Related topics

Spontaeous emission, induced emission, mean lifetime of a metastable state, relaxation, inversion, diode laser.

Principle and task

The visible light of a semiconductor diode laser is used to excite the neodymium atoms within a Nd-YAG (Neodymium-Yttrium Aluminium Garnet) rod. The power output of the semiconductor diode laser is first recorded as a function of the injection current. The fluorescent spectrum of the Nd-YAG rod is then determined and the maon absorption lines of the Nd-atoms are verified. Conclusively, the mean life-time of the $^4F_{3/2}$-level of the Nd-atoms is measured in appoximation.

Equipment

Basic set optical pumping	08590.93	1
Sensor f. measurem. of beam power	08595.00	1
Digital multimeter	07134.00	1
Oscilloscope, 20 MHz, 2 channels	11454.93	1
Screened cable, BNC, l 750 mm	07542.11	3

Problems

1. To determine the power output of the semiconductor diode laser as a function of the injection current.
2. To trace the fluorescent spectrum of the Nd-YAG rod pumped by the diode laser and to verify the main absorption lines of neodymium.
3. To measure the mean life-time of the $^4F_{3/2}$-level of the Nd-atoms.
4. For further applications see experiment 2.6.09 "Nd-YAG laser".

Set-up and procedure

Fig. 1 shows the set-up of the Nd-YAG laser equipment set, though a few components have to be disregarded when only the semiconductor diode laser and the effect of optical pumping are to be demonstrated. The schematic representations of Fig. 2 and Fig. 3 show the appropriate set-ups:

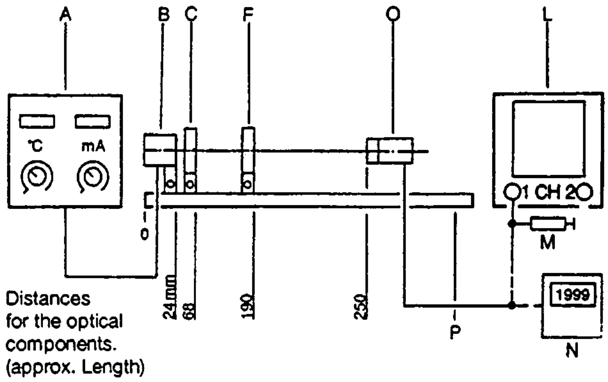


Fig. 2: Investigation of semiconductor laser.

Caution: Never look directly into a non attenuated laser beam

Fig. 1: Experimental set-up of the Nd-YAG laser system.

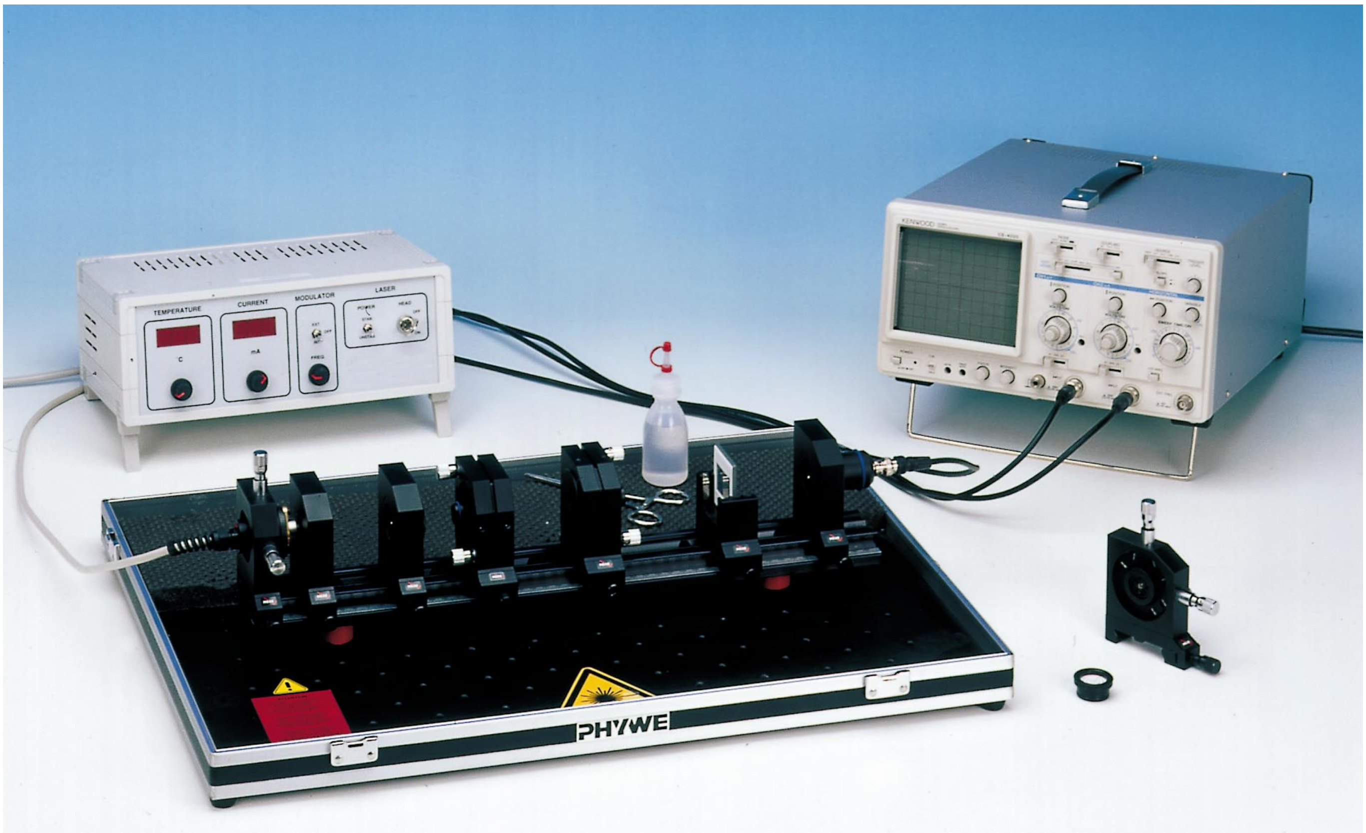
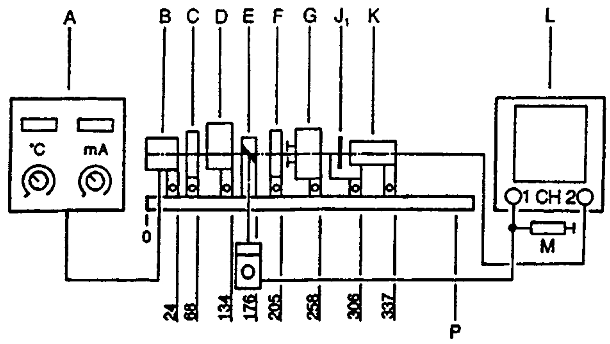


Fig.3 : Optical pumping of Nd-YAG crystal. Measurement of mean life-time.



A Control unit for semiconductor laser

B Semiconductor laser unit with internal Peltier-Cooler

C Collimator lenses set (f = approx. 6 mm)

D Chopper for laser beam with DC-motor, now included in A

E Beamsplitter with high transmission for semi-conductor laser beam, now included in A

F Focusing lens, (f = approx. 50 mm)

G Nd-YAG crystal, in holder, one side with AR-coating/mirror

J_1 Filter-plate, long pass type, transmission for > 850 mm

K PIN-diode detector head with internal battey (9 V)

L Oscilloscope 20 MHz, 2 channels, sens.: 5 mV/unit

N Multimeter with amplifier;

O Sensor head for beam power measuring (silicon-diode)

P Mounting plate for rail and components

The first object of the experiment is to set the semiconductor laser into operation. Before beginning work on the experiment, the module is connected to the control unit in the power-off condition. The module is positioned on the guide and clamped. All controls on the front panel of the control unit should be fully turned to the left. The unit is switched on by the mains switch at the back of the unit. The red warning lamp on the diode laser module turns on and signals that laser radiation is present. The two LCD displays show the set value of temperature in °C and the injection current in mA. If the control is moved in the direction of higher temperature, then it takes a few seconds until the set value has stabilized at the laser diode.

The laser output beam can be made visible with the IR converter screen. The beam output is so intense that the beam can even be seen on black anodized screens. It can be seen that the diode laser beam is very divergent. The laser diode is switched off to fit the collimator. The injection current is set to lowest value before switching off. The collimator is then placed in front of the diode laser module. The collimator has a focal length of 6 mm. The focus is located about 1–2 mm in front of the entry surface. After switching on the laser diode, the collimated light can be seen on the converter screen.

With this experiment, it is now neccesary to block off the emitted beam so that it cannot leave the experimental area in an uncontrolled manner.

The light from the laser diode is almost parallel for a certain collimator position. Since the diode is a 12-stripe element, the beam profile is a flat rectangle. The center of the rectangle should be located about 32 mm above the upper edge of the guide and it should run parallel to the guide. If this is not the case, the beam path can be adjusted with the adjustment screws on the diode laser module.

After this, the diode laser is switched off again and the focusing unit is positioned on the guide. This unit contains a convex lens with a focal length of 50 mm. It is later used as the field lens for focusing the diode laser beam in the YAG rod. It is practical to set up the focusing module at a distance of about 120 mm from the collimator. A scale is provided on the guide to simplify the setting up. A focus of the diode laser beam is produced at a distance of about 50 mm from the main plane of the convex lens. The YAG rod should be positioned at this point so that the focus is situated within the rod.
The position of the focus on the scale is noted before the diode laser module is switched off.

For measuring the power output of the semiconductor diode laser, the power meter O (see Fig. 2) can be placed either the right or left of the convex lens. The latter one reflects about 8% of the incident power. Care should be taken to ensure that the beam is fully concentrated on the power meter.

Laser diodes emit intensive visible light in a narrow spectral range of only a few nanometers. The wavelength of diode emission matches an absorption band of the Nd-YAG crystal very well. It is possible to achieve efficiencies of 50–80% in this manner. However, at present there are not any laser diodes available with output power greater than 10 W. On

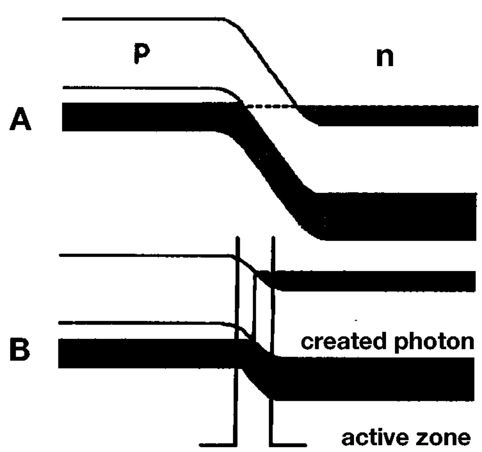


Fig.4: (A) pn junction without applied voltage (B) with applied forward voltage. The active zone contains both electrons and holes which produce a photon on recombining.

account of the attractive features of laser diodes which, in contrast to discharge lamps, do not require any heavy duty power supplies for high voltages (approx. 1000 V), intensive research has started in the manufacture of highpower laser diodes. A further advantage of laser diodes is their very small size which enables a large number of individual diodes to be integrated on one common chip. Rows of pump-light sources with optical output powers into the kW region can be built up with this type of laser diode array. The laser diodes are a special class of lasers. They differ from “conventional” lasers in two points:

I. In classical lasers, the laser-active atoms (molecules or ions) are independent of one another and only the same energy levels are used for the laser process. This means in principle that in order to produce population inversion, an infinite number of atoms can contribute to the effect (Boltzmann statistics). This is not the case with the semiconductor lasers. Here, a defined energy level can only be occupied by two active particles (electrons, Pauli Principle). But in semiconductors, the wave functions of the individual atoms overlap to form a common energy band and the extent to which the level is occupied follows the Fermi Dirac statistics. When considering the laser process, the transition between the distribution of polulation in two energy bands instead of two energy levels must be taken into account as for conventional lasers.

II. The second important difference concerns the propagation of the laser light within a limited pn zone. The spatial intensity distribution of the laser beam is defined by the laser medium and not by the resonator as for “normal” lasers.

These two points leads to the fact that the beam characteristics and the spectral properties of semiconductor lasers are significantly different from those of conventional lasers:

for I: Laser diodes do not habe any inherently defined emission wavelength because it is not two discrete energy levels that are reponsible for the laser process (as with traditional lasers), but rather energy distributions of electrons in energy bands.

for II: The production and guidance of the laser light takes place in a very narrow space (pn layer), (Fig. 4). In contrast to the conventional laser, the dimensions of the resonator are about the same order of magnitude as the wavelength of the laser beam. The spatial distribution of the laser beam and the mode structure are defined by waveguides, whereas the light is freely propagated within a resonator on a conventional laser.

These two points influence the application of laser diodes. Before the laser beam from laser diodes can be used in the usual manner, the strong divergence must be corrected by sometimes complex optical systems. Also, the corrected parallel beam does not have a round cross-sectional shape, but is elliptical and occasionally almost rectangular. The corrections required for the beam of a laser diode and the difficulties in obtaining the required focusing characteristics with comparable power densities mean that the expense involved in the optics obviates the cost advantages of laser diodes. Because of this, a way is sought to not use the laser diode as a primary high power laser, but instead as a pump light source for conventional laser systems due to its excellent characteristics.

Fig. 5: (GaAl) As semiconductor laser with double heterostructure and stripe geometry.

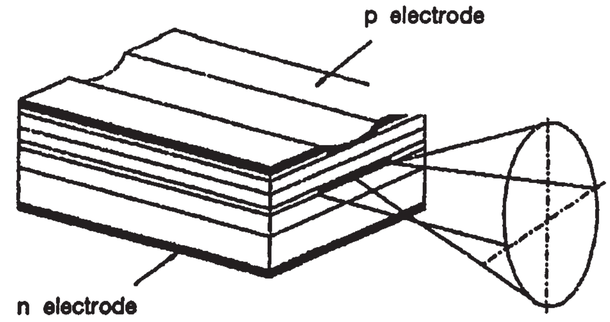


Fig. 5 shows a diagrammatic representation of a (GaAl) As semiconductor laser with double heterostructure and stripe geometry. The n doped GaAs substrate is situated above the n electrode, on which multiple layers of galluim-aluminium arsenide with different aluminium content are deposited. Charge carriers are injected into the very thin (approx. 0.2 μm) active layer by applying a voltage via the upper contact strip which is only a few μm wide. The active zone is embedded between the heterojunction boundaries which act as barriers for the charge carriers. If the flow of current is high enough, population inversion is formed in the active volume. The laser beam leaves the active zone through the exit window. The crystal has such a high refractive index that the end surfaces have a sufficient degree of reflection so that no further coating is required; they therefore act as laser resonator mirrors.

A laser diode with 12 stripes and an output power of 250 mW was used for pumping the Nd-YAG rod. The diode’s collimated beam has a cross-sectional area of approximately 3 mm $\times$15 mm.

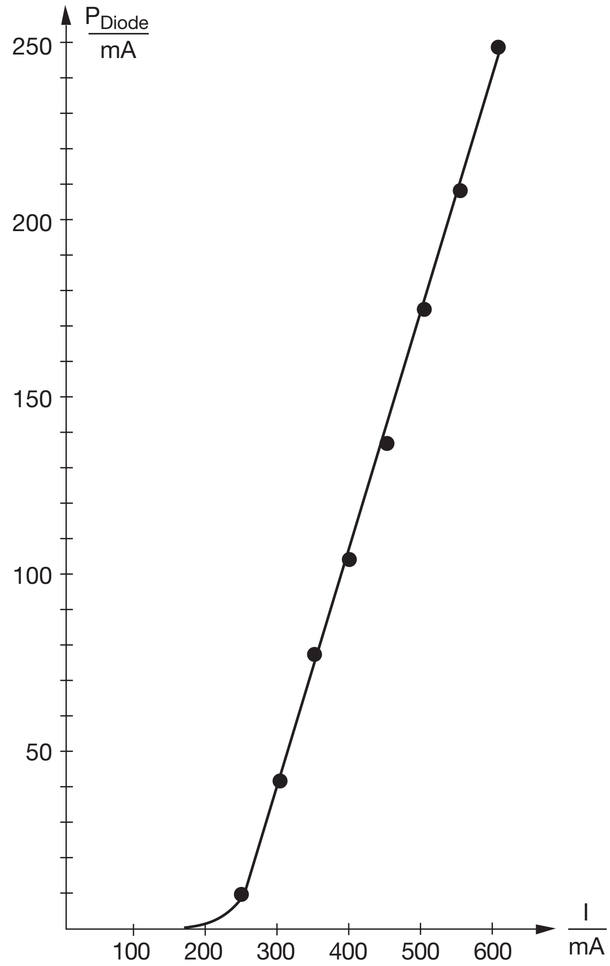
A further characteristic of the diode laser is the strong dependence of the laser wavelengths on the temperature of the semiconductor laser (about 0.25 nm/°K) and the injection current (about 0.05 nm/mA). Users who need a defined wavelength must maintain the temperature and the injection current at the required values.

Fig. 3 shows the arrangement of the optical components for studying the effect of optical pumping of the Nd-YAG rod and for measuring the mean life-time of the $^4F_{3/2}$-level of neodymium.

For tracing the fluorescent spectrum of the Nd-YAG rod, chopper (modulator) and beam splitter (which are actually included in control unit A) are switched off and the detector K is replaced by the powermeter O with filterplate J_1 in front.

For measuring the mean life-time, the modulator within the control unit A is switched on. Its frequency is set to about 500 Hz, which means the Nd-YAG rod receives rectangular pulses of 500 Hz. At the same time, the modulator signal is branched from the rear of unit A to channel two of the dual trace oscilloscope. The PIN-detector K is connected to channel one.

Fig. 6: Power of the semiconductor diode laser as a function of the diode injection current for T = 32.5 °C.



Theory and evaluation

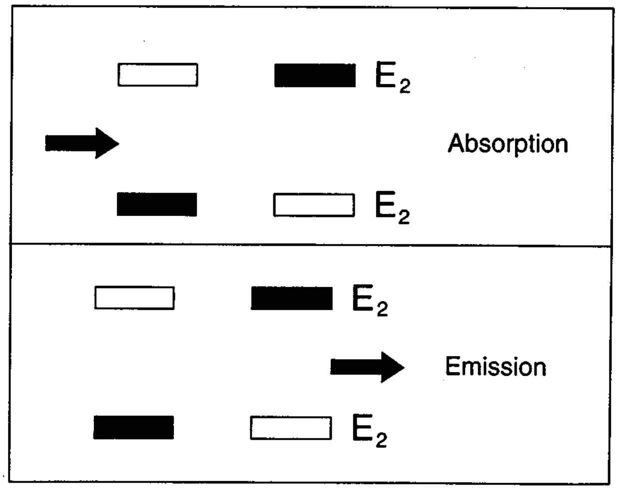
1. Fig. 6 shows the power of the semiconductor diode laser as a function of the diode injection current. The relationship between injection current and power output is linear except for small injection currents. Under 170 mA there is no longer a laser power output (threshold current). For 600 mA we observe a power output of about 250 mW.

2. 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 is taking place between the energy levels.

A transition from one 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 reserve 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

Fig. 7: Absorption and emission.



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.

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

$dn_1 / dt = -B_{12} \cdot n_1 \cdot u_{ph}$		absorption
$dn_2 / dt = -B_{21} \cdot n_2 \cdot u_{ph}$		induced emission
$dn_2 / dt = -A_{21} \cdot n_2$		spontaneous emission

B_{12} is the Einstein coefficient of absorption
B_{21} is the Einstein coefficient of induced emission
A_{21} is the Einstein coefficient of spontaneous emission

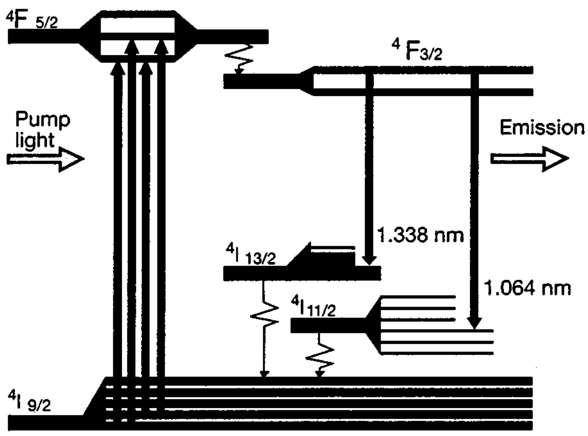
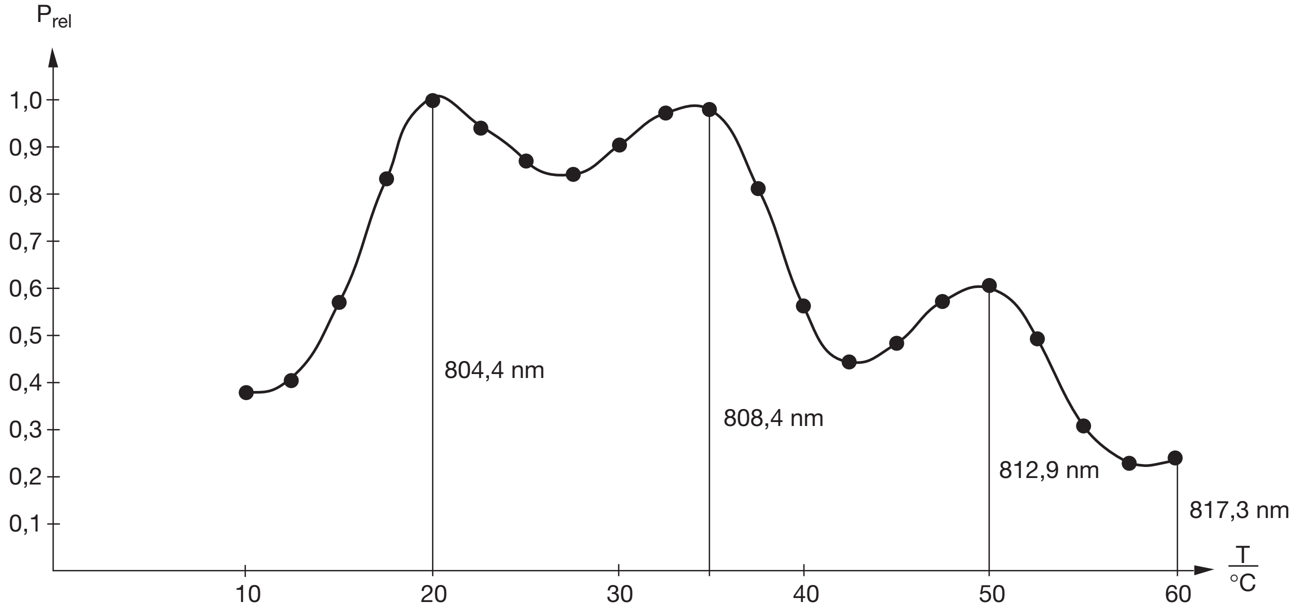


Fig. 8: Relevant energy levles of Nd-YAG for optical pumping with laser diodes having wavelengths around 805 nm.

Fig. 9: Relative fluorescent power of the Nd-YAG rod as a function of the diode temperature (wavelength) for $I = 450$ mA.



n_1 and n_2 are the densities of the atoms in the state 1 and 2 respectively. U_{ph} is the energy density of the external field.

By integration of the equation for spontaneous emssion, 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

$\pi \approx 1/A_{21}$ mean life-time

This states the time which passes before the nubmer of excited atoms has reduced to 1/e or before n_2 (t) has reached the value $1/e \cdot n_2(t_0)$.

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 especially high for metastable levels such as the level $^4F_{3/2}$ of neodymium.

The relevant energy levels of the Nd atom are illustrated in Fig. 8. Here, only those are shown which are significant for optical pumping with laser diodes and which are important in the laser process discussed later. The levels are labelled with their spectroscopic designations. 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 $^4I_{9/2}$ from 5 substates and the state $^4F_{5/2}$, which is pumped from three substates. Since the wavelength of the pump-light source (diode laser) can vary within low limits, a total of four transitions can be pumped with high efficiency. The Nd atoms of the $^4F_{5/2}$ state pass very quickly into the laser output level $^4F_{3/2}$. The laser transition which is most interesting technically, occurs in the $^4I_{11/2}$ state with an emitted wavelength of 1064 nm.

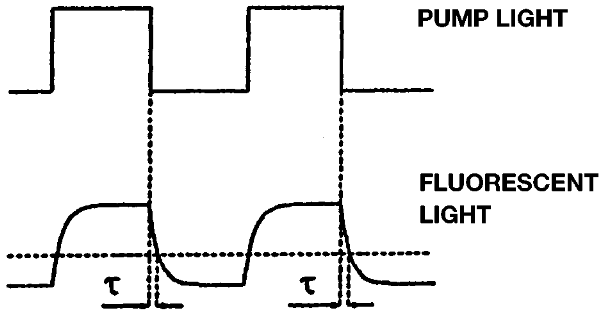
From here, the Nd atoms relax again into the ground state $^4I_{9/2}$ until the pumping process starts from the beginning again. The neodymium therefore has an ideal four-level system.

The relative fluorescent power due to the transition $^4F_{3/2} \rightarrow {}^4I_{11/2}$ is recorded as a function of the diode temperature (wavelength) for an injection current of $I = 450$ mA. Four peaks arise in the graphic depiction of Fig. 9. They can be allocated to the well-known central wavelengths 804.4 nm, 808.4 nm, 812.9 n, and 817.3 nm.

3. The reply of the Nd-YAG rod on the incoming rectangular pulses is to be understood as follows:

   The initial level for emission with a wavelength of 1064 nm is the $^4F_{3/2}$ level which, compared to normal optical transitions, has a very long life-time of about 200 µsec. This means that 200 µsec pass before the intensity of the spontaneous emission has decayed to a value of l/e of the inital value. If the Nd-YAG crystal is optically pumped periodically, then the variation of the spontaneous emission with time can be displayed on an oscilloscope. With the long life-time of 200 µsec, this can even be measured with simple oscilloscopes. The modulator of the supply unit is used for this experiment.
   The RG 850 filter is positioned close behind the YAG rod to suppress the pump radiation that is not absorbed. Fluorescent light above 850 nm passes through the filter to the photodetector K. The signal from the rear of supply unit A is passed to channel two of the oscilloscope and the fluorescence signal of K to channel one. The oscilloscope shows the following figures:

Fig. 10: Oscilloscope traces of signals from rear of supply unit A (upper) and detector K (lower).



Fluorescent light is still observed if the pump is switched off. At the point at which the intensity of the fluorescent light has fallen to 1/e (0.37) of the initial intensity, the time τ is measured. This time corresponds to the life-time of the $^4F_{3/2}$ level (accepted reference value is about 230 μsec). The inverse of the life-time gives the probability A_{21} for spontaneous emission.