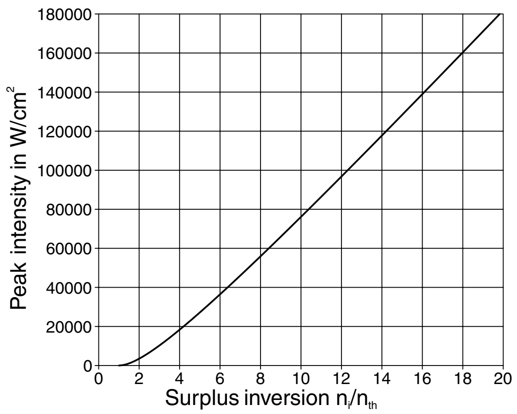


Fig. 1.11: Attainable peak intensity of the cw Nd YAG-Laser at T=1% in Q-switch mode

In the case of the CO_2 laser one can obtain a slight increase of the output power termed as super pulse instead of giant pulse for the YAG laser. For the He Ne Laser with a lifetime of the starting level of some nano seconds no increase of the laser power under Q-switch operation will be obtained. In the case of the Nd YAG laser with its lifetime of appear. 250 µsec of the starting level the duration of the giant pulse amounts 50 nsec, so that peak powers can be achieved which are considerably higher than the pump power itself. There are some techniques to realise the giant pulse operation of a laser. But they all work with the same fundamental operation: the laser oscillation is prevented until a sufficient surplus inversion is attained. Of course it is also important that the releasing of the oscillation takes place sufficient quickly. In the ideal case for the blocked resonator and for the released resonator. If for instance the threshold is varying slowly in time also n_i / n_{th} is reducing as well as the attainable peak power. The switching of the Q of the resonator can be achieved with pure mechanical, electro-optical modulator, acousto-optic modulator or by means of a saturable absorber. These different types of Q-switch devices are described in the following chapters.

1.3.5.1 Mechanical Q-switch

At the beginning of the laser technique one uses due to the lack of better methods rotating apertures or laser mirrors as shown in Fig. 1.12. In this set-up a wheel with laser mirrors ground on the wheel turns with an angular velocity ω. If one of the mirrors is in exact position with respect to the optical axis of the resonator the Q reaches its maximum. In all other cases “the resonator is not a resonator”

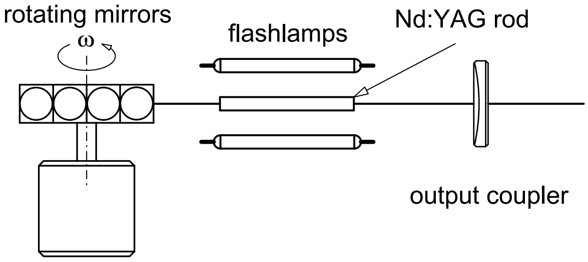


Fig. 1.12: Mechanical Q-switch with rotating mirrors.

1.3.5.2 Optical Q-switch devices

These more modern proven devices are until nowadays in use.

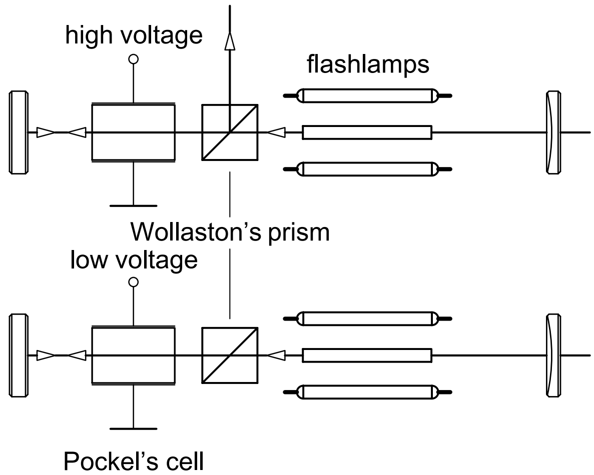


Fig. 1.13: Electro-optical Q-switch device

The Pockel’s cell consists of a crystal which becomes birefringent under the in uence of an electrical field. At a certain voltage this crystal acts as a quarter wave plate. The light (stimulated emission) which has a defined state of polarisation due to the polarising beam splitter passes through the cell. Depending on the applied voltage to the cell the light stays inside the resonator (high Q) or it leaves it via the beam splitter (low Q). This set-up is mainly used for pulsed (ash lamp pumped) Nd YAG laser.
For cw YAG laser with only a few percent of output coupling the damping of the above device is not sufficient for secure suppressing of laser oscillation. For cw pumped systems the acousto-optic Q-switch of Fig. 1.14 is better suited. In this set-up a standing sound wave is introduced by applying a periodic electrical field to a crystal. The generated sound waves are producing a periodic compression and decompression of the crystal which leads to a spatial variation of the index of refraction inside the crystal causing a de ection of the passing light. When the applied electrical field is switched off the light travels unaffected through the crystal, the Q value now is high. This type of Q-switch is used within this Laser of the workstation.

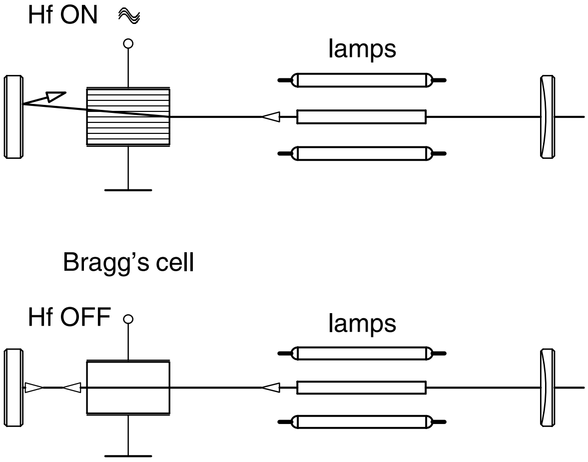


Fig. 1.14: Acousto optical Q-switch device

2 Laser Resonator

2.1 Types of resonators

The most simple optical resonator, the Fabry-Perot resonator, consists of a pair of plane or spherical mirrors located opposite one another. They are centred to a common optical axis and are aligned perpendicular to this axis

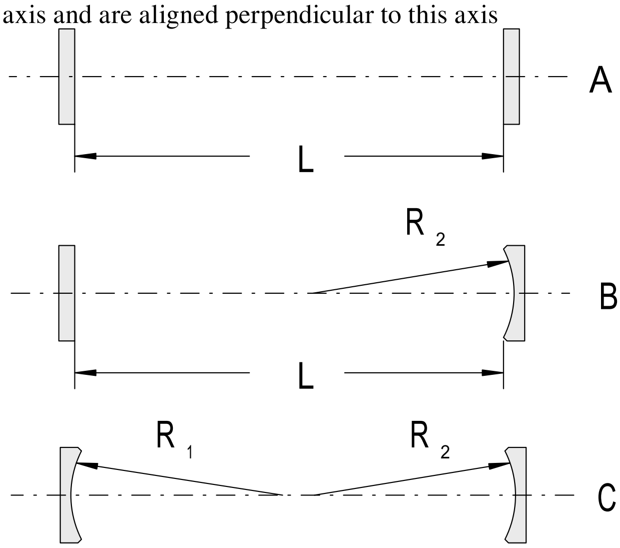


Fig. 2.1: Types of resonator

There are basically three different types of optical resonators:

plane parallel resonator	A
hemispherical resonator	B
spherical resonator	C

For lasers in the low to medium power range (1 mW-200W), the hemispherical resonator is mainly used. Its features include high output powers with relatively uncritical mechanical adjustment. Apart from other parameters, the output power depends on how much of the laser-active material is used. In this respect the terms pump volume and mode volume are used. The pump volume is the volume of the active material which is illuminated by the pump radiation. In contrast the mode volume is the volume which the laser modes fill within the laser-active material. By selecting the focusing, the pump radiation and the resonator shape the designer can in uence both quantities. In the optimum case the pump volume should be a little larger than the mode volume. The mode volume depends on which beam parameters are chosen within the laser resonator. These parameters are determined by the selection of the type of resonator , the radius R of curvature and separation L of the mirrors. However, it should be noted that within certain limits the separation L of the mirrors cannot be varied at will for a given radius R of curvature.

2.2 Stability criterion

The range in which a resonator configuration exhibits any kind of optical stability is found by the stability criterion. A resonator is optically stable if, after any number of re ections, the light still remains in the resonator due to the imaging characteristics of the mirrors used and does not leave the resonator by protruding beyond the edges of the mirrors. For the plane parallel resonator (A), in which the light beam is only re ected and not modified in shape, it must be ensured that both plane parallel mirrors are adjusted exactly parallel to one another. This type of resonator is the most difficult to adjust and to maintain in a correctly adjusted condition. The spherical resonator (C) is the most simple to adjust, but has the disadvantage that undesired transverse modes can easily start to oscillate. This means that the laser power is split up over a number of modes which are separated spatially from one another and which cannot be focused to a common point as with longitudinal modes. The hemispherical resonator represents a satisfactory compromise and the stability range for this type of laser is determined in the following. First of all, the g parameters are defined.

$$g_i = 1 - \frac{L}{R_i} \qquad \textbf{g-parameter}$$

L is the mirror separation and R is the radius of curvature of the laser mirror. The index i is 1 for the left mirror and 2 for the mirror on the right side. If the product $g_1 g_2$ satisfies the condition

$$0 \le g_1 \cdot g_2 \le 1 \qquad \textbf{stability criterion}$$

then the resonator is optically stable and the light, once produced, does not leave the resonator by passing over the edges of the mirror. Instead the light remains within an upper limit referred to a distance parallel to the optical axis of the resonator. The stability diagram for the case of interest here is shown in Fig. 2.2 for the hemispherical resonator. For this resonator g_1=1, since $R_1 = \infty$ (plane mirror). All resonators are unstable above the limiting curve $g_1 g_2$ = 1 and are stable below this limit. Since g_1 = 1, then with a fixed R_2 the distance of mirror 2 can only be changed from

$$L = 0\ (g_2 = 1) \text{ to } L = R_2\ (g_2 = 0).$$

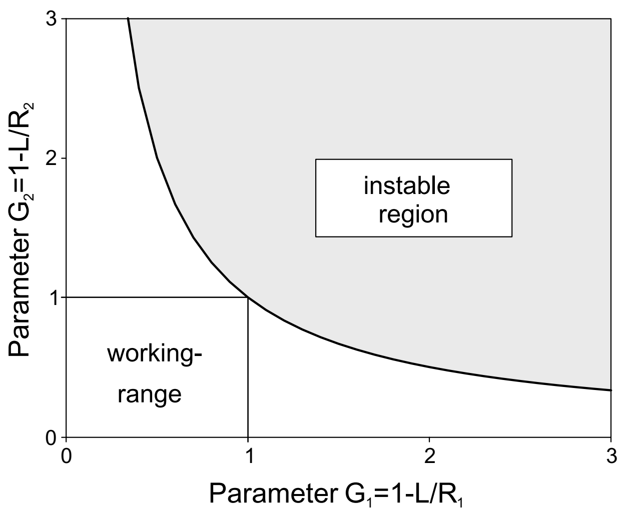


Fig. 2.2: Stability diagram

The distance that is actually adjusted within this range depends on the application for which the laser is to be optimised for. The closer the resonator is operated to the stability limit, then the more sensitive it is to maladjustment, because even small changes in separation can take the resonator into the unstable region (e.g. thermal expansion). The mirror separation can be decreased to prevent this problem, but the mode volume is reduced and this in turn significantly affects the output power of the laser.

2.3 Resonator modes

2.3.1 Longitudinal modes

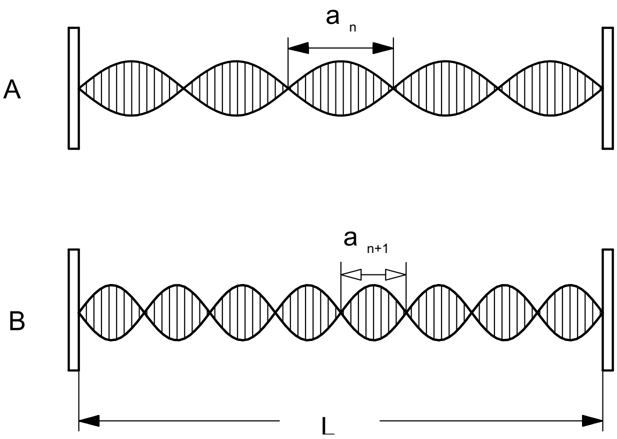


Fig. 2.3 : Standing waves in a resonator with plane parallel mirrors. In the upper example five longitudinal modes fit into the resonator of length L and in the lower one n=8

The light wave is re ected at the mirrors and returns along the same path. The electric field strength of the wave is therefore zero at the mirrors. For a certain separation L of the mirrors only waves can be formed which have a field strength of zero at both mirrors. Obviously, this is possible for a large number of waves for which an integer number n of their half wavelengths λ/2 fit in the resonator Fig. 2.3. The waves which fit into the resonator are termed oscillating modes or simply modes. If this integer number is n, then all waves fit into the resonator for which

$$n \cdot a_n = L$$

is true. The next neighbouring mode fulfils the condition

$$(n+1) \cdot a_{n+1} = L$$

The separation between the wavelength of two neighbouring modes is $2a_{n+1}$-$2a_n$. If λ is the wavelength, ν the frequency and c the velocity of the wave, then the following applies with:

$$a_n = \frac{\lambda_n}{2} \text{ and } \nu = \frac{c}{\lambda}$$

or:

$$|\delta\lambda| = |\lambda_{a(n+1)} - \lambda_{a(n)}| = \frac{2 \cdot L}{n \cdot (n+1)}$$

The magnitude of δν is termed the mode spacing. For a resonator with a length L of e.g. 50 mm, the mode spacing δν amounts to 3 GHz. In principle there are a very large number of modes which can fit into the resonator. However, the laser-active material can only amplify a certain limited range of these modes. For the Nd-YAG laser the wavelength at which the maximum gain occurs is 1064 nm. The region in which amplification takes place is given by the gain bandwidth (similar to the emission bandwidth). It should therefore be expected that for a resonator length of 50 mm with a mode interval of 3 GHz, 30 longitudinal modes will start to oscillate and the laser emission should consist of a combination of discrete frequencies. From the model of the rate equations we already know that in the steady-state operation of the laser the inversion is reduced until its threshold is reached and that the excess pump photons are converted into laser light. This also means that the gain reaches the value at which the losses are just compensated. According to Fig. 2.5 this would be a horizontal straight line touching the gain curve at its maximum. In this pictures only one mode would be able to oscillate, i.e. the one situated closest to the point where the line and curve meet. Just this one mode would take the complete inversion by itself in a "winner takes it all" manner.

2.3.2 Gain profile

Laser materials which consists of atoms or molecules with different properties behave in a different manner. This is particularly noticeable in the situation with gas lasers, e.g. the He-Ne laser, in which the atoms, to a certain extent, move freely in a discharge tube. Following the Maxwell-Boltzmann distribution, there are groups of atoms which have different velocities. These different groups represent their own classes and gain profiles. The whole gain profile is no longer homogeneous but is instead inhomogeneous. These types of laser principally oscillate on a number of modes (multimode operation).

However, experience has shown that there are no purely homogeneous or inhomogeneous systems. Therefore, the gain profile of the Nd-YAG laser is mainly homogeneous, it also has smaller inhomogeneous parts which lead to the Nd-YAG laser oscillating multimode. Optically pumped systems with homogeneous gain profiles are particularly susceptible to variations in pump power and to disturbances in the resonator length due to vibration, noise, etc.

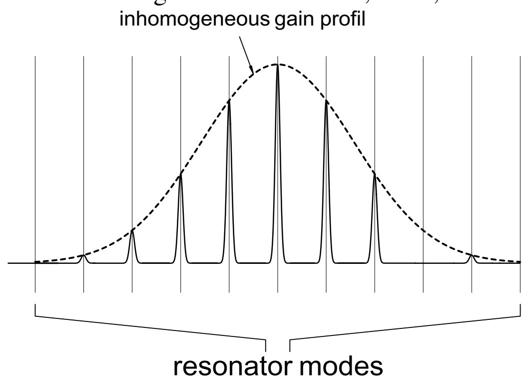


Fig. 2.4: Inhomogeneous gain profile with shown resonator modes. Each individual mode has almost independent operating conditions within the group

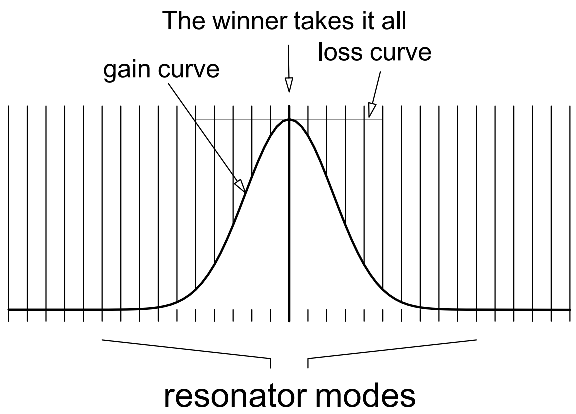


Fig. 2.5: Homogeneously broadened gain profile with shown resonator modes

The gain characteristic of the system resonator/laser material is modulated by these types of effects and additional modes can occur. This effect is in fact exploited to generate modes which are coupled together. This method of operation is termed mode locking due to gain modulation. Very short laser pulses in the picosecond region can be produced using this type of operating.

2.3.3 Transverse modes

For the sake of simplicity, the laser and resonator properties were discussed for an example of a plane parallel resonator. In practice this type of resonator is not used due to its disadvantageous characteristics. The hemispherical resonator has become very popular, since it exploits in a special manner the desired mode characteristics of the plane parallel resonator and the advantages of adjustment associated with the spherical resonator. However, a disadvantage accompanies this advantage. Whereas almost exclusively longitudinal modes excite in the plane parallel resonator, transversal modes can also arise in spherical resonators.

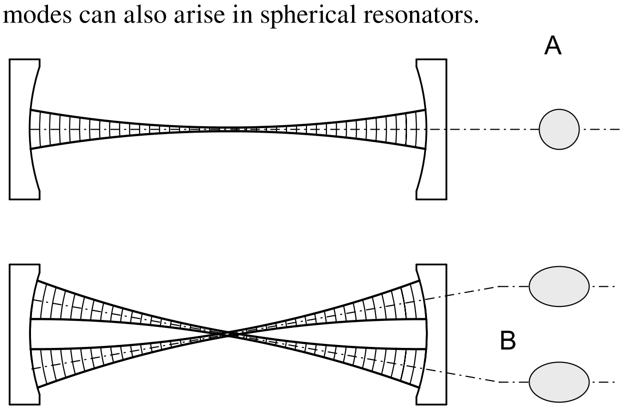


Fig. 2.6: A spherical resonator with oscillation in the fundamental TEM00q (A) and a transverse mode TEM01q (B)

This effect is shown in Fig. 2.6. In contrast to Fig. 2.3 showing the standing waves in the diagram of the electric field of the laser beam, here the geometrical shape of the beam within the resonator is illustrated. When the laser operates in the steady state, the wave-fronts at the mirrors have the same radius of curvature as the mirrors themselves. The situation is drawn in case A in which a radiation field has formed symmetrically about the optical axis. At the resonator output one can see a round Gaussian shaped intensity distribution.
But it is also possible for a radiation field to be set up at an angle to the resonator's optical axis. In principle a multitude of this type of radiation field can develop, because in all of these cases the radius of curvature for the radiation field at the mirrors is the same as that of the mirrors. At the resonator output one can now observe intensity distributions spatially separated and no longer symmetrical about the axis of radiation. Since these modes do not oscillate in the direction of the optical axis (longitudinal) but are mainly transversal, these modes are termed transversal modes. Owing to the large number of modes, a convention has been adopted in which the relevant modes are given a universal designation:

$$TEM_{mnq}$$

TEM stands for Transverse Electromagnetic Modes. The indices m, n and q are integer numbers which state the number of intensity spots minus one in the X axis (m) and the number in the Y axis (n) which are observed. The basis for this consideration is the fundamental mode TEM_{00q} which produces just a round spot. In the example in Fig. 2.6 (B) the designation is:

$$TEM_{01q}$$

The number q states how many nodal points the standing wave in the resonator has. This number does not have any significance for the user of the laser and is therefore generally omitted.

3 The pump-light source

High power Nd-YAG lasers are still mainly pumped with discharge lamps. Commercially available laser systems can output up to 2,000 watts of continuous-waves laser power. If one bears in mind that the overall efficiency of the Nd-YAG laser is about 1 - 2%, then the discharge lamps must have a light output power of approximately 100 - 200 kW. From the light produced, only 2,000W is converted into laser power and the rest appears as heat which must be extracted using complicated cooling systems.
The reason for this "poor" efficiency is that the light produced by the discharge lamps has a broad spectral distribution and the Nd-YAG crystal can only accept the offered light in a number of narrow absorption bands.
Up to the present time it has not been possible, in spite of complex and intensive research, to develop discharge lamps which have an emission tuned to the absorption bands of the Nd-YAG crystal.
The spectral distribution of the radiation output of gas discharge lamps are a composition of several different light emission processes. Each of it strongly depends on the power density inside the lamp and consequently the low power spectrum differs significantly from the high power operation.
The total radiation is a mixture of line and continuum radiation. Line emission generally occurs from transitions within bound states of the used gas atoms and ions whereas the

continuum results from recombination of unbound electrons with ions. For lower power density inside the lamp the line spectra and at a higher density the continuum dominates.

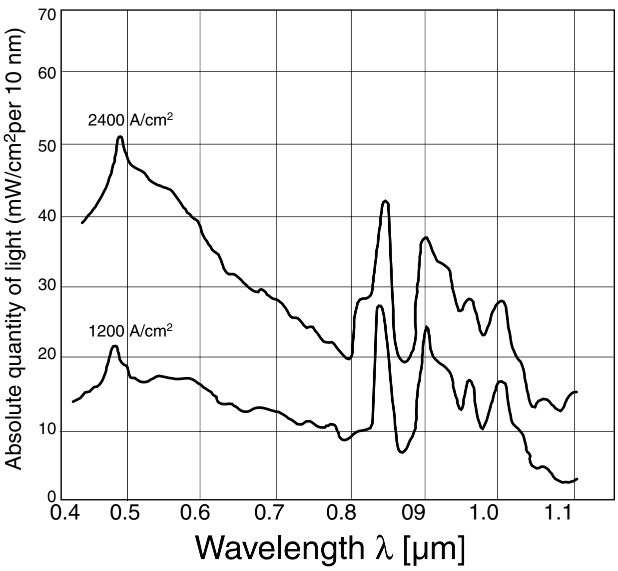


Fig. 3.1: Emission spectrum of Krypton discharge lamps

This behaviour can be seen from the graphical representation (Fig. 3.1) of the spectral distribution of a Krypton filled discharge lamp for two different power densities.

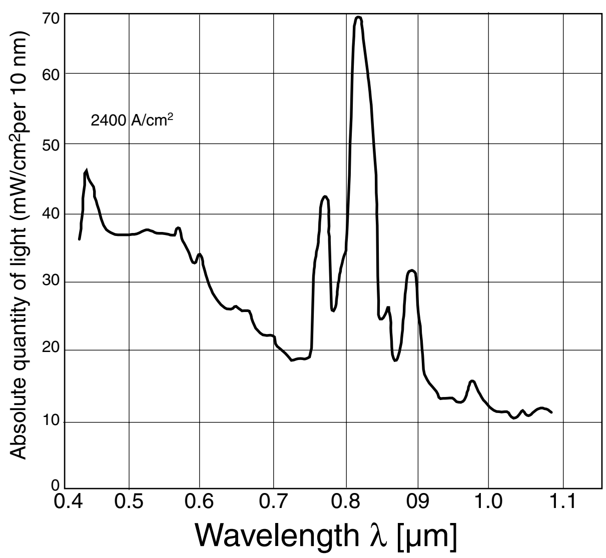


Fig. 3.2 Emission spectra of a Xenon discharge lamp

In the case for Xenon filled discharge lamps the line spectra even vanishes at a higher power density.
To decide which lamp should be used for optical pumping of Nd:YAG Laser one has to compare its absorption spectra (Fig. 3.3) with the spectral emission of the lamp.

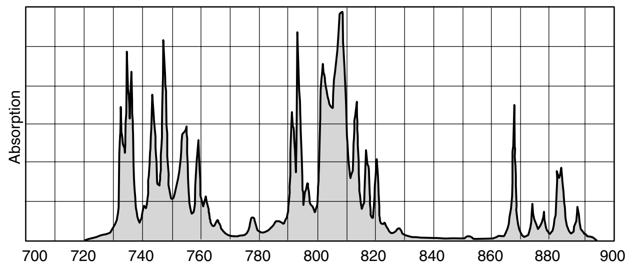


Fig. 3.3: Absorption spectrum of Nd:YAG

In Fig. 3.3 the absorption spectra of the Nd:YAG is shown in a spectral range from 700 to 900 nm showing the two principle pump bands from 730 to 760 and 790 to 820 nm. The highest absorption is at 808 nm and consequently this band is used by pumping with diode lasers. Nowadays such diode laser pumped Nd:YAG laser are available up to 1000 W of output power. However the prices are still too high to compete with the lamp pumped systems. For continuous Laser operation krypton-filled gas discharge lamps have been proven to be the best choice since the line spectrum fits the absorption spectra better than that of xenon-filled pump lamps and the output power is about twice at the same power density. In the next step of our considerations we have to find a way to bring the light into the Nd:YAG crystal. From basic Laser facts we know that the output power depends up to a certain extend on the length of the active material. Furthermore we know that within the optical resonator a so called mode volume exists, which on the other hand determines the useful diameter of the active medium. It makes no sense to use Nd:YAG material that extends this constraint. Commonly the Nd:YAG rod therefore has the shape of a rod. In the early days of Laser technology helical ash lamps have been used. Not only the expensive production of such helical lamps but also the fact that a lot of light is waisted led to the development of linear pump lamps.

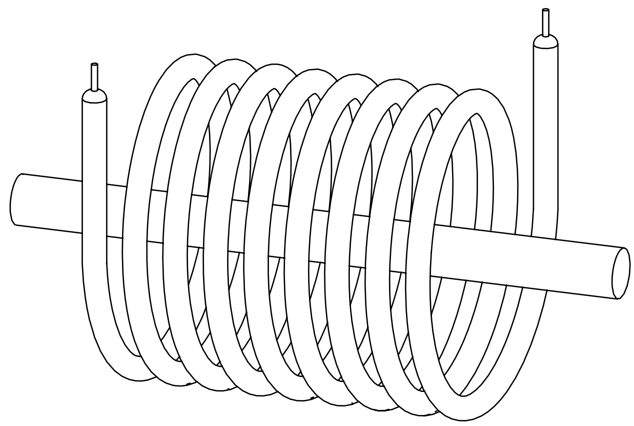


Fig. 3.4: Helical ash lamp with Laser rod

The basic idea was to place the lamp into a hollow re ective cavity with an elliptical cross section. If the lamp is placed to one of the focal points (Fig. 3.5) for instance at f1 the light is guided to the second focal point f2 thus enhancing the yield of used light

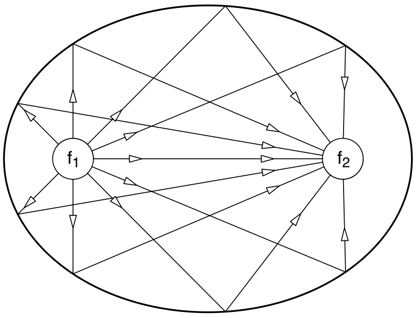


Fig. 3.5: Ray tracing inside an elliptical cavity

A technical arrangement of a lamp pumped Nd:YAG Laser with an elliptical cavity is shown in Fig. 3.6.

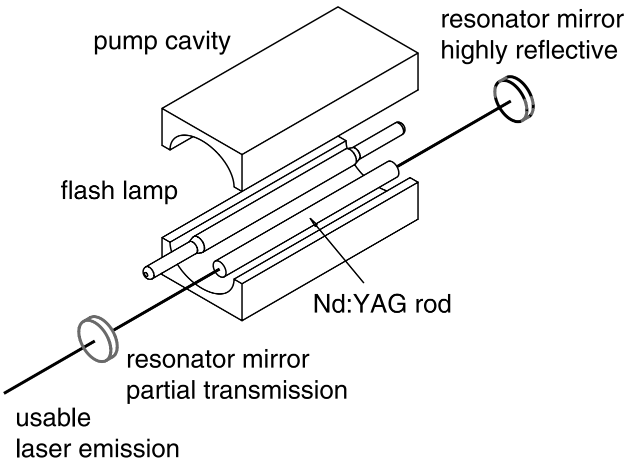


Fig. 3.6: Arrangement of linear pump lamp and Laser rod

In accordance to Fig. 3.5 the Nd:YAG rod is positioned along the focal line or the elliptical pump cavity and the pump lamp along the other one. Due to production and polishing reasons the cavity is made from two parts. The inner surface of the cavity is polished and plated with gold. The optical resonator is formed by two mirrors, one with partial transmission to extract the generated Laser light. As we know from analysing the radiation spectra of the pump lamp in comparison with the absorption band of the Nd: YAG we recognised that from the pump light only a few percent are converted to Laser light. Therefore the residual light energy must be removed in order not to overheat the Laser rod. For this reason the lamp as well as the Laser rod is cooled by a stream of water. In some configurations both the lamp and the rod are surrounded by so called flow tubes and the cooling water flows inside this tubes. In compact systems as used within this workshop the entire cavity is immersed by flowing water. Here are also flow tubes are used, however they are used as shields in such a way that the unused light radiation will not reach the Nd:YAG rod reducing the heat load.

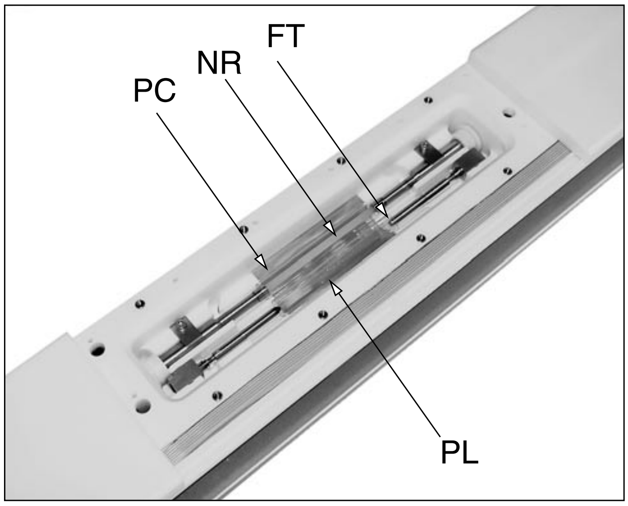


Fig. 3.7: Pump cavity of the Nd:YAG Laser used

PC	Gold plated pump cavity (lower half)
PL	Pump lamp
NR	Nd:YAG rod
FT	Flow tube

4.0 Focusing of Laser Light

We are facing the problem to focus a Laser beam to the smallest possible diameter to achieve the highest intensity for Laser material processing. The beam of the Nd:YAG Laser has to be focused to a diameter of the order of magnitude of its wavelength. Under these circumstances the laws of geometrical optics fail because they anticipate parallel light beams or plane light waves which in reality exist only in approximation.

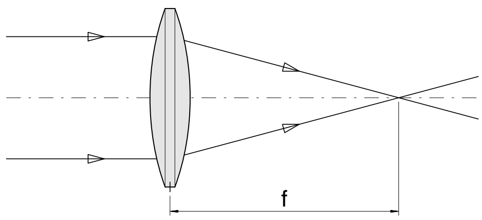


Fig. 4.1: Focusing a beam in geometrical optics

Real parallel light beams do not exist in reality and plane wave fronts exist only at a particular point. The reason for the failure of geometrical optics is the fact that it has been defined at a time where the wave character of light was still as unknown as the possibility to describe its behaviour by Maxwell‘s equations. To describe the propagation of light we use the wave equation

$$\Delta\vec{E} - \frac{n^2}{c^2} \cdot \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

When we consider the technically most important case of spherical waves propagating in the direction of z within a small solid angle as the Laser actually does, we arrive at the following statement for the electrical field:

$$\vec{E} = \vec{E}(r,z)$$

with

$$r^2 = x^2 + y^2 + z^2$$

In this case the solution of the wave equation provides fields which have a Gaussian intensity distribution over the cross-section. Therefore they are called Gaussian beams. Such beams, especially the Gaussian fundamental mode (TEM_{00}) are generated with preference by lasers. But the light of any light source can be considered as the superposition of many such Gaussian modes. Still, the intensity of a particular mode is small with respect to the total intensity of the light source. The situation is different for the laser. Here the total light power can be concentrated in the fundamental mode. This is the most outstanding difference with respect to ordinary light sources next to the monochromasy of laser radiation. Gaussian beams behave differently from geometrical beams.

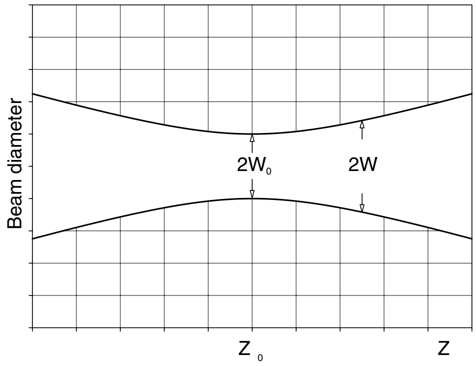


Fig. 4.2: Beam diameter of a Gaussian beam as fundamental mode TEM_{00} and function of z.

A Gaussian beam always has a waist and its radius w results out of the wave equation as follows:

$$w(z) = w_0 \cdot \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \qquad 4.1$$

w_0 is the smallest beam radius at the waist and z_r is the Rayleigh length. In Fig. 4.2 the course of the beam diameter as a function of z is represented. The beam propagates within the direction of z. At the position $z = z_0$ the beam has the smallest radius. The beam radius increases linearly with increasing distance. Since Gaussian beams are spherical waves we can attribute a radius of curvature of the wave field to each point z. The radius of curvature R can be calculated using the following relation:

$$R(z) = z + \frac{z_r^2}{z}$$

This context is re ected by Fig. 4.3. At $z = z_r$ the radius of curvature has a minimum . Then R increases with 1/z if z tends to z = 0 . For z=0 the radius of curvature is infinite. Here the wave front is plane. Above the Rayleigh length z_r the radius of curvature increases linearly. This is a very essential statement. Due to this statement there exists a parallel beam only in one point of the light wave, to be precise only in its focus. But within the range

$$-z_r \le z \le z_r$$

a beam can be considered as parallel or collimated in good approximation.

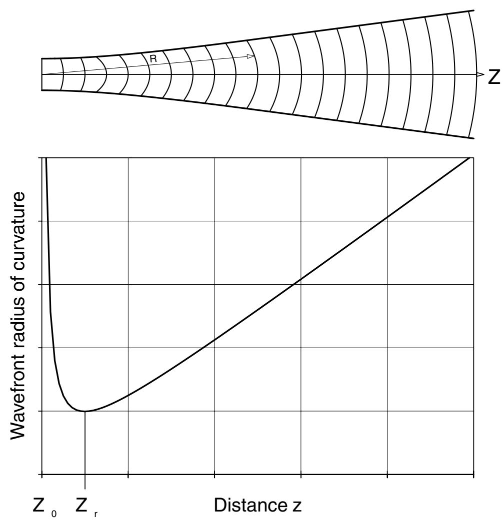


Fig. 4.3: Course of the radius of curvature of the wave front as a function of the distance from the waist at z=0

In Fig. 4.4 the Rayleigh range has been marked as well as the divergence θ in the far field, that means for $z \gg z_0$. The graphical representation does not well inform about the extremely small divergence of laser beams another outstanding property of lasers.

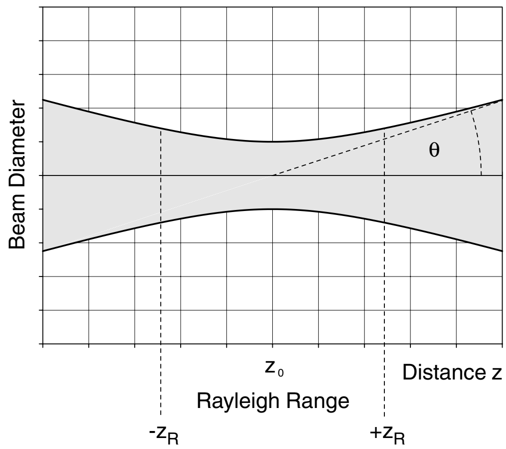


Fig. 4.5: Rayleigh range Z_R and divergence θ for the far field $z \gg z_R$

The reason for this is that the ratio of the beam diameter with respect to z has not been normalised. Let‘s consider, for example, a HeNe-Laser (632 nm) with a beam radius of w_o=1mm at the exit of the laser. For the Rayleigh range 2 Z_r we get:

$$2 \cdot z_R = 2w_0^2 \frac{\pi}{\lambda} = 2 \cdot 10^{-6} \frac{3.14}{623 \cdot 10^{-9}} = 9{,}9 \text{ m}$$

That means that within a range of nearly 10 m the beam can be considered as parallel. In the next example we want to analyse the situation where a Gaussian beam is focused by a lens.