Part 1: Laser in continuous wave operation

Safety instructions

Both the diode laser used for optical pumping and the Nd-YAG laser can cause severe, irreparable damage to the eyes! Because the emitted wavelengths (805 nm and 1064 nm, respectively) are invisible to the eye, the imminent danger is especially high. Therefore, during the experiment the provided laser protection glasses must be worn all the time.

The laser must never be left unattended. Unintentional beam reflections into the room (e.g. by wristwatches) must be avoided! The diode laser and the Nd-YAG laser have output powers of up to 0.5 W, i.e. they belong into the laser class 3B. That means the focused beam can burn the skin and materials that are held in the beam path can be ignited!

CAUTION: The glasses DO NOT protect against the frequency-doubled radiation at 532 nm!

1 Theoretical principles

1.1 The principle behind a laser

Atoms possess (in principle infinite) discrete electronic energy levels, which can be represented by an energy-level diagram. Often this is simplified to only two levels of energy: The state of lowest energy (ground state) and an excited energy state. During absorption and emission of light, transitions between individual energy levels according to specific selection rules occur. In the following, the different transitions will be described as a function of their probability and the density of involved atomic states.

Absorption of a photon

An atom is excited from the energy state 1 (E_1) to state 2 of higher energy (E_2), if a photon with the energy difference $\Delta E = E_2 - E_1$ is absorbed (Fig. 1(a)). This process, which will lower the number of photons in the external field by one, occurs with the following rate:

$$\left.\frac{dN_1}{dt}\right|_{\text{absorption}} = -B_{12} N_1 \rho_{\text{photon}}, \tag{1}$$

where N_1 is the density of electrons in energy state 1, B_{12} is the probability factor for the transition from state 1 into state 2, and ρ_{photon} is the radiation density of the incident field.

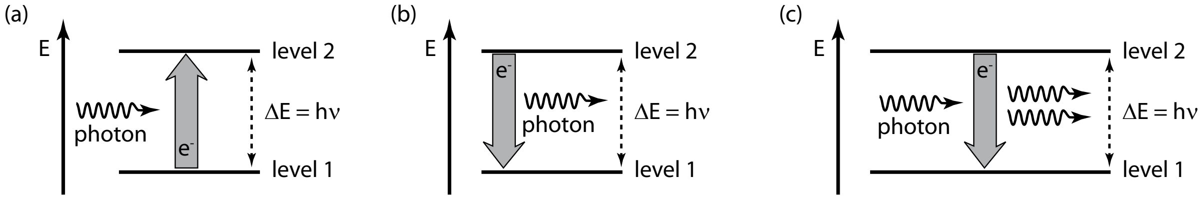


Figure 1: (a) Absorption of a photon. (b) Spontaneous emission of a photon. (c) Induced emission of a photon.

Spontaneous emission

In case of spontaneous emission, an electron decays from a higher energy level and emits a photon of the frequency υ (Fig. 1(b)). This process occurs statistically random and emits the photon isotropically in the entire space (even in the absence of an external field). It can be compared with the radioactive decay of an excited nucleus, represented by the time constant $\tau = \frac{1}{A_{21}}$ which is the mean lifetime of the electronic state 2 before spontaneous emission occurs. By spontaneous emission the number of electrons at level 2 decreases with time, as given by:

$$\left.\frac{dN_2}{dt}\right|_{\text{spontaneous}} = -A_{21}N_2. \tag{2}$$

Induced emission

If the higher energy state 2 is already occupied, an incoming photon from the external radiation field can trigger an emission event, which is called induced emission (Fig. 1(c)). In this process a second photon is created which has the same properties as the original one, i.e. same direction of propagation, same energy and identical phase. As there is a fixed phase relationship between incident and induced photon (namely zero), constructive interference occurs. The rate of induced emission is proportional to both the occupation of the higher energy level N_2 and the external photon field ρ_{photon}:

$$\left.\frac{dN_2}{dt}\right|_{\text{induced}} = -B_{21}N_2\rho_{\text{photon}}, \tag{3}$$

where B_{12} is the proportionality constant for the transition from level 2 to level 1 by induced emission. Albert Einstein showed that the proportionality constants in equations 3 and 1 are identical:

$$B_{12} = B_{21} \tag{4}$$

(See e.g. A. Einstein: Strahlungs-Emission und -Absorption nach der Quantentheorie, Verhandlungen der Deutschen Physikalischen Gesellschaft, Berlin 18, 318-323 (1916) and A. Einstein, Zur Quantentheorie der Strahlung, Physikalische Zeitschrift 18, 121-128 (1917))

Laser

In the optical spectral range (of e.g. sunlight or conventional light sources) the induced emission is a very unlikely but interesting process: In principle, the induced emission allows to increase the number of photons in an external radiation field due to interaction with excited atoms in a medium. Thus, incident light can be significantly amplified by creating new photons with the same frequency, direction of propagation and phase in a kind of chain reaction, as the induced photons themselves can trigger new induced emission events. The physical principle of "**l**ight **a**mplification by **s**timulated **e**mission of **r**adiation" is realized by a special light source: the laser.

In order to achieve light amplification by means of induced emission, two fundamental conditions must be satisfied:

1. The probability of induced emission processes have to be higher than the one of spontaneous emission.
2. Absorption processes must not simultaneously prevent the amplification of the light.

The probability of doubling a photon by an induced emission event will be greater than the probability of the absorption of the photon, if (after equations 1, 3, and 4) the excited electronic state is more populated than the ground state: $N_2 > N_1$. At thermodynamic equilibrium (at a given temperature T), the distribution of the occupied states follows the Boltzmann distribution:

$$\frac{N_2}{N_1} = \exp\left(-\frac{\Delta E_{21}}{k_B T}\right), \tag{5}$$

with the Boltzmann constant k_B. It's quite obvious that this allows at most an equal occupation of states. But laser activity only becomes feasible if the population of occupied states are inverted.

Population inversion

In the so-called population inversion the occupation number of at least two energy levels are inverted: A higher energy state is more occupied than a lower energy state (and hence the population inversion represents a non-equilibrium condition):

$$N_2 > N_1. \tag{6}$$

But relaxation processes (both optical and non-radiative transitions) lead to a restoration of the equilibrium state. Therefore, a mechanism is needed which constantly supplies energy to the system and hence will maintain the population inversion despite the relaxation processes. This process is called "laser pumping".

In this context, the irradiation of light, which leads to the occupation of an otherwise unexcited state, is called optical pumping. Another kind of pumping mechanism is the electrical pumping (examples for the latter are electric glow discharges in gas lasers or electrical currents in a diode laser). If the pumping is sufficiently intense, the atoms are excited more quickly than they return to the ground state by spontaneous emission. Hence, there are more atoms in the excited state than in the ground state and the desired population inversion is achieved.

Two level laser system

Absorption processes raise electrons from the lower energy level 1 to the higher level 2. At the same time, electrons fall back into the ground state due to spontaneous and induced emission processes. For more photons to be generated by induced emission than lost by absorption, occupation inversion is necessary. As it is known, this is not possible in the equilibrium state, especially since spontaneous emission also occurs. Optical pumping is also not suitable for creating an inversion, since the pumping light equally contributes to both absorption and induced emission. Thus the two-level system is not a suitable for laser operation and therefore an inversion state can only be achieved by introducing additional energy levels.

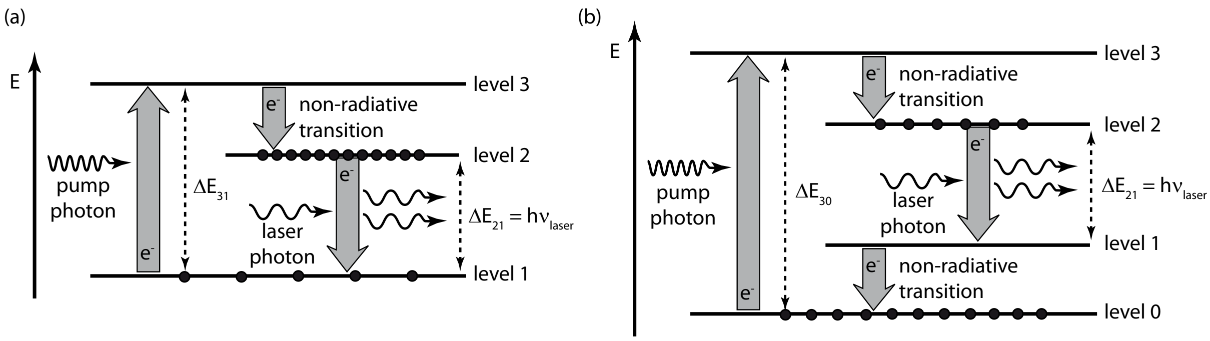


Figure 2: (a) Schematic diagram of a (a) three-level laser system and (b) four-level laser system.

Three level laser system

In a three-level laser system, optical pumping results in the transitions of electrons from level 1 to level 3, which ideally has a very short lifetime and therefore remains virtually unoccupied even if it is heavily pumped (see Fig. 2(a)). By means of non-radiative transitions, a large portion η (quantum yield) of the pumped electrons relax from level 3 into the metastable laser level 2. This prevents the direct relaxation of electrons from level 3 back to level 1 by spontaneous or induced processes. In this way, an electron density builds up at level 2. The laser transition subsequently takes place from level 2 into the ground state 1. But it is disadvantageous that more than half of all the electrons, which initially populated the ground state, have to be brought into the upper laser level 2 by optical pumping until population inversion occurs in the three-level laser system.

Four-level laser system

It is obviously much more favorable to choose a non-occupied state as the lower laser level and thus motivate a four-level laser system. This differs from a three-level system by the presence of a further state (level 0), which can be the only one that is significantly occupied (see Fig. 2(b)). The transition of electrons from the lower laser level 1 to the ground level 0 happens by means of non-radiative processes.

The lifetime of level 1 should be very short so that it remains quasi unoccupied as it is the case for level 3. On the other hand, the metastable upper laser level 2 can be occupied. As soon as optical pumping occurs, population inversion occurs between the laser levels (even at low intensities of the pump light). Therefore, light amplification is possible!

1.2 Laser resonators

As mentioned before, the amplification of light can be described as a kind of chain reaction, where incident photons create new photons in the laser active material (also called active medium) by means of induced emission. Now the question is, which photons are initially there to start the amplification.

For this keep in mind that stimulated and spontaneous emissions are competing with each other all the time. Therefore, before becoming an amplifying medium, the active medium which is pumped by an external energy source is initially just a “lamp” as there is only spontaneous emission. This is due to the fact that the field ρ_{photon} of photons with the right laser energy for the induced emission process has to be build up first.

Only the placement of the active medium inside an optical resonator creates the necessary conditions for stimulated emission to become predominant over spontaneous emission. The simplest optical resonators, the Fabry-Perot resonators, consist of two flat or spherical mirrors (see Fig. 3). Both mirrors are mounted opposite each other and are centered with respect to a common optical axis in such a way that the mirror surfaces are perpendicular to the optical axis.

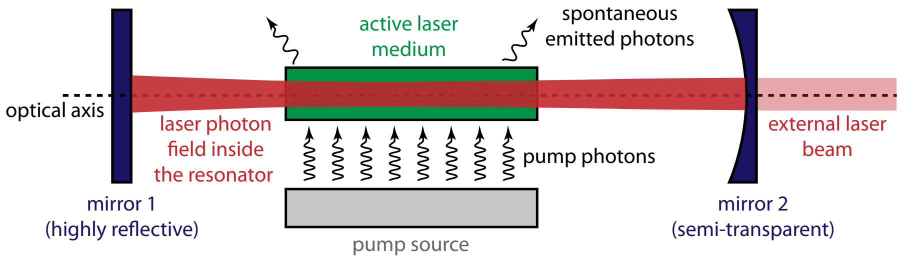


Figure 3: Optically pumped active medium inside an optical resonator.

When the laser starts up, the active medium spontaneously emits photons in all directions. However, a small part of the emission occurs along the axis of the resonator. These spontaneous photons can travel back and forth through the resonator and hence the active medium. As the laser medium posses a finite size and the probability for the induced emission is also finite, this optical feedback is a necessary requirement for a photon to create several replicas before the initially photon is coupled out of the resonator (as the actual laser beam) or is lost due to absorption or diffraction processes.

Thus, over time, the photon field ρ in the cavity increases considerably. According to equations 2 and 3 the probability of stimulated emission increases compared to the spontaneous emission. At the same time, the resonator acts as a mode filter: only the wave perfectly perpendicular to the axis of the cavity will be propagated and certain frequencies will be favored (the resonance frequencies of the resonator). In this way, the resonator produces a specific radiation.

Resonator modes

Given a predetermined distance L of the resonator mirrors, only those waves, whose field strength at both mirrors disappears, can propagate in a plane-parallel resonator. This is the case if L corresponds to an integer multiple of half the wavelength λ: $L = \frac{n\lambda}{2}$. The directly neighboring mode satisfies the condition $L = \frac{(n+1)\lambda'}{2}$. Obviously, adjacent modes are equidistant and have the wavelength spacing:

$$|\delta\lambda| = |\lambda' - \lambda| = \frac{2L}{(n+1)n} \tag{7}$$

With $\nu = \frac{c}{\lambda}$ equation 7 yields the so-called mode spacing:

$$\delta\nu = \frac{c}{2L}. \tag{8}$$

In principle, there are many modes that fit into the resonator. However, the laser medium only amplifies modes within a limited range, which is given by the so-called gain bandwidth (the laser-active energy levels posses a Gaussian like energy broadening - a more detailed discussion is given in the second part of the introduction).

Stability of the laser resonator

A resonator is optically stable if the light remains in the resonator after any number of reflections and does not leave it (e.g. by hitting the edges of the mirror). In the unstable case, however, the light beam travels out of the resonator after a finite number of reflections. In order to characterize the geometry and stability of resonators, the so-called g-parameter can be derived:

$$g_i = 1 - \frac{L}{R_i}, \tag{9}$$

where L is the mirror distance and R_i the mirror radius ($i = 1$ left mirror, $i = 2$ right mirror). Here, $R_i > 0$ if the mirror is concave and $R_i < 0$ if the mirror is convex.

The range in which a resonator is optically stable is determined by the so-called stability criterion. The resonator is optically stable if the product of the g-parameters of both mirrors satisfies the so-called stability criterion (all other resonators are unstable):

$$0 \leq g_1 \cdot g_2 \leq 1. \tag{10}$$

For the special case of a hemispherical resonator systems, Eq. (7) can be simplified: The g-parameter of the planar mirror is $g_{\text{plane}} = 1$, since $R_{\text{plane}} = \infty$. Thus, in the case of a fixed radius of curvature R of the spherical mirror, the distance L of both mirrors can be varied between $L = 0$ ($g_{\text{spherical}} = 1$) and $L = R$ ($g_{\text{spherical}} = 0$). Hence, the stability criterion for hemispherical resonator system is:

$$0 \leq L \leq R. \tag{11}$$

The choice of a particular distance L within this range, which is ultimately used in the actual setup, depends on the intended use of the laser system. An operation close to the stability limit makes the system more sensitive to misalignment: Even small changes in the distance, e.g. caused by thermal expansion, can bring the resonator into the unstable regime. A smaller distance between the mirrors avoids this problem, but reduces the useable volume for the active medium, which in turn strongly influences the performance of the laser.

The condition in equation 10 can be illustrated by a stability diagram (see Fig. 4). The g-parameters of the two mirrors are plotted on the both axes, respectively.

All stable resonators lie between the two axes ($g_1 \cdot g_2 = 0$) and the two branches of the hyperbola ($g_1 \cdot g_2 = 1$). The dotted line represents the position of the symmetrical resonators ($g_1 = g_2$). Among the symmetrical resonators, three types are distinguished which are on the boundary of the instability range and are just stable: the plane-parallel ($g_1 = g_2 = 1$), the concentric ($g_1 = g_2 = -1$) and the confocal resonator ($g_1 = g_2 = 0$).

Losses in laser resonators

A very important aspect and a characteristic property of a resonator is given by its optical losses. E.g. at every reflection on a resonator mirror the light is diffracted. At the location of the second mirror, a diffraction pattern is thus formed, which diameter is larger than the mirror diameter.

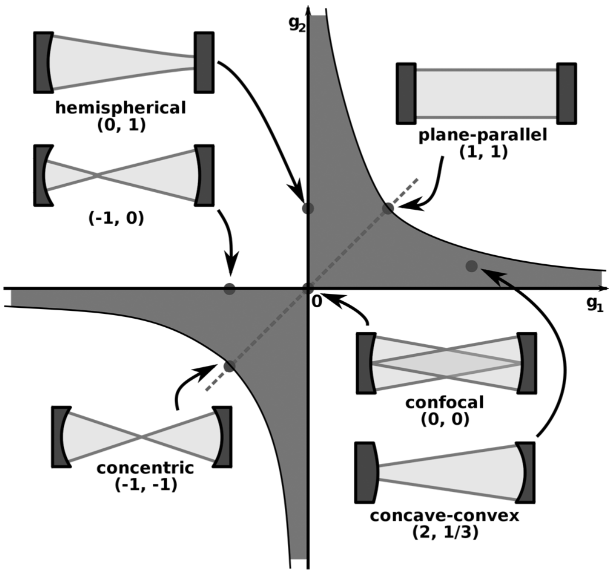


Figure 4: Stability diagram with different kind of resonators.

Additional losses include e.g. losses due scattering of light at imperfections of the mirrors or other optical elements inside the resonator, absorption, or the (un)intentional out-coupling of a part of the laser beam.

1.3 Rate equations for the description of a four-level laser system

Transitions in which photons are emitted (either spontaneous or induced) can be described by rates. If the state of a laser-active medium is known to a good extent, then approximate expressions for the population inversion n and the photon density ρ (both per unit volume) can be derived using the rate-equilibrium model.

Inversion

The state of the active medium can be described in sufficient detail by considering the occupation densities of the energy levels involved in the laser process. For the four-level laser system we define the total number of electrons n_{tot} in the volume of the active medium and assume it to be constant:

$$n_{tot} = N_0 + N_1 + N_2 + N_3 = \text{const} \quad \rightarrow \quad \frac{dn_{\text{tot}}}{dt} = 0, \tag{12}$$

where N_i is the electron density at energy level i (see Fig.2(b)).

Due to the assumption that the upper pumping state and the lower laser level relax rapidly, there is a negligible population in these two states ($N_3 \approx 0$, $N_1 \approx 0$). Hence the total number of electrons and the inversion n can be approximated:

$$n_{\text{tot}} \approx N_0 + N_2 \quad \wedge \quad n = N_2 - N_1 \approx N_2 \tag{13}$$

It follows that:

$$\frac{dn}{dt} = \frac{dN_2}{dt}. \tag{14}$$

In other words, the time dependence of the population inversion n results from the temporal change in the occupation of the upper laser state(level 2). In this case, the occupation of level 2 is changed by different processes, as discussed in the following:

1. Optical Pumping:

$$\left.\frac{dN_2}{dt}\right|_{\text{pumping}} = \eta W_{03} N_0 = W_p N_0, \tag{15}$$

where W_{03} is the probability of the transition from state 0 to state 3, $W_p = \eta W_{03}$ is the so-called pump rate (number of cycles of the electrons per unit time) and η is the quantum yield (probability for the relaxation from state 3 to state 2).

2. Spontaneous emission

$$\left.\frac{dN_2}{dt}\right|_{\text{spontaneous}} = -\Gamma N_2 \quad \text{with} \quad \Gamma = \frac{1}{\tau_{\text{spont}}}, \tag{16}$$

where τ_{spont} is the time constant of spontaneous emission.

3. Induced process

$$\left.\frac{dN_2}{dt}\right|_{\text{induced}} = -\sigma c\rho\,(N_2 - N_1) = -\sigma c\rho n, \tag{17}$$

where σ is the effective cross section for the interaction of a photon with an atom of the active medium and c is speed of light. Hence, $\rho \cdot c$ represents the photon current density through the laser active medium. This yields (with the before-mentioned approximations $n_{\text{tot}} \approx N_0 + N_2$ and $n = N_2 - N_1 \approx N_2$):

$$\frac{dN_2}{dt} = -\sigma c\rho\,(N_2 - N_1) - \Gamma N_2 + W_{\text{p}} N_0 \tag{18}$$

or:

$$\frac{dn}{dt} = -\sigma c\rho n - \Gamma n + W_{\text{p}}\,(n_{\text{tot}} - n) \tag{19}$$

Density of photons

If it is taken into account that a photon is generated in each emission process and one is lost in each absorption process, an equation for the temporal change in the density of photons can also be established. The density of photons ρ is changed by the following processes:

1. Induced emission process

$$\left.\frac{d\rho}{dt}\right|_{\text{induced}} = -\left.\frac{dN_2}{dt}\right|_{\text{induced}} = \sigma c\rho\,(N_2 - N_1) = \sigma c\rho n \tag{20}$$

2. Losses (decoupling at the mirror, scattering, diffraction, spontaneous emission...)

$$\left.\frac{d\rho}{dt}\right|_{\text{losses}} = -\frac{\rho}{\tau_{\text{ph}}}, \tag{21}$$

where τ_{ph} is a decay constant representing the photon losses. The temporal change in the density of photons results as the sum of these effects:

$$\frac{d\rho}{dt} = \rho\left(\sigma c n - \frac{1}{\tau_{\text{ph}}}\right) \tag{22}$$

Obviously, it is not sufficient for laser operation ($\rho \neq 0$) to generate just any kind inversion. The inversion must exceed a certain threshold value n_{th}, since $\frac{d\rho}{dt} > 0$ is only achieved for:

$$n > n_{\text{th}} = \frac{1}{\sigma c \tau_{\text{ph}}} \tag{23}$$

Stationary solution of the rate equations

$\frac{dn}{dt}$ and $\frac{d\rho}{dt}$ describe coupled, non-linear differential equations, which are generally only solvable numerically. In the following, however, the special case of the (somehow achieved) stationary case of laser operation will be discussed, for which analytical solutions of the differential equations can be found. Then $\frac{dn}{dt} = 0$ and $\frac{d\rho}{dt} = 0$. From equation 19 follows:

$$\frac{dn}{dt} = -\sigma c\rho n - \Gamma n + W_{\text{p}}\,(n_{\text{tot}} - n) = 0 \tag{24}$$

and thus:

$$n = \frac{W_{\text{p}} n_{\text{tot}}}{\sigma c\rho + \Gamma + W_{\text{p}}} \tag{25}$$

Obviously, in the four-level laser system, inversion ($n > 0$) is established as soon as the system is pumped ($W_p > 0$). As long as the laser is operated below or just at its threshold, no photon field is build up ($\rho = 0$ for $n < n_{\text{th}}$). But for small pump powers ($W_p \ll \Gamma$) the inversion increases proportionally to the pump power:

$$n = n_{\text{tot}} \frac{W_{\text{p}}}{\Gamma} \tag{26}$$

Above the laser threshold ($n > n_{\text{th}}$), equation 22 yields for the photon density in the stationary case:

$$\frac{d\rho}{dt} = \rho \left(c\sigma n - \frac{1}{\tau_{\text{ph}}} \right) = 0 \tag{27}$$

Independent of an exact value for ρ, the equation can only be satisfied if the minimum condition in equation 23 for the population inversion is satisfied. Hence, in the steady case condition with a positive photon density ($\rho > 0$) no inversion beyond the threshold value can be generated even with the strongest pumping mechanisms (see Fig. 5(a)). Instead of the population inversion the photon density increases, which thus limits the inversion at the threshold value because of an increased probability of induced emission.

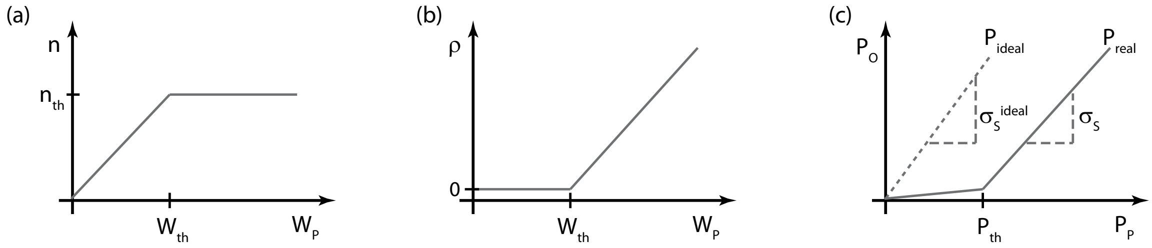


Figure 5: (a) Inversion n as a function of pump rate W_{P}. (b) Photon density ρ as a function of pump rate W_{p}. (c) Laser output power P_{o} as a function of pump power P_{P}.

If the value of the inversion at the laser threshold in the steady case condition is known, an expression for the photon density can be derived. For this purpose, the inversion threshold value according to equation 23 is put into equation 25:

$$\rho = \tau_{\text{ph}} \left[W_{\text{p}} \left(n_{\text{tot}} - n_{\text{th}} \right) - \Gamma n_{\text{th}} \right] \tag{28}$$

Or with the definition of a threshold pump rate:

$$W_{th} = \Gamma \frac{n_{\text{th}}}{n_{\text{tot}} - n_{\text{th}}} \quad \rightarrow \quad \rho = \tau_{\text{ph}} \left(n_{\text{tot}} - n_{\text{th}} \right) \left(W_{\text{p}} - W_{\text{th}} \right) \tag{29}$$

With $n_{\text{th}} \ll n_{\text{tot}}$ follows (see also schematic dependence in Fig. 5(b)):

$$\rho = \tau_{\text{ph}} n_{\text{tot}} \left(W_{\text{p}} - W_{\text{th}} \right). \tag{30}$$

Laser output power

Both the pump rate and the photon density (inside the laser resonator) are values which are not directly accessible to the measurement. However, the photon density inside the resonator is connected to the easily measurable magnitude of the laser output power P_{o}, while the pump rate is related to the pumping power P_{P}. The energy content E of the resonator can be represented as the product of the photon density ρ, resonator volume V and energy E_{21} of a single laser photon:

$$E = \rho V \Delta E_{21} \quad \text{with} \quad \Delta E_{21} = h\nu_{21} = E_{\text{photon}} \tag{31}$$

The laser output power P_{o} is the part of the resonator energy which is coupled out of a semi-transparent mirror per unit of time (see Fig. 3). In stationary operation, the total energy content of the resonator is constant. The photons, which are coupled out of the resonator through the semi-transparent mirror, are then replaced by photons created by induced emissions in the laser medium. Thus, the output power results in:

$$P_{\text{o}} = E \frac{T}{\tau_{\text{R}}} = \rho V \Delta E_{21} . \frac{T}{\tau_{\text{R}}}, \tag{32}$$

where τ_R is the time period a photon needs to travel back and forth through the resonator and T is the transmissivity of the one resonator mirror which is responsible to couple out the laser beam. With ρ from equation 30 follows:

$$P_{\text{o}} = V \Delta E_{21} T n_{\text{tot}} \left(W_{\text{p}} - W_{th} \right) \frac{\tau_{\text{ph}}}{\tau_{\text{R}}} \tag{33}$$

In equation 33 the product $N_{\text{tot}} = n_{\text{tot}}V$ describes the number of electrons in the laser-active medium. To achieve a certain pump rate W_{p}, the active medium must be supplied with power:

$$P_{\text{p}} = N_{\text{tot}}\Delta E_{30}W_{03} = n_{\text{tot}}V\Delta E_{30}\frac{W_{\text{p}}}{\eta}, \tag{34}$$

where $W_p = \eta W_{03}$ is defined as in equation 15 and ΔE_{30} is the energy needed for the excitation of an electron from the lower pump level 0 into the upper pump level 3. Accordingly, there exists a threshold pumping power P_{th} to W_{th}:

$$P_{\text{th}} = n_{\text{tot}}V\Delta E_{30}.\frac{W_{\text{th}}}{\eta} \tag{35}$$

Putting equations 34 and 35 into 33 provides the desired expression for the laser output power. For $P_{\text{p}} < P_{\text{th}}$, $P_{\text{o}} = 0$, and for $P_{\text{p}} \geq P_{\text{th}}$:

$$P_{\text{o}} = \eta\frac{\Delta E_{21}}{\Delta E_{30}}\frac{T\tau_{\text{ph}}}{\tau_{\text{R}}}\left(P_{\text{p}} - P_{\text{th}}\right), \tag{36}$$

where η is the quantum yield, T is the transmissivity of the mirror, P_{p} is the pump power and P_{th} is the threshold pump power.

Above the threshold pump power, the laser output power increases linearly with pump power (see Fig. 5(c)). The slope of this line is an important characteristic of the laser and is called slope efficiency:

$$\sigma_{\text{s}} = \eta\frac{\Delta E_{21}}{\Delta E_{30}}\frac{T\tau_{\text{ph}}}{\tau_{\text{R}}}. \tag{37}$$

In case of an ideal laser without any undesired losses, every photon created by induced emission will leave the resonator through the output mirror and will not be lost due to other processes ($1/\tau_{\text{ph}} = T/\tau_{\text{R}} \rightarrow \frac{T\tau_{\text{ph}}}{\tau_{\text{R}}} = 1$). Hence, the ideal efficiency of a laser system is:

$$\sigma_{\text{s}}^{\text{ideal}} = \eta\frac{\Delta E_{21}}{\Delta E_{30}}. \tag{38}$$

In addition, $W_{\text{th}} = 0$ (according to equation 29) and therefore $P_{\text{th}} = 0$ (according to equation 35) both apply to an ideal laser system. The output characteristic for such a system is described by a line through the origin (see Fig. 5(c)). The laser output power also depends (amongst other things) on how much of the laser-active material is used. The pump volume is the volume of the active material that is illuminated by the pump beam. The mode volume, on the other hand, is the volume that the laser modes fill within the laser-active material. The choice of the focusing of the pump beam or of the resonator geometry can influence both variables. In the optimum case, the pump volume should be somewhat larger than the mode volume. The latter depends on the beam path, which is established within the resonator. The beam path is determined by the selection of the resonator type, the radii of curvature of the mirrors and the distance between them. It should be noted, however, that the mirror distance cannot be arbitrarily selected at a given mirror radius (see stability criterion).

The energetic ratio of laser and pump photons is referred to as a quantum efficiency, which in case of the diode-pumped Nd-YAG laser of the experiment is given by:

$$\frac{\Delta E_{21}}{\Delta E_{30}} = \frac{810\ \text{nm}}{1064\ \text{nm}} = 0.76. \tag{39}$$

1.4 Solid State Laser

As active media, solid-state lasers contain crystals or glasses which are doped with optically active metal ions or ions of rare earth metals. These ions absorb optical radiation in a wide spectral range. By means of relaxation processes or optical transitions, the population of a metastable electron level takes place over various intermediate levels. This metastable level serves as the initial level of the laser emission which preferably occurs in the visible and infrared spectral range. The laser wavelength is determined by the involved active ion, the type of the transition (usually several transitions are possible) and the host crystal.

Active media

One of the most important prerequisites for "good" solid state lasers is the use of optically perfect active media which do not contain impurities, streaks or bubbles. Usually, however, a crystal or glass fulfills this condition insufficiently, so that the quality of the laser radiation is low. In addition, the following characteristics have/should be met:

1. Existence of metastable states that can serve as the upper laser level.
2. High quantum yield.
3. Transparency for the laser light wavelength.
4. Strong, not too sharp absorption lines or bands when the medium is optically pumped.
5. Mechanical hardness and chemical stability.
6. Absence of internal stresses and refractive index variations.

Optical resonators

There are different ways to realize a resonator system:

1. The laser-active medium itself can be used as a resonator. For this purpose, the resonator mirrors are vaporized directly onto the end faces of the parallel and evenly polished crystal. One of the mirrors should be highly reflective to the emitted laser light, so that the main part of the radiation exits on the other, low-reflecting side. This kind of resonator is used for diode lasers, which will be used as the pump laser in the experiment. In addition, the side faces of the semiconductor laser should be strongly roughened in order to prevent undesirable optical feedback in the transverse direction.

2. The use of open resonators with external mirrors is necessary if the radiation field is to be influenced within the resonator (e.g. by diaphragms or filters, see the explanations for pulsed laser generation in the second part of the instructions). For this purpose, the crystal is ground at the Brewster angle or is evaporated with a dielectric anti-reflective coating in order to avoid reflection losses at its end faces and therefore to keep the internal resonator losses as small as possible.

For the Nd-YAG laser in this experiment an open hemispherical Fabry-Perot resonator is used. In this case, one side of the YAG rod, coated with a layer which is highly reflective for the laser wavelength (1064 nm), forms the left (plane) resonator mirror. The evaporated layer system is designed in such a way that a maximum of the pump light (with only 20% losses) can be transmitted.

Nd-YAG lasers

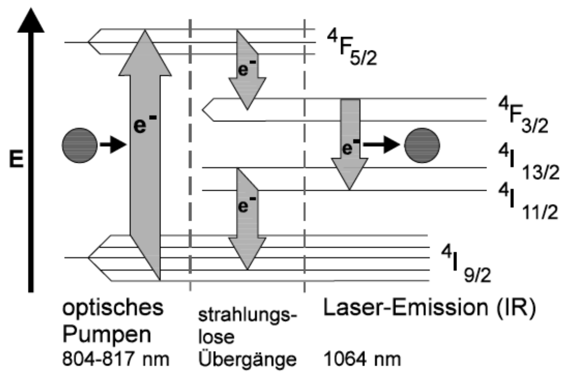


Figure 6: Important energy levels of the Nd^{3+} ion for optical pumping with diode lasers and for the laser process.

The Nd-YAG laser is one of the most popular four-level solid-state laser, which was realized for the first time in 1964. The laser-active material consists of Nd^{3+} ions, embedded in a transparent host crystal (YAG = Yttrium Aluminum Garnet, $Y_3Al_5O_{12}$). The neodymium atom has an ideal four-level system (see Fig. 6): Electrons in the upper pump state $^4F_{5/2}$ relax rapidly to the laser output level $^4F_{3/2}$ with a high quantum yield η. This level is metastable (lifetime: 230 μs) because of prohibited electrical dipole transitions ($\Delta l = \pm 1$). The technically most interesting laser transition is then carried out in the $^4I_{11/2}$ state, which is almost unoccupied in thermal equilibrium (emission wavelength $\lambda = 1064$ nm). From here, the electrons relax into the ground state $^4I_{9/2}$ until the pumping process begins anew.

The ground state $^4I_{9/2}$ consists out of five sub-states and the state $^4F_{5/2}$, which is the pump level, has three sub-states. Since the wavelength of the pump light source (diode laser) can be varied within small limits, a total of four high-efficiency transitions can be pumped (pump wavelengths: 804.4 nm, 808.4 nm, 812.9 nm, 817.3 nm).

1.5 Semiconductor laser

If a Nd-YAG lasers is pumped with a discharge lamp, the total efficiency of the laser system is only of the order of 3-5%, which means that only a fraction of the pump light is converted into laser power. The remaining portion end up as heat, which must be removed by means of complex cooling systems. The reason for this "bad" efficiency lies in the broad spectral distribution of the light of the discharge lamps. As it is known, the Nd-YAG crystal can only absorb pump light in several narrow absorption bands. Diode lasers eliminate this disadvantage: They emit intense laser radiation in a narrow spectral range (a few nanometers), which fits well into the absorption band of the Nd-YAG crystal. Thus, it is possible to achieve total efficiencies of about 50%. In the experiment, a semiconductor laser is used as a pump light source for the Nd-YAG laser. It is an AlGaAs diode laser with a double heterostructure and strip geometry.

Active media

The connection of an n-type and a p-type semiconductor provides a pn (semiconductor) diode, the basic element of a semiconductor laser. Because of the splitting of the originally discrete energy levels of the crystal atoms, conduction and valence bands arise. The band structure is characterized by a potential barrier caused by the different charge distributions in the n- and p-type semiconductor. In the immediate vicinity of the pn junction, surplus electrons can optically recombine with holes which yields the emission of a photon (see Fig. 7). The frequency of the radiation is thereby determined by the band spacing ΔE.

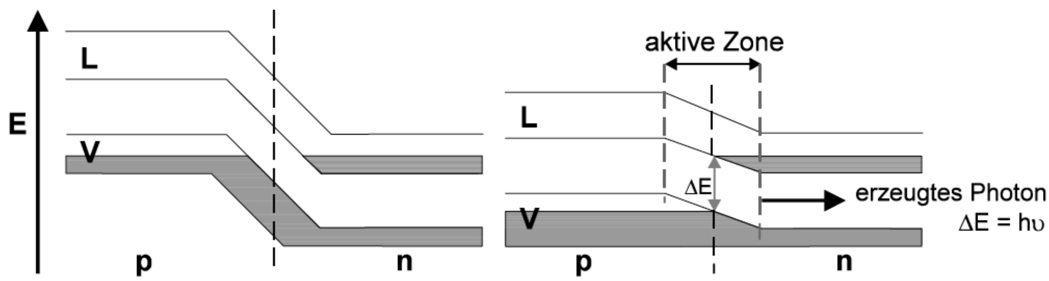


Figure 7: The pn junction of a semiconductor diode with the conduction band L and valence band V. Left without applied voltage, right with applied forward voltage. The active region contains both electrons and holes which generate photons by recombination.

Excitation by charge carrier injection

Optical recombination processes in a pn-junction require the generation of electron-hole pairs. In case of semiconductor injection lasers this is accomplished by charge carrier injection. The application of an external voltage to a semiconductor diode (forward direction) leads to a lowering of the potential barrier. Therefore charge carriers are injected into the active zone: Electrons and holes move to the pn-junction and cause an increase in the charge carrier density. As soon as the relaxation process between conduction and valence band is slower than the charge carrier replenishment, the amplification condition is fulfilled. The (induced) recombination of electron-hole pairs then leads to laser radiation parallel to the pn transition.

Properties of semiconductor lasers

1. The wavelength of a diode laser grows with increasing temperature: The increase in the refractive index of the semiconductor material causes an extension of the active zone and thus of the resonator. As a result, stable modes become unstable at a certain temperature and others modes, for which more favorable conditions now prevail, are

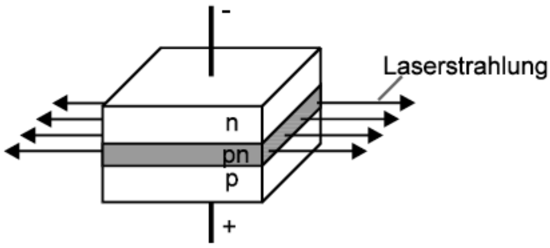


Figure 8: Schematic diagram of an injection laser.

excited. A subsequent lowering of the temperature results in a retuning of the laser wavelength but not necessarily into the original mode (hysteresis). Applications in which the tunability of the laser diode is of primary importance should therefore be carried out in a jump-free area of the characteristic curve (see Fig. 9(a)).

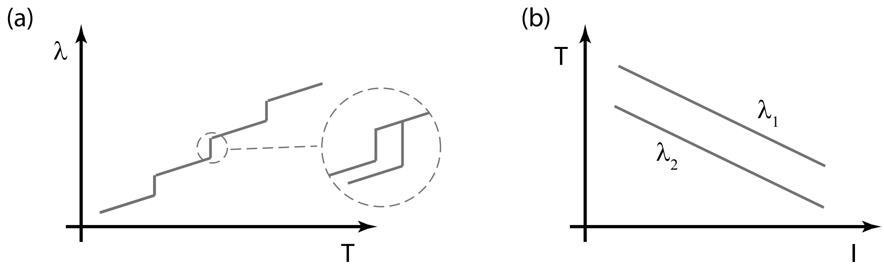


Figure 9: (a) Emitted wavelength λ of a diode laser as a function of crystal temperature T. Inset shows the hysteresis effect. (b) Curve of constant wavelengths as a function of temperature T and the injection current I of a semiconductor laser.

If the injection current is varied (and thus the output power), the change in wavelength (approx. 0.05 nm/K) is predominantly caused by the increase in the refractive index as a result of an increasing charge carrier density in the active zone. At higher output powers, the temperature in the active zone also increases as a result of the heat loss. The wavelength of a diode laser depends on the temperature T and the injection current I as follows:

$$\lambda(T,I) = \lambda(T_0,I_0) + \alpha_T(T-T_0) + \alpha_I(I-I_0) + \sum_{k=2}^{n}\left\{\alpha_T^k(T-T_0)^k + \alpha_I^k(I-I_0)^k\right\}, \tag{40}$$

where $\alpha_T$and α_I are coefficients of the power expansion, T_0 is the reference temperature and I_0 is the reference current. Normally, it is sufficient to consider only the linear terms. From the requirement $\lambda(T,I) = \lambda_C = \text{constant}$ and with $\lambda_0 = \lambda(T_0,I_0)$ follows from equation 40:

$$T = T_0 + \frac{(\lambda_C - \lambda_0)}{\alpha_T} - (I - I_0)\frac{\alpha_I}{\alpha_T} \tag{41}$$

The temperature T decreases linearly with the injection current for a constant wavelength. This yields straight lines with a negative slope in Fig. 9(b).

2. Because of the small width of the active layer (it is in the order of the wavelength), the rectangular beam profile of the diode laser is strongly divergent because of diffraction.

3. Thermal drift and material inhomogeneities complicate the operation of diode lasers in a defined laser mode. Without special countermeasures, the local intensity distribution is highly inhomogeneous and is subjected to temporal fluctuations. To generate continuous laser emission with stable spatial and spectral distribution, diode lasers with a so-called semiconductor heterostructures are used.

1.6 Nonlinear optics (NLO): Frequency doubling

One of the most striking non-linear optical effects is the second harmonic generation (SHG). This means the conversion of a light with frequency ω into light with doubled frequency 2ω inside a non-linear optical medium.

The generation of the second harmonic is, amongst other things, of importance for the generation of short-pulsed laser radiation, in particular by successive frequency doublings (the limit is given by the absorption of hitherto known crystals).

Linear optics

The propagation of light in matter is described by the frequency-dependent optical constants “refractive index” and “absorption coefficient”. In linear optics, these quantities are independent of the intensity of the incident light. Reflection, refraction, propagation speed and attenuation / amplification of the light are therefore constants of the medium in question and only dependent on the frequency of the light.

As a consequence, there are two important principles, which are used everywhere in linear optics:

1. The superposition principle states that light waves do not influence each other and can be freely superimposed to each other (interference).
2. The conservation of frequency states that no new light frequencies are generated during the interaction of light with matter.

However, these two principles are only valid at relatively small irradiation intensities (e.g. for “normal” light sources). In the case of the high light intensities of lasers, however, neither the superposition principle nor the conservation of frequency is valid.

Frequency doubling

The interaction of light with matter can be explained using the classical oscillator model: The electric field strength $\vec{E}$ of the light wave exerts a force on elastically bound electrons, under whose influence the electrons begin to oscillate against the heavy core atoms with the frequency of the electromagnetic wave. Hence, there is a oscillating dipole. The sum of all dipole moments per unit volume of the medium is the so-called electrical polarization $\vec{P}$. In the simplest case this is directly proportional to the applied electric field strength. The polarization, i.e. the oscillating electric dipoles, is the starting point of a new electric field strength whose frequency coincides with that of the exciting field, but its phase is shifted due to the inertia of the elastically bound electrons. The exciting field and the field emitted by the dipoles overlap to a resulting field strength, which is also shifted in phase against the original field. This phase shift appears macroscopically as a changed light velocity and is described by the refractive index. In addition, attenuation of the light wave can occur, characterized by the absorption coefficient.

The relationship between the deflection of an electron (or its polarization $\vec{P}$) and the acting field strength $\vec{E}$ can be represented by a characteristic curve (see Fig. 10): The linear curve is characteristic of elastically bound electrons. For “normal” light the model of elastically bound electrons is fully valid (see Hooke’s law). In the case of the high field strengths of a laser, however, the deflections can become so great that the non-linearity of the polarization curve is noticeable. In the non-linear part of the curve, the electrons undergo anharmonic vibrations under the influence of a sinusoidal field strength. This implies the occurrence of upper waves in the polarization. The linear relationship between polarization and field strength is no longer valid. Instead, the polarization is now a complicated function of the field strength, which also contains higher orders besides the linear term in $\vec{E}$.

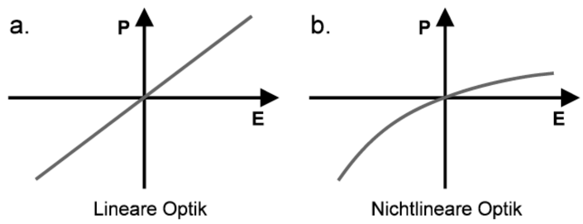


Figure 10: Polarization P of the dipoles in the presence of an electric field E in an optically linear (a) and a non-linear medium (b).

The majority of effects in non-linear optics can be described in the context of a Taylor expansion of the dielectric polarization in respect to the electric field strength:

$$\vec{P} = \varepsilon_0 \left(\chi \vec{E} + \chi' \vec{E}^2 + ... \right) \tag{42}$$

If the external field strength $\vec{E}$ describes a pure sine wave ($\vec{E}(t) = \vec{E}_0 \sin(\omega t)$), the polarization in the linear and quadratic term is given by:

$$\vec{P} = \varepsilon_0 \left(\chi . \vec{E}_0 \sin \omega t + \chi' \vec{E}_0^2 \sin^2 \omega t \right). \tag{43}$$

Here, a possible phase shift between $\vec{E}$ and $\vec{P}$ was neglected. Using the following trigonometric identities:

$$\cos(2\omega t) = \cos^2(\omega t) - \sin^2(\omega t) \quad \wedge \quad \sin^2(\omega t) + \cos^2(\omega t) = 1 \tag{44}$$

yields:

$$\vec{P} = \frac{\varepsilon_0}{2} \chi' \vec{E}_0^2 + \varepsilon_0 \chi \vec{E}_0 \sin(\omega t) - \frac{\varepsilon_0}{2} \chi' \vec{E}_0^2 \cos(2\omega t) \tag{45}$$

or:

$$\vec{P} = \vec{P}(0) + \vec{P}_{\mathrm{L}}(\omega) + \vec{P}_{\mathrm{NL}}(2\omega), \tag{46}$$

where $\vec{P}(0)$ is a DC component, which does not contribute to any radiation within the dipole model, $\vec{P}_{\mathrm{L}}(\omega)$ emits light with the frequency of the fundamental wave and $\vec{P}_{\mathrm{NL}}(2\omega)$ is responsible for the frequency-doubled contribution (see Fig. 11). Thus, the infrared light at 1064 nm becomes visible green light at 532 nm.

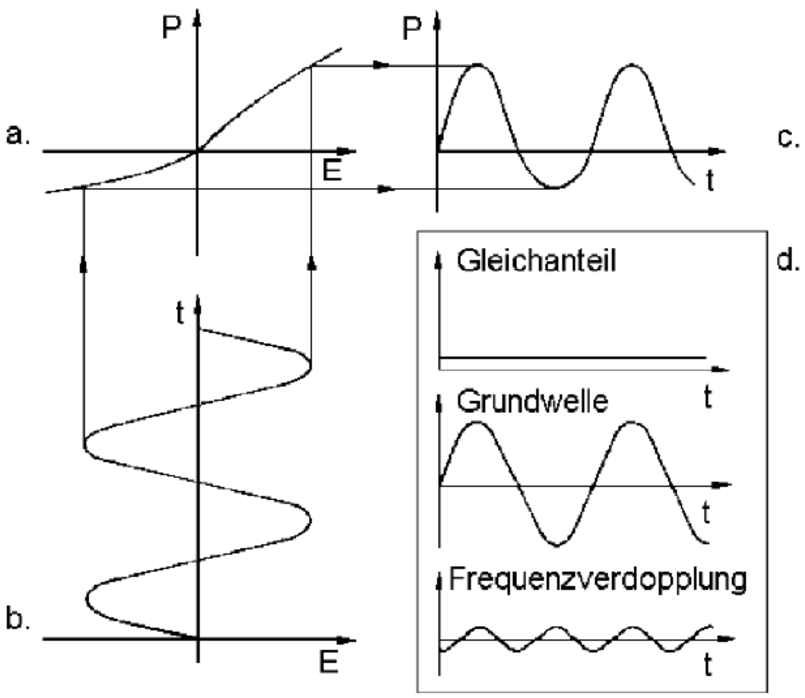


Figure 11: An electron with a non-linear polarization characteristic (a) is exposed to a sinusoidal external field strength (b). Hence, the time dependency of the polarization and therefore the vibration of the electron is non-harmonic (c). The Fourier decomposition of the non-harmonic oscillation yields a DC, a linear and a frequency-doubled contribution (d).

Phase adjustment

The non-linear polarization wave, which is induced by the irradiated electromagnetic wave, propagates with the same phase velocity through the crystal as the irradiated electromagnetic wave. But the second harmonic wave, which is generated by the second order term of the polarization function, generally propagates at a different phase velocity due to the dispersion relation of the medium. Therefore, the different phase velocities of the fundamental and second harmonic wave in general prevent the effective generation of frequency-doubled light in a non-linear crystal. This is due do the fact that frequency-doubled photons, which were generated at different positions of the non-linear crystal, normally have different phases to each other and therefore interfere destructively.

To avoid the destructive interference of the second harmonic wave, a so-called phase matching has to be done. If the fundamental wave (ω) and the harmonic wave (2ω) have the same propagation velocity in the same direction, the fundamental wave can contribute to the amplification of the harmonic wave during the whole path through the crystal. Since the propagation velocities of the fundamental and harmonic waves in a medium are determined by the corresponding refractive indices, the latter must therefore coincide. By exploiting the birefringence of anisotropic crystals, it is possible to "adapt" the refractive indices so that:

$$n_o(\omega) = n_e(2\omega), \tag{47}$$

where $n_o(\omega)$ is the refractive index of the fundamental wave and $n_e(2\omega)$ is the refractive index of the second harmonic wave.

This situation is most frequently realized by an angle adjustment of the non-linear, birefringent crystal because there is a matching angle θ_0 to the optical axis for which the velocity of the fundamental, polarization and harmonic waves is the same when the light beam travels under this angle along the c-axis of the crystal. In particular, the polarization wave and the harmonic wave are no longer out of phase. If the light hits the crystal under a slightly deviating angel, the efficiency of the frequency doubling is significantly reduced.

Crystals for frequency doubling

Second-order, non-linear optical effects are bound to crystals with piezoelectricity. Whereas in crystals which show inversion symmetry these effects cannot occur. Because in crystals with an inversion center (mirror symmetry with respect to a point), following equation holds:

$$\vec{P}\left(\vec{E}\right) = -\vec{P}\left(-\vec{E}\right). \tag{48}$$

However, using equation 42 results both in:

$$\vec{P}\left(\vec{E}\right) = \varepsilon_0\left(\chi\left(\vec{E}\right) + \chi'\left(\vec{E}\right)^2\right) \tag{49}$$

and:

$$-\vec{P}\left(-\vec{E}\right) = -\varepsilon_0\left(\chi\left(-\vec{E}\right) + \chi'\left(-\vec{E}\right)^2\right) = \varepsilon_0\left(\chi\vec{E} - \chi'\left(\vec{E}\right)^2\right) \tag{50}$$

The identity required in equation 48 can only be obtained if $\chi' = 0$. Thus, only a purely linear relation between $\vec{P}$ and $\vec{E}$ exists and frequency doubling cannot occur.

In the experiment, the frequency doubling is generated by a KTP crystal ($KTiOPO_4$). This type of crystal fulfills all requirements for frequency doubling:

1. It has a very high non-linear susceptibility.
2. It posses good transparency in the investigated wavelength range (both for the fundamental and harmonic wave).
3. It is birefringent and therefore can fulfill the phase matching condition.

1.7 Questions for self-control

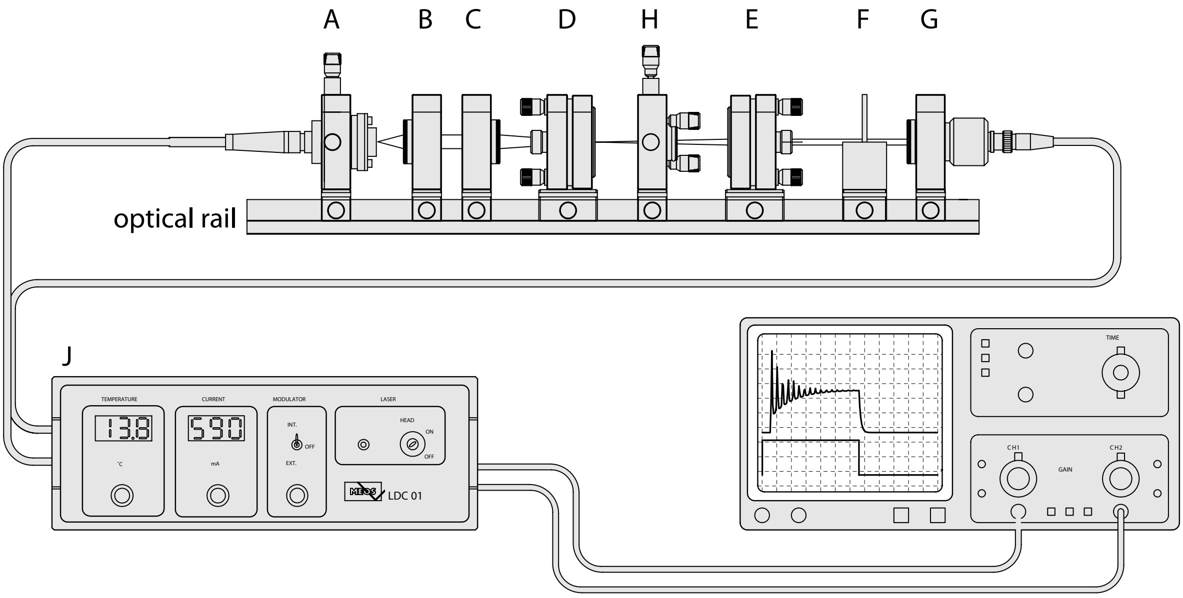
1. Why can no population inversion be generated by optical pumping in a two-level laser system?
2. What are the advantages of four-level laser systems compared to three-level systems?
3. According to which criteria should a laser medium be selected in order to optimize the efficiency of the laser?
4. Why should temperature and injection current be controlled for a diode laser?
5. How do diode lasers differ from "conventional" lasers?
6. Why can a diode laser pump a Nd-YAG laser much more efficiently than a conventional light source?

2 Experimental procedure

Both the diode laser which is used for optical pumping and the Nd-YAG-laser which will be assembled in this experiment can lead to irreparable damage of your eyes! The emitted radiation lies within the not visible infrared range (805 nm or 1064 nm, respectively) which increases the danger. Therefore, the continuous use of laser safety glasses throughout the whole experiment is mandatory! An unattended operation of the laser system is not allowed! Reflections of the laser beam into the room (e.g. caused by watches, rings, etc.) should be prevented at all cost. Both the diode laser and the Nd-YAG-laser are Class 3B laser systems, i.e. that a focused beam can burn your skin and ignite materials.

Danger: The laser safety glasses DO NOT protect against the frequency doubled laser light with a wavelength of 532 nm**.**

2.1 Components of the Nd-YAG-laser system



A The **diode laser module** consists of a XY adjustment unit in which the laser diode is mounted. A Peltier's cooling element for the control of the diode temperature and a thermistor for the measurement of the temperature are all located inside the laser diode. A warning lamp, which signals the presence of laser radiation, is fitted to the upper side of the module.

B **Collimator** with a short focal length ($f = 6$ mm) and a large aperture in order to collimate the strongly divergent laser diode beam.

C The **focusing unit** has the duty to focus the collimated diode laser beam into the YAG rod which is mounted in Module D. The lens has a focal length of 60 mm.

D **Laser mirror adjustment holder with Nd:YAG rod**. Module D and E form the resonator of the Nd-YAG laser. The adjustable holders have the duty of adjusting the relevant resonator mirror so that the common optical axis is aligned perpendicular to the mirrors. At the left side of the plane-parallel YAG rod is a coating which is highly reflective at the laser wavelength of 1064 nm and therefore forms the left resonator mirror. The vapour deposited system is designed in such a way that the mirror transmits 80% of the pump light.

E **Laser mirror adjustment holder**. This module contains the second resonator mirror. Each setup has at least the mirror labeled as "SHG 100". The coating of this mirror is optimized for the "**S**econd **H**armonic **G**eneration", i.e. that it has a high reflective coating of approximately 99.98 % regarding the fundamental wavelength at 1064 nm to keep as much power as possible inside the resonator. The mirror has a radius of curvature of 100 mm. Setup number 1 has an additional mirror labeled as "R 100-2" which is optimized for most efficient operation at a wavelength of 1064 nm and has a transmission of approximately 2% for this wavelength. For the "R 100-2" the radius of curvature is also 100 mm.

F The **filter plate holder** can be equipped with two filters. The color filter RG1000 suppresses the pumping radiation of 808 nm as it is only transparent for wavelengths above 1000 nm. The second filter which is labeled as BG39 suppresses all infrared radiation including the laser diode radiation and transmits the green light with a transmission of app. 60%.

G **Photo detector** with a PIN-photo diode. By means of the attached BNC cable the detector is connected to the current-to-voltage converter with integrated voltage amplifier at the backside of the control unit. A target-screen with a laser detection card, which converts the infrared radiation into visible light, can be inserted into the mounting plate of the photo detector.

H **Frequency doubler** with a KTP crystal for the generation of the second harmonic at 532 nm.

I **Photo diode power sensor** with mountable 1:1000 attenuator and power meter. Important notes for its usage:

(a) At high powers the photo diode will saturate which tampers the reading of the power meter. For even higher powers the photo diode can be damaged. Therefore, you must use the 1:1000 attenuator for the characterization of the diode laser. If the "R 100-2" mirror is used, also the characterization of the Nd-YAG laser should be done with the attenuator.

(b) The reading of the power meter depends on the set wavelength as the current generated at the photo diode depends both on the power and wavelength of the incoming light. A false reading results if one forgets to set the right wavelength for the different experiments.

(c) If you don't know what kind of power your laser beam has, always start at the highest possible measurement range. Adjust the measurement range after determine the maximal occurring power within your measurement. Try not to change the range within one measurement as different ranges may have different offsets.

J **Control unit**

(a) The temperature of the laser diode crystal is displayed on the LED panel in °C. The desired value of the temperature is set by the potentiometer. The controller needs a stabilization time of about $10-30$ s.

(b) The current of the laser diode, also termed injection current, in mA. The desired value can be set by the potentiometer.

(c) Modulator of the injection current. In the "INT" position the injection current is internally switched on and off to the pre-set current which is set by the "mA" knob. The switching frequency can be set by the knob "FREQ." in a range from $0.5-60$ kHz. The rise and fall time amounts to 1 μs. When the front panel switch is set to "EXT." the current can be modulated by means of an external source which is connected to the "EXT. MOD." input at the rear panel.

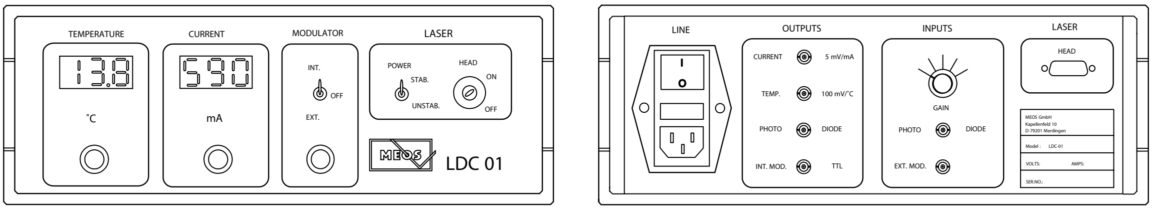
(d) The key switches the laser current off. An additional switch is provided to drive the laser diode output power in a stabilized or non-stabilized mode. An integrated monitor photo diode inside the laser diode combined with a control loop holds the output power to a constant level. **IMPORTANT:** To ensure the longest possible lifetime of the laser diode the key switch "HEAD" should only be used when the injection current is set to its lowest level. When the "HEAD" key is in the "ON" position the red LED located at the backside of the laser head is powered to indicate that laser emission can occur.

(e) Outputs at the rear panel:

i. "CURRENT" monitor signal set to 5 mV/mA.

ii. "TEMP" monitor signal set to 100 mV/°C.
iii. "PHOTO DIODE" is connected to the internal photo detector amplifier and provides a voltage signal for the oscilloscope.
iv. "INT.MOD" monitor signal of the internal modulator set to TTL level.

(f) Inputs at the rear panel: The controller is supplied with a fast amplifier in connection with the photo diode module G of the experimental set-up. The input "PHOTO DIODE" has a low impedance of 50 Ω and is amplified by a factor set with the "GAIN" knob. The input assigned "EXT. MOD." allows the connection of an external source to modulate the injection current. The input is DC coupled and the signal of the external source must be positive in a range from 0 – 5 V.



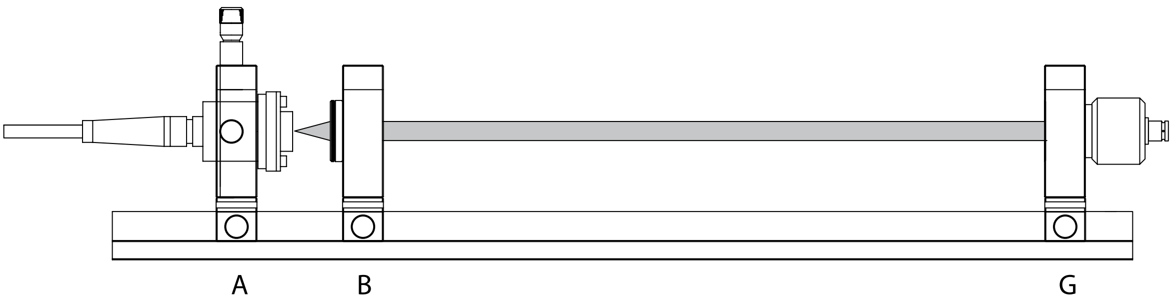
2.2 Experiments

ATTENTION: Before positioning/removing any kind of optical element, always decrease the injection current to the minimal value and turn the safety key to the "Off" position.

IMPORTANT: Only touch the optical components at the black powder coated surfaces! A fingerprint on an optical component will be considered as a MAJOR ERROR in the execution of the experiment and will be considered as such in the final mark scheme.

And because it cannot be mentioned often enough: ALWAYS WEAR LASER PROTECTION GLASSES!

2.2.1 Collimation and focusing of the laser diode



The objective of this first experiment is to set the semiconductor laser into operation. The laser module A is positioned on the optical rail as far to the left side as possible and clamped. The collimator B is put near the laser module and the photo detector G is mounted on the far right side of the optical rail. Never remove the photo diode G from the optical rail because it acts as a blocking element for the laser beam, so that it cannot leave the experimental area in an uncontrolled manner.

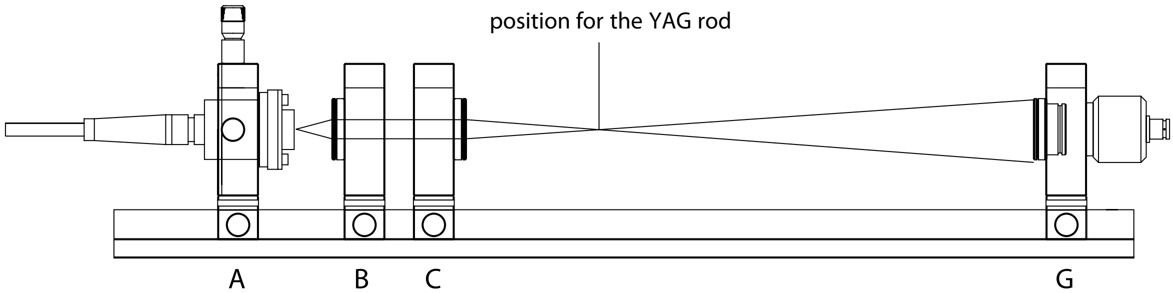
The current control on the front panel of the control unit should be fully turned to the left. The control unit is now switched on by the main switch at the back panel and thereafter the safety key on the front panel. The red warning lamp on the diode laser module turns on and signals that laser radiation can be present.

The two LED displays of the control unit show the set values of temperature in °C and injection current in mA. Set the injection current to 400 mA and the temperature to 25 °C. The temperature control takes a few seconds until the set value has been stabilized at the laser diode.

Now the pump laser beam can be made visible with an IR converter screen and shows its very divergent beam profile.

Move the collimator and check the change in beam profile. If the collimator is set almost in direct contact to the diode laser module, the light of the laser diode will be almost parallel over the whole length of the optical rail. Since the diode is a single stripe element, the beam profile will be a flat rectangle (approximately 3 mm x 5 mm). Make sure that the shape of the collimated light does not change over the length of the optical rail. If this is achieved, fix the collimator.

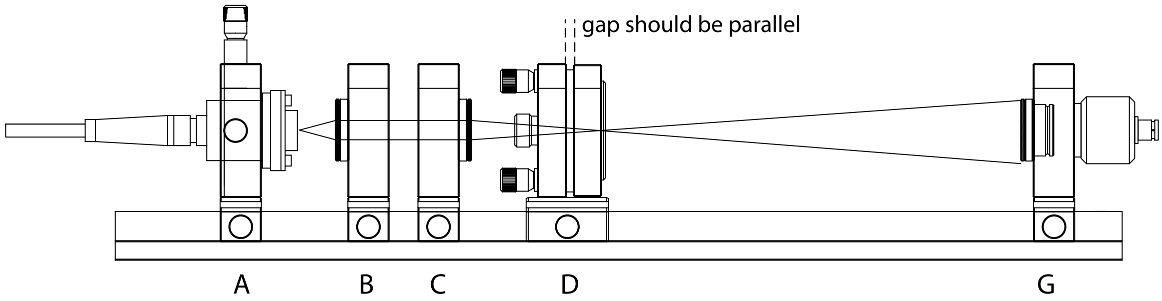
The rectangle should be aligned to the center of the photo diode G. This guarantees that the pump beam is aligned to the optical axis of the whole laser system. A target screen with an IR converter card can be inserted into the mounting plate of the photo detector for monitoring. If the diode laser does not hit the center of the photo diode, the beam path can be adjusted with the two adjustment screws on the diode laser module. After the beam path is aligned to the optical axis, pay attention to not accidentally change these two adjustment screws later on. I repeat: DO NOT CHANGE THE ALIGNMENT OF THE DIODE LASER BEAM PATH LATER ON! You may get the impression that a change in the beam path can increase the output power of the Nd-YAG laser system. But if this is really the case, the laser mirrors are not aligned properly in the first place. And a misalignment of the pump beam path in such a way that it is no longer parallel to the optical axis can lead to complete failure of all further experiments and hence a lot of frustration.



Next the focusing unit is positioned on the optical rail. This unit contains a biconvex lens with a focal length of 60 mm. Later on it is used for focusing the diode laser beam into the Nd-YAG rod. Set up the focusing module at a distance of about 50 – 100 mm from the collimator.

The position of the focus point can be determined with an IR converter card.

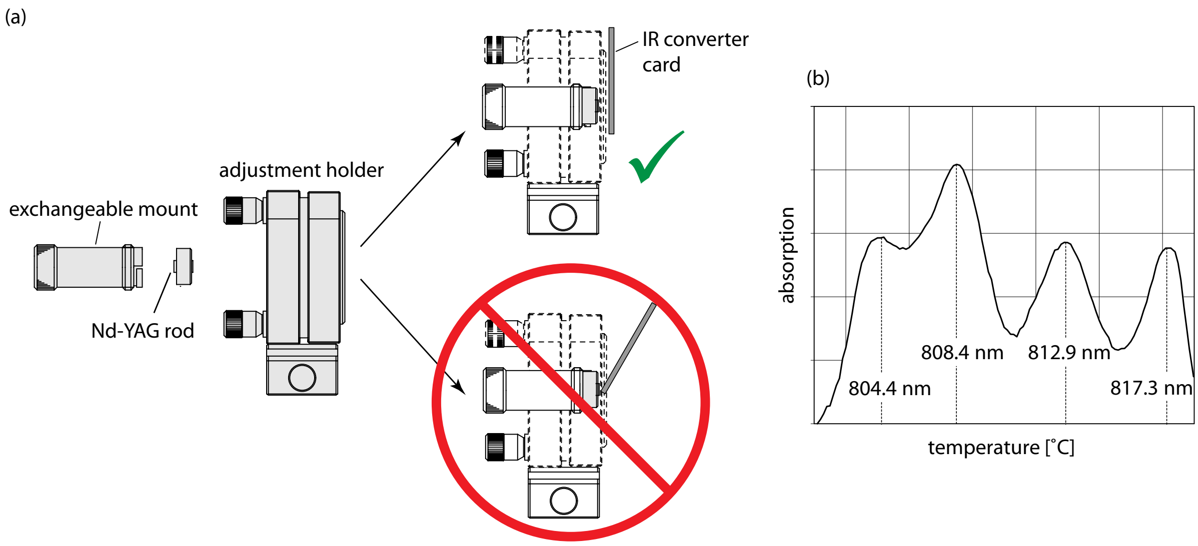
2.2.2 Absorption spectrum



First check the modules D and E. Together these modules will create the resonator. The task of the corresponding adjustment holders is to align both mirrors in such a way that the optical axis of the resonator is perpendicular to the mirrors and parallel to the optical rail. In first order this is achieved when the gaps between the moveable and fixed plates of the adjustment holders are aligned parallel to each other.

Set up module D, which contains both a mirror and the Nd-YAG rod, right after the focusing module. After turning on the diode laser, the position of the focus can be determined with the IR converter card. Now move module D in such a way that the Nd-YAG rod is put into the focus point.

PAY ATTENTION TO NOT TOUCH THE SURFACE OF THE CRYSTAL OR ANY OTHER OPTICAL ELEMENT WITH THE CONVERTER CARD! SCRATCHES CAN MAKE THE WHOLE OPTICAL ELEMENT USELESS!! As long as you put the IR converter card flush to the outer casing of module D, everything should be fine.



In the following experiment the dependence of the diode laser's wavelength on the diode temperature is determined. For this the well-known absorption lines of the Nd-YAG crystal are used. There are four absorption transitions which can (in principal) be pumped with the laser diode used in this experiment. The maxima of the absorption spectrum are located at: 804.4 nm, 808.4 nm, 812.9 nm, and 817.3 nm.

The photo detector (G) can be positioned nearer to the Nd-YAG crystal to maximize the signal. But pay attention to an adequate distance so that the light intensity does not saturate the detector. The photo detector is connected to the current-voltage converter and voltage amplifier of the control unit. The corresponding output is connected to an oscilloscope.

At the start of the measurement the semiconductor laser module is switched on again. The residual pump light passing through the YAG rod can be observed with the IR converter card. If the diode temperature is now changed, an increase or decrease in the intensity of the residual light can be observed which is caused by the wavelength dependence of the semiconductor laser.

Set the injection current to 400 mA. Once set, the level of injection current must be maintained when carrying out the following measurement, because it also affects the wavelength and the output power.

As a measure of the intensity of the transmitted radiation, the signal of the photo detector is taken with the oscilloscope. The measurement is taken beginning with the lowest possible temperature. A period of at least one minute must expire before the laser diode has cooled down to the lowest temperature setting. Then the measurements are taken in suitable temperature steps up to a temperature of maximal 40 °C. Keep in mind that the controller needs a stabilization time of about 10 s in case of smaller temperature changes. If the signal is constant over a wider temperature range, too much light hits the photo detector or the setting of the voltage amplification is too high. Increase the distance between Nd-YAG rod and detector and/or decrease the amplification factor.

The (qualitative) transmission spectrum of the Nd-YAG crystal is obtained by plotting the measured voltage as a function of temperature. The minima of transmission can be assigned to the before-mentioned absorption maxima.

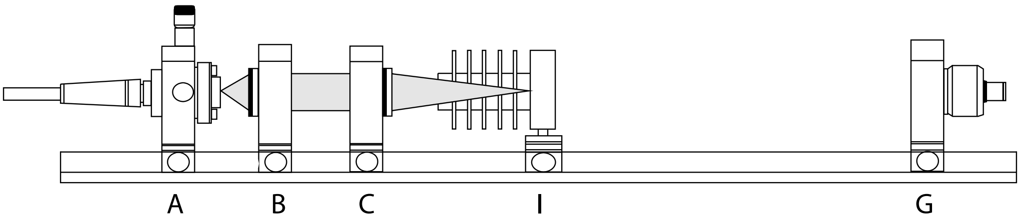
Note: For the following experiments the position of the absolute transmission minimum is relevant, because the pump efficiency is highest at this point. It is necessary to be able to vary the pump power without leaving this absorption peak, i.e. the power must be able to be changed without changing the wavelength. As the injection current affects the wavelength (see Fig. 9), the temperature has to be adjusted for each setting of injection current I_{inj}, which can be done with the following relation:

$$T(I_{\text{inj}}) = T_{\min}(400\text{ mA}) - 0.004\ ^\circ\text{C/mA} * (I_{\text{inj}} - 400\text{ mA}) \quad (51)$$

where $T_{\min}(400\text{ mA})$ is the determined temperature of the transmission minimum for an injection current of 400 mA.

2.2.3 Laser diode output characteristic

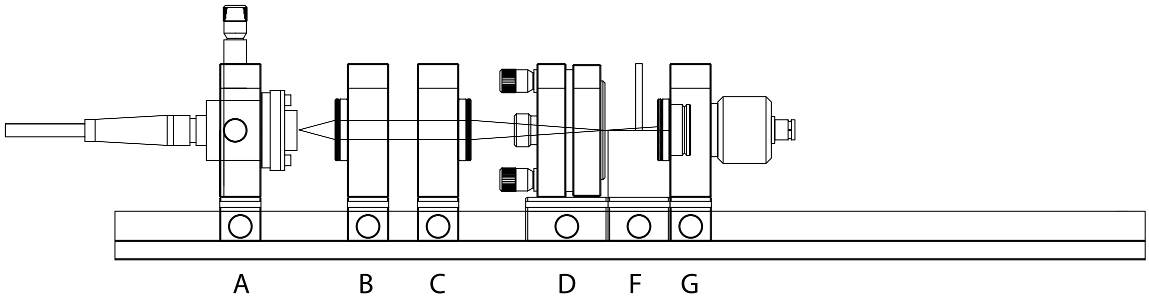
The output power of the diode laser as a function of the injection current can be measured with a photo diode power sensor (module I).



First move the photo detector (module G) back to the far right side of the optical rail. Remove module D and replace it with the power sensor (module I). **IMPORTANT:** Use the 1:1000 attenuator for this part of the experiment! This means the real, physical attenuator you have to mount on the photo-sensor, **NOT** the attenuation factor you can set in the electronic of the power meter (the latter one should ALWAYS be set to 1).

Both the laser threshold and the linearity of the laser characteristic above the critical injection current shall be investigated (see Fig. 5(c)). Measure enough data points for a linear regression and comment on the residuals of the fitting. Do not increase the injection current above 700 mA.

2.2.4 Lifetime of the $^4F_{3/2}$ level



The initial level for emission with a wavelength of 1064 nm is the $^4F_{3/2}$ level, which has a very long lifetime of about 230 μs compared to normal optical transitions. If the Nd-YAG crystal is periodically pumped with the diode laser, then the variation of the spontaneous emission as a function of time can be displayed on an oscilloscope.

For this, first remove the power sensor (module I) and place module D with the Nd-YAG crystal back to the optical rail as it was described in section 2.2.2. Additionally, insert the filter plate holder (F) equipped with the color filter RG1000, which suppresses the pumping radiation of 808 nm but transmits the fluorescent light at 1064 nm. Finally, position the photo detector (G) near to the filter plate holder to increase the yield of the detected fluorescent light. Set the injection current to 400 mA.

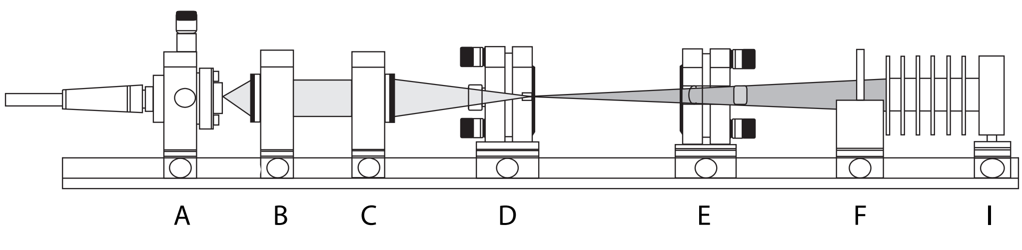
The TTL signal from the internal modulator (rear panel of the control unit) and the output from the photo detector amplifier are connected to a two channel oscilloscope. Now the internal modulator of the control unit is switched on. The laser diode will switched on and off with an adjustable frequency which is set by the associated knob on the front panel.

Now the exponential decay of the fluorescent light should be visible on the oscilloscope (keep in mind that you can also use the voltage amplification at the rear panel of the control unit). If you see an additional, fast decaying component for the first few μs, you either excite an additional energy level with shorter lifetime or the photo detector is just saturated. In such cases just change the injection current and/or the temperature of the diode laser (decreasing the power and/or changing the wavelength).

Save the decay curve and fit it with an adequate decay function (consider possible offsets you have to include in your fitting).

2.2.5 Nd-YAG laser output characteristic

Shift the filter plate holder (F) and photo detector (G) to the right side of the optical rail. Insert module E, which contains the second mirror, onto the optical rail. The maximal distance between modules D and E for stable operation is given by the stability criterion for hemispherical resonators. A more “practical” distance is given by temporarily placing the KPT crystal (module H) inside the resonator and positioning module D in such a way that you are able to comfortably turn all the screws of the KPT crystal holder without the danger of touching the mirrors. Then also check if the Pockels-cell with the Brewser window (module K) fits into the resonator.



Check the modules D and E, which will form the resonator. The task of the corresponding adjustment holders is to align both mirrors in such a way that the optical axis of the resonator is perpendicular to the mirrors and parallel to the optical rail. In first order this is achieved when the gaps between the moveable and fixed plates of the adjustment holders are aligned parallel to each other.

Turn on the diode laser and set the injection current to 600 mA (temperature setting corresponding to equation 51). Check with an IR converter card, if there is already laser emission at 1064 nm visible behind the RG1000 filter plate.

If no radiation is seen, check if the resonator is aligned properly. For this, cover the Nd-YAG crystal with the IR converter card (**DO NOT TOUCH THE CRYSTAL WITH THE CARD** see section 2.2.2). Now you should see a faintly glowing point caused by the diode laser radiation which hits the backside of the IR converter card. Withdraw the card until the diode laser barely pass the edge of the card and rotate the card. If the resonator is not aligned properly, the reflected laser beam from module E can be seen at some position. You may misalign module E on purpose in order to see the reflection clearly. Turn the screws of module E in such a way that the diode laser beam is reflected back into itself. Now there should be laser emission at 1064 nm visible behind the RG1000 filter plate.

As soon as there is laser radiation visible, put the power sensor (module I) behind the filter plate. If you use a “SHG” mirror, no attenuator is needed. But if you use the “R 100-2” mirror, also the characterization of the Nd-YAG laser should be done with the attenuator.

The laser output power is then optimized by adjusting the resonator. The best course of action is to iteratively switch between the two mirrors starting with module E: Once you adjust the alignment of one mirror in such a way that maximal output power is achieved, switch to the other one and do the same. Repeat this procedure until the maximum output power is achieved. Guiding values are: 20 – 40 mW in case of the “SHG” mirror and 100 – 200 mW in case of the “R 100-2” mirror.

If the output power is far below the maximal achievable power, an improvement may be achieved by slightly moving the lens holder. Once the resonator is reasonably aligned, the lateral movement of the lens in such a way that the output power gets maximized will guarantee that the Nd-YAG crystal is really in focus of the pump beam.

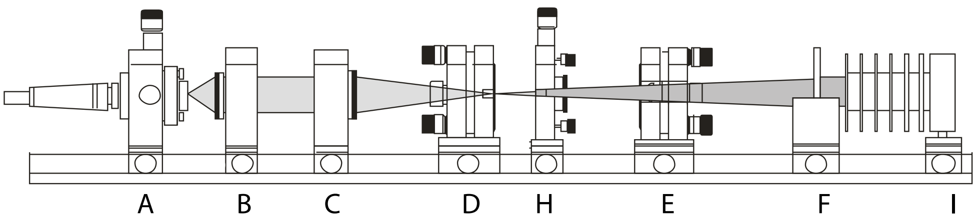
Keep in mind that there are many free parameters in your system you can change. At this point there are four parameters which represents the tilts of the two mirrors in two dimensions, one parameter representing the position of the laser focus, one for the length of the resonator, and two which determine the direction of the pump beam. Including more optical elements into the system (e.g. the KPT crystal with its four adjustment screws) even increase the dimension of the parameter space.

It’s quite obvious that there is not only “one single” or a “right” set of parameters under which you can achieve laser emission. In fact there are many local maxima in the parameter space you may adjust your laser system into. If you reach a maximal output power, which is far below the guiding values mentioned above, then maybe you just adjusted the system in one of this local maxima. In such a case be brave and turn the screws on the mirror adjustment holder much more than previous done in order to get away from this local maximum.

Once the laser has been adjusted, measure the output power as a function of injection current (temperature setting corresponding to equation 51, do not increase the injection current above 700 mA). Both the laser threshold and the linearity of the laser characteristic above the critical injection current shall be investigated (see Fig. 5(c)). Measure enough data points for a linear regression and comment on the residuals of the fitting. Finally, determine the slope efficiency and the laser threshold of the Nd-YAG laser system.

2.2.6 Frequency doubler

ATTENTION: The laser protection glasses DO NOT protect against the radiation at 532 nm! On the other hand, the laser power at this wavelength is normally only around 1 mW, which corresponds to a commercially available laser pointer. Therefore, scattered light at this wavelength is not dangerous. Nevertheless: NEVER LOOK DIRECTLY INTO THE BEAM! Especially as the filter plates may not completely remove the much more powerful laser radiation in the IR range.



If the previous experiments were conducted with the R100-2 mirror, swap it with the SHG100 mirror. Keep in mind that the intensity of the fundamental wave should be as high as possible for an efficient frequency doubling.

The second harmonic at 532 nm of the fundamental wave at 1064 nm is generated by means of a KTP crystal, which is mounted in module H. As the KPT crystal will lead to a slight beam displacement within the resonator, both mirrors have to be realigned. Normally, you have the smallest adjustment work if the module H is placed very close to module D.

Also change the filter plate to the BG39 type, which suppresses all infrared radiation. Now switch on the laser and set an injection current of 600 mA.

Depending on how well adjusted the KPT crystal is, green laser light will be generated. If no green light is visible, check the KPT crystal: It should be adequately pre-adjusted when its end surfaces are vertically and centrally to the resonator axis.

At this point you may temporarily remove the photo diode module G from the optical rail and project the laser beam on a wall. You will see the transversal mode of the laser beam and how small adjustments to the mirrors or the position of the KPT crystal will significantly influence the beam profile.

Remount the photo diode module G and put the power sensor (module I) after the filter plate.

Now maximize the output power of the green light by achieving the best phase matching and therefore the highest conversion efficiency. To do so, the crystal can be rotated on its axis, turned over and shifted into the XY direction. Also do not forget to readjust the resonator.

When the adjustment is finished, measure the power of the green light as a function of injection current (temperature setting corresponding to equation 51). Try to verify the quadratic dependence of the second harmonic to the fundamental wave power.