

# Laser and nonlinear optics

Laser-setup and operating mode,  
Generation and characterization of ultrashort light pulses,  
Generation of optical harmonics

Tutors:

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## 1 Introduction

In this advanced lab course we will present you a device that impacts our present life drastically. You will learn about the principles of lasers and their most important components.

The second part will treat the principles of nonlinear optics, which describes the interaction of highly intensive light with matter.

To benefit from this lab course you have to prepare yourself accurately.

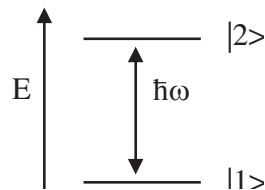


Please read the instructions to the lab course carefully and work out the asked questions.

## 2 Physical Background

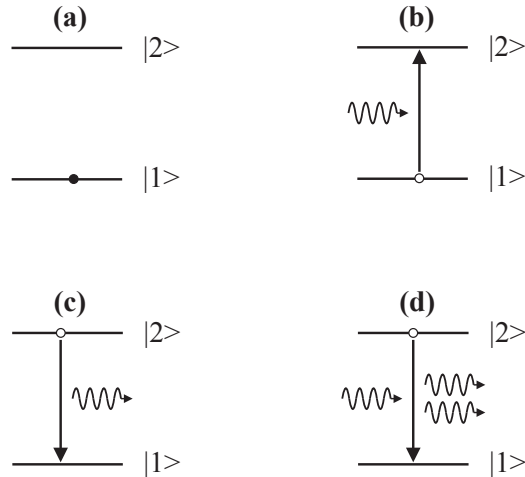
### 2.1 Interaction of radiation with matter: absorption and emission

Transitions in molecules or atoms will be simplified. First we will concentrate on two energy levels  $|1\rangle$  and  $|2\rangle$  with energy gap  $E_2 - E_1 = \hbar\omega$  ( $\omega$  = frequency of the resonant radiation field ; energy conservation!).



Interaction with the radiation field is induced by electric dipole coupling (in most cases).

The following situations occur:



(a) **Ground state:**

An isolated atom in the ground state does not change its state.

(b) **Absorption:**

Atoms or molecules from state  $|1 \rangle$  (population density  $n_1$ ) go over to state  $|2 \rangle$  absorbing photons of appropriate frequency.

$$\frac{\partial n_q}{\partial x} = -\sigma n_1 n_q; \quad \frac{\partial n_q}{\partial t} = -\sigma c n_1 n_q \quad (1)$$

$n_1, n_q$  population density in ( $\text{cm}^{-3}$ )     $x$  = propagation direction  
 $\sigma$  = absorption cross-section ( $\text{cm}^2$ )     $c$  = speed of light

(c) **Spontaneous emission:**

Molecules or atoms of state  $|2 \rangle$  (population density  $n_2$ ) go over to state  $|1 \rangle$  emitting a photon of frequency  $\omega$ .

$$\frac{\partial n_2}{\partial t} = -\frac{n_2}{\tau} \quad (2)$$

$\tau$  = lifetime of state  $|2 \rangle$ .

(d) **Induced emission:**

Molecules or atoms of state  $|2 \rangle$  can be transferred to state  $|1 \rangle$  by photon radiation of frequency  $\omega$ . The energy difference will be emitted as a photon of the same frequency, direction and phase as the incoming photon.

$$\frac{\partial n_1}{\partial t} = \sigma' c n_2 n_q; \quad \frac{\partial n_q}{\partial t} = \sigma' c n_2 n_q \quad (3)$$

$\sigma'$  = cross-section for stimulated emission ( $\text{cm}^2$ )

To a two level system applies:

$$\sigma' = \sigma. \quad (4)$$

Processes b) and d) can be summarized for a two level system as follows:

$$\frac{\partial n_q}{\partial t} = \sigma n_q c \cdot (n_2 - n_1) = \sigma n_q c \Delta n \quad (5)$$

$\Delta n$  = population inversion

Applying  $\frac{\partial n_2}{\partial t} + \frac{\partial n_1}{\partial t} = 0$  and the losses per unit of time due to scattering, absorption of impurities or other system losses we can write:

$$n_q(t) = n_q(t=0) \cdot e^{(\sigma(n_2 - n_1)t - \delta t) \cdot c} \quad (6)$$

Amplification of the radiation field occurs if  $\sigma(n_2 - n_1) > \delta$ . To fulfill this condition level 2 must be higher populated than level 1 (population inversion).

According to the above derivation the spectrum of the laser transition should be infinitely sharp. However due to the following broadening mechanisms it has a characteristic line width:

- homogeneous broadening
- inhomogeneous broadening

The dominant broadening mechanism depends on the laser medium and the operating conditions (e.g. pressure and temperature for gas lasers).

According to this discussion  $\sigma = \sigma(\nu)$  is a function of frequency.



**Question 1:**

Compare induced and spontaneous emission with respect to a) spatial directional characteristics and b) temporal directional characteristics.



**Question 2:**

Give examples for homogeneous and inhomogeneous broadening mechanisms of absorption lines.

## 2.2 Principles of lasers

A neodymium ion embedded in a YLF-crystal (Yttriumlithiumfluoride) can be described by the simplified energy level scheme in figure 1:

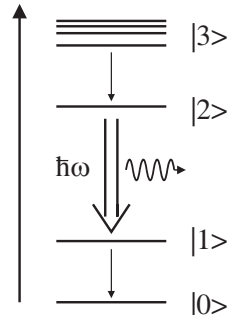


Figure 1:  
 Energy level scheme for  
 a four level laser.

Transitions from the pump level  $|3\rangle$  to the upper laser level  $|2\rangle$  and from the lower laser level  $|1\rangle$  to the ground state occur very rapidly (ca.  $10^{-12}$  s) and radiationless (=heat), whereas state  $|2\rangle$  has a noticeably longer life time (ca.  $3 \cdot 10^{-4}$  s). Light pumps can be absorbed by the pump levels and lead to a high population of the upper laser level. Therefore light of the frequency  $\omega$  will be amplified according to equation 6.

In order to use the population inversion created by the pumping source several times the active medium is placed between two mirrors of reflectivity  $R_1$  and  $R_2$  (figure 2). These mirrors form the optical resonator of the laser.

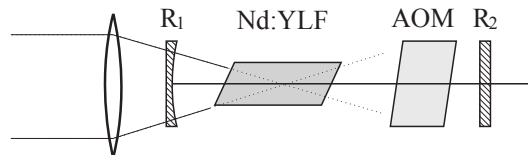


Figure 2: Principles of a laser resonator

Lasing is triggered by a spontaneously emitted photon, that is emitted perpendicular to the mirrors by chance and finishes temporally when the population inversion vanishes (e.g. stop of pumping). Using the partially transparent mirror 2 part of the laser radiation is coupled out of the resonator. In extension of equation 6 the light intensity in the laser after one round-trip in the resonator with a laser medium of length  $l$  is:

$$I_1 = I_0 R_1 R_2 \cdot e^{2l(\alpha - \delta)}, \quad (7)$$

$I_0$ : initial intensity       $\alpha$ : amplification coefficient ( $\alpha = \sigma(n_2 - n_1)$ )  
 $\delta$ : losses per unit length       $R_1, R_2$ : reflectivity of the mirrors

Lasing is observed if for one round-trip in the resonator:

$$I_1 > I_0 \leftrightarrow \alpha > \delta - \frac{\ln(R_1 R_2)}{2l}, \quad (8)$$

which leads to:

$$n_2 - n_1 > \frac{\delta}{\sigma} - \frac{\ln(R_1 R_2)}{2l}. \quad (9)$$

This equation is called threshold or oscillator condition. Therefore the oscillation threshold of a laser medium depends on the reflectivity of the mirrors and the power coupled out of the resonator (available laser power).



**Question 3:**

Nd:YLF lasers are „four-level-lasers“. Discuss the setup of a three-level-laser. Is it physically and technically possible to achieve a two-level-laser?



**Question 4:**

What limits the maximum pump power of a laser? What role does the radiationless process play?

**2.2.1 The laser resonator**

To feed back the laser light in the resonator we need a stable resonator. Therefore:

$$0 < g_1 \cdot g_2 < 1 \quad (10)$$

$g_i = 1 - \frac{L}{r_i}$  stability parameter, L length of the resonator,  $r_i$  focal length of the final mirror

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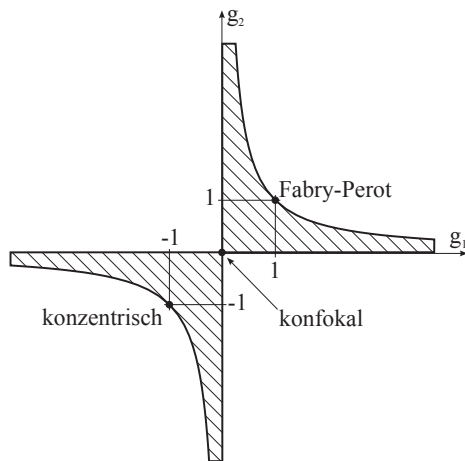


Figure 3: Stability diagram.

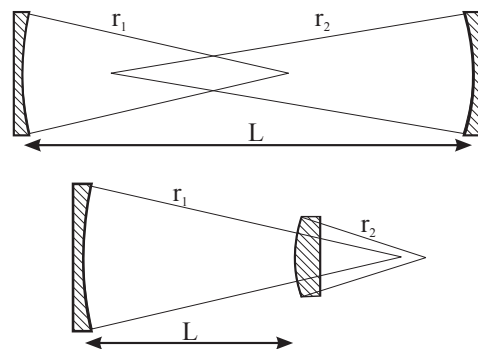


Figure 4: Possible stable resonator configurations.

With every round-trip the field distribution in the resonator is reproduced and even constricted without losses.

From electrodynamics we know that every resonator has longitudinal and transverse eigenmodes due to its boundary conditions, which has large impact on the properties of the laser radiation.

### 2.2.2 Longitudinal modes

Two parallel mirrors placed at a distance  $L$  from each other constitute a Fabry-Perot-Interferometer. Possible values for the angular frequency obey the condition of a standing wave:

$$2L = n\lambda = n \cdot \frac{c}{\nu} = n \cdot \frac{c \cdot 2\pi}{\omega}$$

$$\rightarrow \omega_n = \frac{n \cdot c \cdot \pi}{L}$$

with  $n \in \mathbb{N}$ ,  $n=10^3 \dots 10^7$

Therefore the distance between the angular frequencies of the longitudinal eigenmodes is  $\Delta\omega = c \cdot \pi / L$ . To generate ultrashort light pulses in a resonator we have to amplify many of these longitudinal eigenmodes. This requires a minimum resonator length.

Only the eigenmodes of the resonator with a gain per round-trip  $\geq 1$  contribute to the laser activity. This is schematically shown in figure 5 whereby only 5 longitudinal eigenmodes situated around the maximum of the amplification curve contribute to the laser activity.

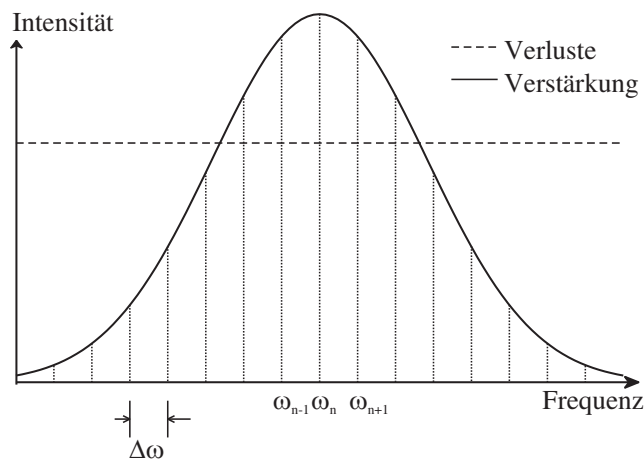


Figure 5: Eigenmodes and amplification curve



**Question 5:**

Determine the mode spacing  $\Delta\lambda$  for a resonator with  $L = 1$  m! Compare the value of  $\Delta\lambda$  and the characteristic laser wavelength of 1047 nm.

### 2.2.3 Transverse modes

The transverse field distribution depends on the geometry of the laser resonator. The geometry is defined by the distance  $L$  and the radius of curvature of both mirrors  $r_1, r_2$  as well as their diameter and shape (e.g. round or rectangular). Knowing these parameters we can compute the stationary spatial distribution of the electromagnetic field in the resonator ( $\rightarrow$  assuming a stable resonator).

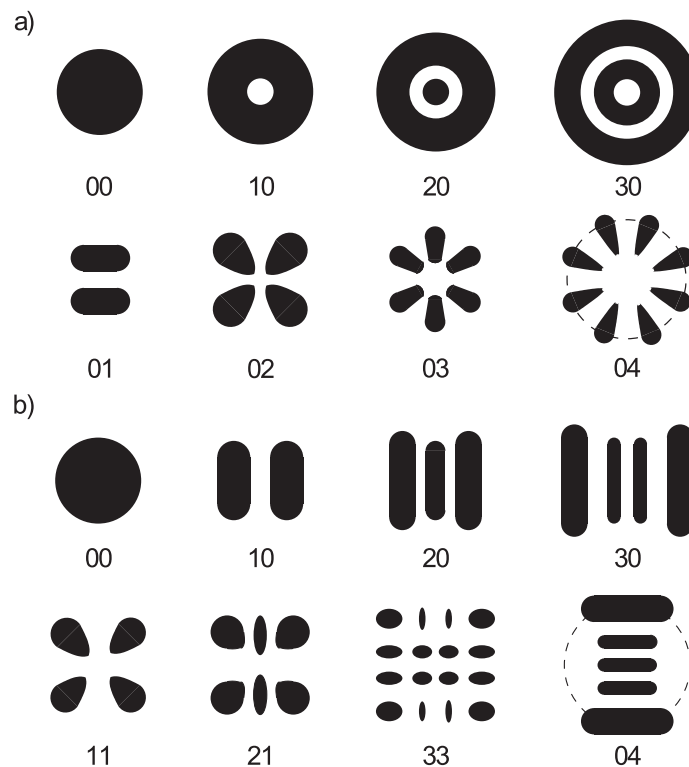


Figure 6: Transverse laser modes

Usually we set the resonator to a  $TEM_{00}$ -mode (ground mode) which is preferred by round resonator components. Using basically round irises (mode apertures) this can also be achieved in the resonator if we e.g. overpump the laser beyond the oscillation threshold (minimum diffraction losses for  $TEM_{00}$ ). However non-optimal-adjustment can lead to higher  $TEM_{mn}$ -modes ( $m, n \in \mathbb{IN}$ ) in the resonator with spatial intensity distribution shown in figure 6. Figure 6a shows the  $TEM$ -modes of a cylindrical coordinate system whereas figure 6b illustrates the  $TEM$ -modes of cartesian coordinates.

### 2.2.4 Passive mode-locking

Ultrashort light pulses ( $10^{-10}$  s and shorter) can be achieved using mode-locking techniques. The various longitudinal eigenmodes of the laser emission are phase-coupled ( $\phi_n = const$ ) to generate a temporally short light pulse via the superposition

of the field components. For passive mode-locking we introduce a nonlinear “switch” to the resonator to suppress temporally long pulse components and support short pulses (high intensities). This “switch” regulates transmission independently of external control depending on the field amplitude of the radiation. Examples are saturable absorbers or kerr-lense mode-locking.

### 2.2.5 Active mode-locking

In this lab course we do not control transmission using the electric field itself but an external acoustooptical modulator (AOM). The AOM is driven by an RF-source which produces an electrical signal of  $\simeq 10\text{ V}$  and  $\Omega/2\pi \sim 80\text{ MHz}$ . The AOM consists of a fused silica crystal fitted with a piezoelectric transducer. The driving signal induces a standing acoustical wave in the crystal and therefore a refractive index lattice with certain periodicity (figure 7).

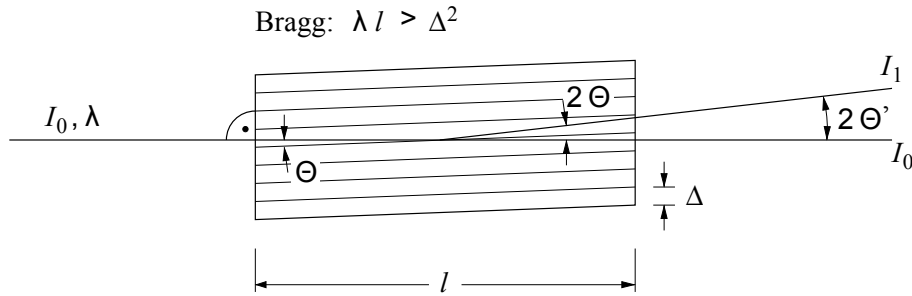


Figure 7: Bragg-AOM

At this temporally modulated induced lattice part of the light  $\Delta T$  is diffracted out of the resonator by an angle of  $2\theta'$ , which effects a periodically changing transmission:

$$\begin{aligned} T(t) &= T_0 + \Delta T \cos(\Omega t) \\ &= T_0 + \frac{\Delta T}{2} (e^{i\Omega t} + e^{-i\Omega t}) \end{aligned}$$

Therefore the components of the electric field  $E_n$  in the frequency domain are:

$$\begin{aligned} E_n(t) &= E_{0,n}(t) \cdot T(t) \\ &= E_n \cdot T_0 \cdot e^{i\omega_n t + \phi_n} + E_n \cdot \frac{\Delta T}{2} e^{i(\omega_n - \Omega)t + \phi_n} + E_n \cdot \frac{\Delta T}{2} e^{i(\omega_n + \Omega)t + \phi_n} \end{aligned}$$

The AOM generates side bands of every single mode at  $\omega_n \pm \Omega$  (figure 8). If the modulation frequency of the AOM fulfills the condition  $\Omega = 2\pi c/2L$  neighboring modes have the same mode as the generated side bands.

$$\omega_n \pm \Omega = \omega_{n\pm 1} \quad (11)$$



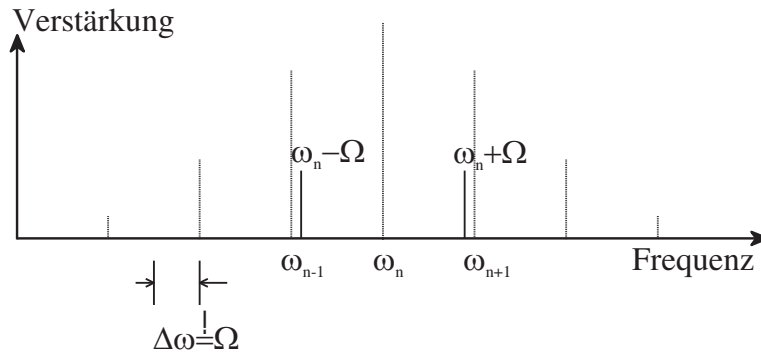


Figure 8: Principle of active mode-locking

Due to this overlapping neighboring modes influence each other and a fixed phase correlation between neighboring modes in the resonator is achieved. Therefore a temporally short pulse is generated (figure 9). Increasing the number of locked modes leads to shorter pulse durations. In non-mode-locked operation (see figure 9c) the outcome is a “white noise”.

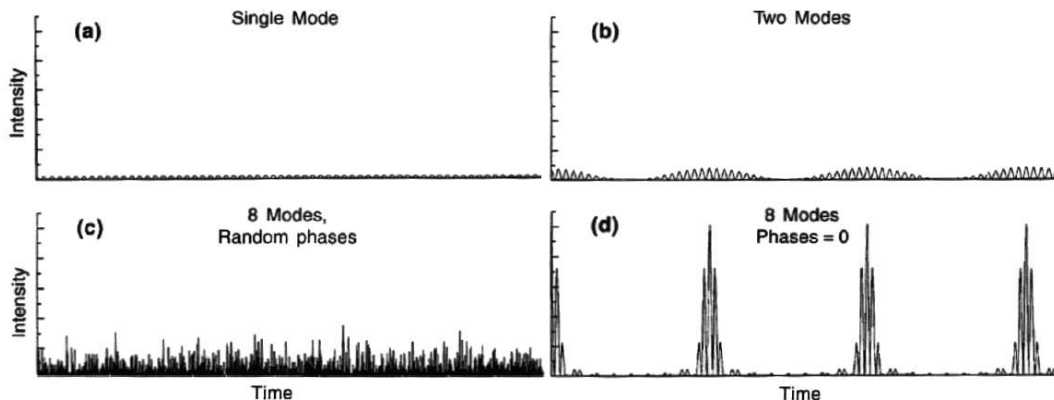


Figure 9: Mode-locking

In the time domain the frequency  $\Omega$  of the transmission variation of the AOM corresponds to the duration of one round-trip in the resonator:  $\Omega = 2\pi c/2L$ . Metaphorically speaking we mount a gate in the resonator which opens in time with the round-trip frequency.

At other times the induced index of refraction lattice diffracts the radiation out of the resonator. Depending on the efficiency of this process and the duration of the gate the duration of the light pulses can be reduced up to the order of some ps ( $10^{-12}$  s). The time-bandwidth-product describes the quality of the mode-locked pulses. To gaussian pulses applies:

$$t_p \cdot \Delta\nu = 0.441 \tag{12}$$

$t_p$  = pulse duration,  $\Delta\nu$  = full width at half maximum

Dispersion, nonlinear processes in the components of the resonator due to the high peak intensities of the laser pulses or insufficient modulation depth of the AOM can lead to deviation from this ideal value.

For mode-locked operation the laser resonator emits a series of single pulses with the following properties:

Pulse duration: 20-50 ps

Pulse spacing: ca.  $6 \cdot 10^{-9}$  s

Peak intensities:  $>200$  W/cm<sup>2</sup>

Wavelength: 1047 nm (near infrared, invisible for the human eye)



**Question 6:**

How does the spectral width of the laser transition (bandwidth of the laser emission) effect the pulse duration of the generated laser pulses? Which role plays the number of locked modes?

## 2.3 Nonlinear optics

### 2.3.1 Classical optics

Because in daily life light intensities are too weak to produce linear effects you have probably observed only classical, linear optical phenomenons so far. The laws of linear optics are based on the assumption that the refractive index  $n = \sqrt{\epsilon}$  in a dielectric medium and therefore the electric susceptibility  $\chi$  only depends on the wavelength:

$$D = \epsilon_0 \cdot E \quad (\text{in vacuum})$$

$$D = \epsilon_0 \cdot E + P(\lambda) = \epsilon_0(1 + \chi) \cdot E = \epsilon_0\epsilon(\lambda) \cdot E \quad (\text{in a dielectric medium})$$

$\epsilon$  = dielectric constant ,  $P$  = induced polarization,  $E$  = electric field

The wave equation in matter which describes the propagation of electromagnetic radiation in x-direction is:

$$\frac{\partial^2 E}{\partial x^2} - \frac{\epsilon}{c^2} \frac{\partial^2 E}{\partial t^2} = 0 \quad (13)$$

The solution of this linear differential equation yields plane waves:

$$E(x, t) = E_o \cdot e^{i(\omega t - k_\omega x)} + c.c. \quad (14)$$

### 2.3.2 Nonlinear polarization

However higher light intensities around  $10^5 \text{ W/cm}^2$  lead to deviations from the classical behavior. In this case the electric susceptibility  $\chi$ , which is simplified to a scalar (in isotropic media) depends also on the amplitude of the electric field  $E$  and can be developed as a Taylor series:

$$\chi = \chi^{(1)} + \chi^{(2)} \cdot E + \chi^{(3)} \cdot E \cdot E + \dots \quad (15)$$

In the following the vector properties of  $E$  and  $P$  are omitted. Therefore the induced polarization yields:

$$\begin{aligned} P(E) &= \epsilon_0 \cdot \chi \cdot E = \epsilon_0 \cdot E \cdot (\chi^{(1)} + \chi^{(2)} \cdot E + \chi^{(3)} \cdot E \cdot E + \dots) \\ &= \epsilon_0(\epsilon - 1)E + P_{NL} \\ D(E) &= \epsilon_0 \epsilon E + P_{NL} \end{aligned}$$

So the linear differential equation is expanded by a perturbation:

$$\frac{\partial^2 E}{\partial x^2} - \frac{\epsilon}{c^2} \frac{\partial^2 E}{\partial t^2} = \frac{1}{c^2} \frac{\partial^2 P_{NL}}{\partial t^2} \quad (16)$$



**Question 7:** How can we imagine nonlinear polarization on atomic scale? Tip: displacement of the electrons.

### 2.3.3 Generation of harmonics

For the first harmonic ( $\omega_{\text{harmonic}} = 2 \cdot \omega_{\text{fundamental}}$ ) the consideration of  $\chi^{(2)}$  is sufficient and the equation simplifies to:

$$\frac{\partial^2 E}{\partial x^2} - \frac{\epsilon}{c^2} \frac{\partial^2 E}{\partial t^2} = \frac{\epsilon_0}{c^2} \frac{\partial^2 \chi^{(2)} E^2}{\partial t^2} \quad (17)$$

With the  $E^2$ -term this yields an induced polarization oscillating with an additional **new** frequency:

$$P_{NL}(x, t) = \chi^{(2)} E_1^2 \cdot e^{i(2\omega_1 t - 2k_1 x)} + c.c. \quad (18)$$

This inharmonic polarization leads to a new field component with doubled frequency  $2\omega$  and propagation direction according to the wave vector  $k_{2\omega}$ .

### 2.3.4 Phase matching

In a dispersive medium normally holds  $2k_\omega \neq k_{2\omega}$ . Therefore the intensity of the first harmonic cannot increase quadratically with the crystal length but oscillates

with  $\sin^2$ . We can explain this behavior looking at a harmonic generated in point  $x$  in the case of  $\Delta k = 2k_\omega - k_{2\omega} \neq 0$  which is not in phase with a harmonic generated in point  $x + \Delta x$  in general. Thus increasing  $\Delta x$  leads to constructive and destructive interference.

$$E_{2\omega} \propto E_\omega^2 \int_{-\frac{l}{2}}^{\frac{l}{2}} \cdot e^{i\Delta k x} dx = \frac{\sin\left(\Delta k \frac{l}{2}\right)}{\Delta k \frac{l}{2}} \cdot l \cdot E_\omega^2 \quad (19)$$

$$\left(\frac{\sin\left(\Delta k \frac{l}{2}\right)}{\Delta k \frac{l}{2}}\right)^2 \cdot l^2 \cdot I_\omega^2 = \text{sinc}^2\left(\Delta k \frac{l}{2}\right) \cdot l^2 \cdot I_\omega^2 \quad (20)$$

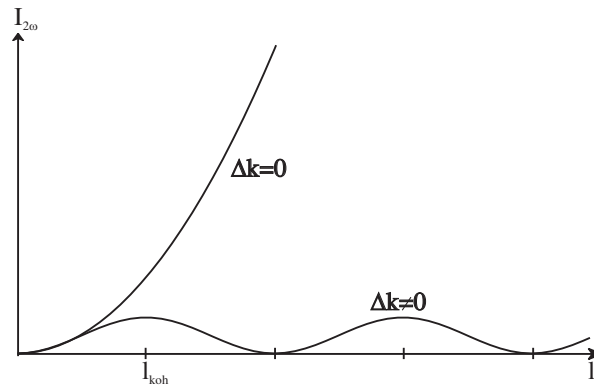


Figure 10: Intensity of the harmonic for  $\Delta k = 0$  and  $\Delta k \neq 0$

To achieve maximum amplification we must make sure that  $\Delta k = 0$ . To reach this phase matching we normally use birefringent crystals with certain orientation.

### 2.3.5 Optical birefringence

Optical birefringence means that the refractive index of a medium depends on the polarization of the incoming light. It occurs in crystals with one or more distinguished directions called optical axis. In crystals with one optical axis (i.e. rotational symmetry of the refractive index) the axis and the propagation direction of the light define a plane. If the light is polarized perpendicularly to this plane the ordinary refractive index  $n_o$  determines the propagation of the light. If the light is polarized parallel the extraordinary refractive index  $n_{eo}$  determines the propagation of the light.

If the setup is chosen to yield an extraordinary polarized harmonic and an ordinary polarized fundamental it holds that  $n_{2\omega} = n_\omega$ . Light propagating at an angle of  $\Theta$  with the optical axis of the birefringent crystal can be adjusted to any desired value

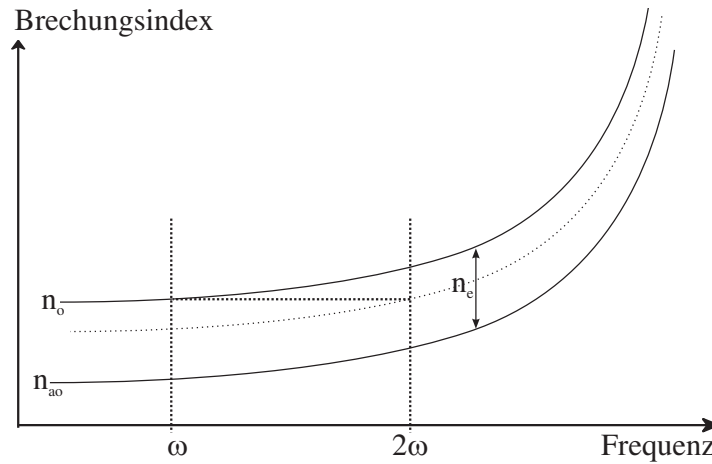


Figure 11: Adaption of refractive index in a single-axis negative birefringent crystal ( $n_{eo} < n_o$ ).

$n_e$  combining both refractive indexes. ( $n_{eo} \leq n_e \leq n_o$ )

$$\frac{1}{n_e^2(\Theta)} = \frac{\sin^2 \Theta}{(n_{ao})^2} + \frac{\cos^2 \Theta}{(n_o)^2} \quad (21)$$

$$= \frac{1}{(n_{ao})^2} + \left( \frac{1}{(n_o)^2} - \frac{1}{(n_{ao})^2} \right) \cdot \cos^2 \Theta \quad (22)$$



**Question 8:**

Why do the refractive indices of fundamental and harmonic have to be identical to efficiently generate the harmonic? Tip: speed of light in the medium

Let's look at a radiating dipole in a single-axis birefringent crystal. The phase of the ordinary polarized field propagates on spheres like in isotropic media. However the extraordinary polarization propagates on ellipsoidal surfaces with constant phasing. In the case of phase matching this is shown in the following figure (harmonic ( $2\omega$ ) extraordinary, laser ( $\omega$ ) ordinary polarized in a nonlinear, birefringent crystal) :

## 2.4 Autocorrelation measurement

Usually the duration of ultrashort light pulses cannot be measured using electrical devices because of their insufficient bandwidth. With autocorrelation measurements we can smartly determine pulse duration up to some fs ( $10^{-15}$ s): One light pulse is split into two equal parts. One part runs through a fix, the other one through a tunable delay line. In an optical nonlinear crystal we make both parts spatially overlapping. In the crystal (here: BBO  $\beta$ -bariumoxide) we generate the harmonic

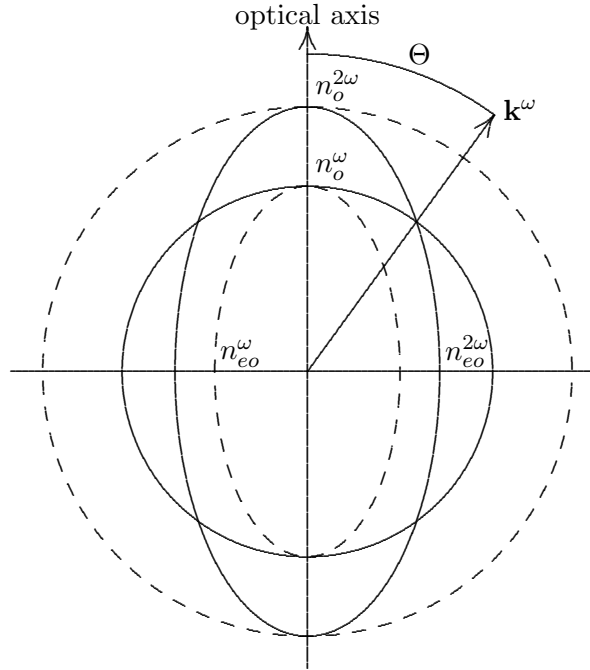


Figure 12: The angle of phase-matching is found where the refractive index ellipsoid of the extraordinary polarized beam of the harmonic ( $2\omega$ ) intersects with the refractive index circle of the ordinary polarized laser beam ( $\omega$ ).

of the laser pulse which is detected as a function of the relatively short delay line. As long as both parts overlap temporally we can measure an autocorrelation signal  $W^{2h}$ , otherwise it disappears.

Mathematically the convolution of the pulse of intensity  $I_L$  with itself is:

$$W^{2h}(t_D) \propto \int_{-\infty}^{\infty} I_L^o(t - t_D) \cdot I_L^o(t) dt \quad (23)$$

The amplitude  $E_\omega^0$  of the field should change slowly compared to  $2\pi/\omega$ .

In mode-locked operation the Nd:YLF-laser generates almost gaussian pulses:

$$I_L(t) = I_0 \cdot e^{-\left(\frac{2\sqrt{\ln 2} \cdot t}{\tau}\right)^2} = I_0 \cdot e^{-At^2} \quad (24)$$

$A = \frac{4\ln 2}{\tau^2}$ ,  $\tau$ : half width of the laser pulse.

Equation (23) and (24) yield together:

$$\begin{aligned} W^{2h}(t_D) &\propto \int_{-\infty}^{\infty} e^{-A(t-t_D)^2} \cdot e^{-At^2} dt = \\ &= \underbrace{e^{-\frac{A}{2}t_D^2}}_I \cdot \underbrace{\int_{-\infty}^{\infty} e^{-2At^2} dt}_{II} \end{aligned}$$

The autocorrelation function depends on the delay line  $t_D$  with the term  $I$ . It describes a gaussian with half width  $\tau'_{\frac{1}{2}}$  which is  $\tau_{\frac{1}{2}}$  times a factor of  $\sqrt{2}$ .

$$\tau' = \sqrt{2} \cdot \tau \quad (25)$$



**Question 9:**

Is it possible to determine the temporal shape of the laser pulse from the autocorrelation function? Compare  $W^{2h}(t_D)$  and  $W^{2h}(-t_D)$ .

### 3 Literature

- /1/ Koechner, Solid-State Laser Engineering, *Springer* (1996)
- /2/ Yariv, Quantum Electronics, *John Wiley & Sons* (1968)
- /3/ Siegman, Lasers, *University Science Books* (1986)
- /4/ Boyd, Nonlinear Optics, *Academic Press* (1992)
- /5/ Svelto, Principles of Lasers, *Plenum Press* (1989)

## 4 Experimental setup

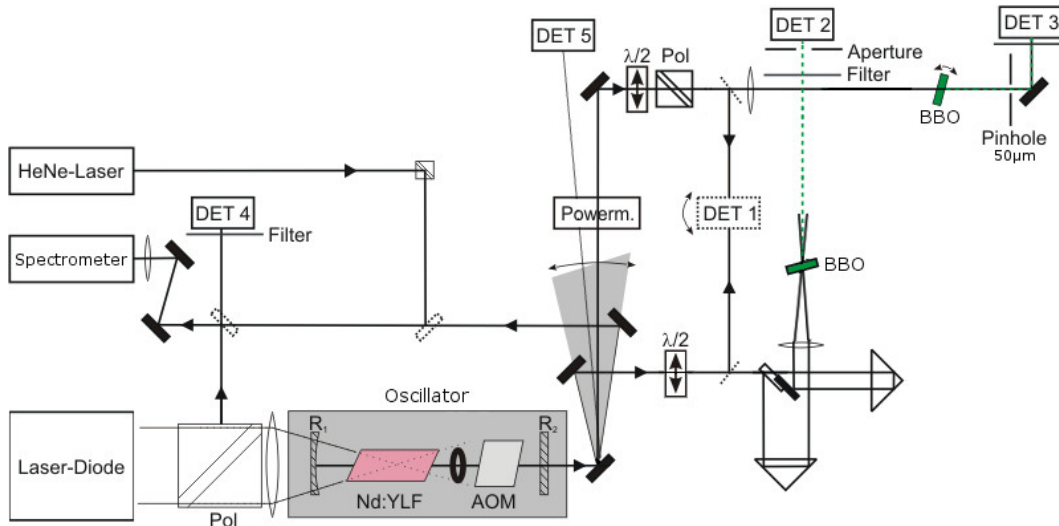


Figure 13: Experimental setup

Pol: polarizer,  $R_{1,2}$ : resonator mirrors, VD: variable delay line,  
BBO: nonlinear crystal ( $\beta$ -bariumoxide),  
DET 1/4/5: fast photodiode, DET 2/3: si-avalanche-diode

## 5 Experiment proceeding and data analysis

### 5.1 Characteristic line of the laser diode

Record the characteristic line of the laser diode. Therefore determine the output power at the polarizer as a function of the input current. As the fiber produces unpolarized light, 50% of the laser radiation is coupled out by the polarizer. Vary the diode current starting with 5 A in steps of 0,5 A up to 20 A. Measure the optical power with a powermeter. The laser diode is running at a voltage of  $U=1,8$  V.

**Do NOT increase the diode current to values higher than 20 A! That might cause permanent damage to the laser diode.**

Analysis:

Plot the characteristic line and determine the degree of efficiency of the laser diode as well as the laser threshold of the laser diode.



## 5.2 Transverse laser modes of the Nd:YLF-laser

Switch on the Nd:YLF-laser and optimize the output laser power with a diode current of 15 A with closed aperture using the right mirror  $R_2$  and the power meter. Observe the occurring modes with the detector card.

Which modes do you find for ideal adjustment of the resonator? Which changes must be made to the aperture diameter and the resonator adjustment to find the different modes of the laser? To find out 'play' with the pumping power, the aperture and the right mirror  $R_2$ .

Classify the observed modes using figure 6.

## 5.3 „Slope efficiency“ of the Nd:YLF-laser in cw-operation

Optimize the laser at a diode current of 15 A with open aperture and reduce the aperture diameter until reaching a  $TEM_{00}$ -mode. Now measure the laser power without AOM as a function of the optical pumping power of the laser diode using the power meter. The slope efficiency is the slope of the characteristic line of the Nd:YLF-laser over the laser threshold. Vary the diode current from 7 A up to 18 A in steps of 0,5 A.

Analysis:

Plot the experimental data. What is the value of the slope efficiency? What is the value of the laser threshold? Please note that only 50% of the output power of the laser diode is used to pump the resonator because of the polarizer.

## 5.4 Mode-locked operation of the Nd:YLF-laser

Now switch on the frequency generator of the AOM ( $f = 79.838.001$  Hz) and find the start of the mode-locking tuning the resonator length with mirror  $R_2$ . To do so, observe the temporal development of the laser emission using the detector on the oscilloscope.

Because of the insufficient speed of the semiconductor diode we cannot measure the pulse duration in that way. This is only possible if we look at the harmonic in the following section.

## 5.5 Autocorrelation function of the laser pulse

Adjust the laser into the autocorrelation setup leading it through both apertures. Optimize the signal of the harmonic by fine adjustment of the coupling, the angle of the crystal and the position of (DET 2).

Now you can optimize the laser operation changing the resonator length and at the same time observing the error bar of the fundamental on the screen. Measure the autocorrelation function of the laser pulse of the Nd:YLF-laser changing the delay line with the measuring program. At the same time measure the autocorrelation signal on the detector (DET 2).

Analysis:

Plot the measured autocorrelation function as a function of the delay time. Fit a gaussian to the measured curve using a suitable program.

How can we determine the pulse duration out of the FWHM of the autocorrelation? Please choose suitable units and representation of your results so that the results of your fit can also be verified graphically!

## 5.6 Angular harmonics

Determine the intensity of the first harmonic (DET 3) as a function of the crystal orientation.

To do so you have to lead the laser through the iris and the generated harmonic through the 50  $\mu\text{m}$  pinhole mounted 15 cm behind the crystal.

Afterwards turn the crystal mounted to a rotating stage using the measurement program. Pay attention to an exact measurement of the principal maximum and the minima.

The refractive indices for the BBO crystal (thickness: 4 mm) are:

at 1047 nm:	at 523.5 nm:
$n_{o/\omega} = 1.65547$	$n_{o/2\omega} = 1.6757$
$n_{ao/\omega} = 1.54273$	$n_{ao/2\omega} = 1.55606$

Analysis:

- Calculate the angle  $\Theta$  of wave vector matching. The crystal surface can be assumed to be orientated perpendicular to the laser beam.
- Plot the intensity of the first harmonic as a function of the rotation angle of the crystal. Determine graphically the angle where the argument of the function  $\text{sinc}^2$  from equation (20) takes the values of  $\pi$  and  $\frac{\pi}{2}$ .
- Calculate the effective path length through the crystal for the incidence angles from b). Pay attention to the calculation of the diffraction at the transition to the optically denser medium. Tip: Snell's law.
- Determine the wavevector mismatching for  $\frac{\Delta k_{eff}}{2} = \pi$  and  $\frac{\pi}{2}$ .
- Explain briefly why the curve does not vanish in secondary minima.

## 5.7 Measurements with the spectrometer

Before measuring you have to calibrate the spectrometer.

Calibration:

For calibration we use a He-Ne-laser because its wavelength ( $\lambda=632,8$  nm) is well known and its spectral width is very low ( $\leq 10^{-3}$  nm). Adjust the spectrometer to

$\lambda_z = 633$  nm and record a spectrum. Afterwards change the wavelength by 10 nm and save the spectrum. From these two measurements you can determine the resolution of the spectrometer and the spectral spacing of the pixels.

Spectrum recording:

Now measure the spectra of the mode-locked Nd:YLF-laser (1047 nm) and the laser diode (800nm) for different diode currents (fluorescence, transition and lasing).

Analysis:

- a) Represent the spectra of the He-Ne-laser graphically (intensity over pixel number). Now you can determine the spectral spacing of two pixels  $\Delta\lambda$  using the spacing of the two lines  $\Delta_{pixel} = \#Peak2 - \#Peak1$ :

$$\Delta\lambda = \frac{10 \text{ nm}}{\Delta_{pixel}} \quad (26)$$

Additionally, the Offset = (623,8 – 633) nm between the actual and the set He-Ne wavelength has to be applied. The conversion formula is

$$\lambda = \lambda_{set} - 0.2 \text{ nm} - \Delta\lambda \cdot (Pixel - \#Peak1). \quad (27)$$

To verify your formula you can convert both He-Ne-spectra. After doing so both laser lines must be identical.

- b) Plot the measured spectra of the laser diode as a function of wavelength and discuss. Compare the laser threshold of the diode and the value from 5.1.

In fact the measured band widths  $\delta_m$  of the laser lines correspond to a convolution of the real spectrum (band width  $\delta_r$ ) with the resolution of the spectrometer  $\delta$ :

$$\delta_r = \sqrt{\delta_m^2 - \delta^2} \quad (28)$$

- c) Why does the resolution of the spectrometer correspond to the measured bandwidth of the He-Ne-laser in the first assumption? Determine  $\delta$  using a gaussian fit to the He-Ne-laser line.
- d) Plot the spectrum of the Nd:YLF-laser. Determine  $\delta_r$  and calculate the pulse duration bandwidth product using the pulse duration from the autocorrelation measurement. Compare your result and a theoretical minimum.

# SAFETY INSTRUCTIONS

A different safety standard must be observed with the laboratory equipment used in this experiment in comparison to usual household equipment. Competence in the use of the apparatus is required to minimize the risk to the experimenter. In particular, the risk in this experiment is

## LASER RADIATION.

The radiation of the Nd:YLF Laser used in the experiment is in the near-infrared region, and therefore invisible to the human eye. The power output of both the laser and the pump source are strong enough that even reflected radiation can harm your retina. Therefore, the use of the

## LASER PROTECTION GLASES

is obligatory everytime the laser or the pumping source is running.

### Please observe the following rules:

- a) First think, then act!
- b) Never trust that insolatings, readouts, etc. are fully functional. In case the laser is not operating, do not try to find the defect by yourself, but ask the tutor.
- c) The laser is shielded by a box of plastic windows. Never open the box while the laser is operating without the instruction of the tutor.
- d) The adjustment of the power supply units in the laboratory must not be changed by the experimenters without the instruction of the tutor.
- e) Never put your hands in the beam of the laser or the pumping source while it is running. Adding/Removing optical elements into/from the experiment is only permitted when the pumping source is turned off.

Read these instructions carefully and ask the tutor if details are not clear.

I declare that I have taken note from the instructions above.

Date:	Name:	Matriculation number:	Signature:
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____