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Fibre Laser

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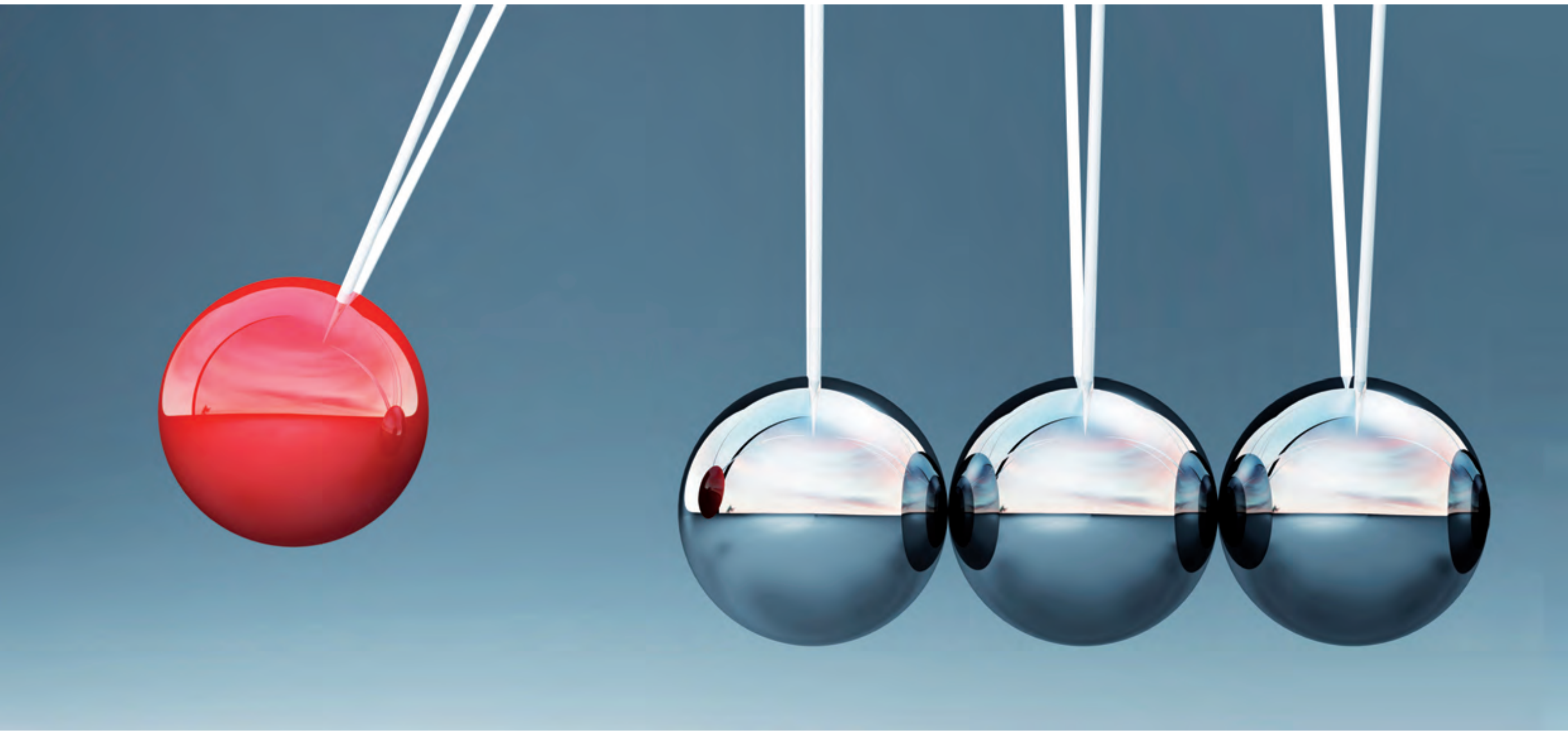

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Laser Sicherheitshinweise

Hiermit erklärt die Firma LD Didactic GmbH,
dass es sich bei dem angebotenen Lasersystem um einen Aufbau handelt, der sowohl in Komponenten als auch im fertigen Aufbau einem Laser der Klasse 3A, 3B oder 4 nach DIN EN 60 825-1 entspricht. Typischerweise ist die Pumpdiode eine Nd:YAG Laser Klasse 4, ein HeNe Laser mit Auskoppler Klasse 3A, aber ein HeNe mit zwei hochreflektierenden Spiegeln nur Klasse 1. Bitte die Anleitung oder Aufkleber beachten.

Aus Haftungsgründen dürfen diese Geräte oder Gerätesammlungen nicht an Privatleute verkauft werden. Der Einsatz von Lasern oberhalb Klasse 2 an allgemeinbildendenden Schulen ist in Deutschland nicht gestattet.

Gewerbliche Abnehmer, Schulen und Universitäten werden hiermit darauf hingewiesen, dass aus dem missbräuchlichen Betrieb der Geräte ein Verletzungsrisiko, speziell für die Augen, resultiert.

Dem Benutzer obliegt insbesondere:
- Die relevanten Unfallverhütungsvorschriften zu beachten, zur Zeit beispielsweise BGV B2 und BGI 832
- die OstrV zu beachten „Verordnung zum Schutz der Beschäftigten vor Gefährdungen durch künstliche optische Strahlung“
- Der Betrieb der Geräte muss rechtzeitig beim Gewerbeaufsichtsamt und der Berufsgenossenschaft angezeigt werden.
- Der Betreiber muss schriftlich einen Laserschutzbeauftragten benennen, der für die Einhaltung der Schutzmaßnahmen verantwortlich ist.
- Die Geräte sind nur für den Betreib in umschlossenen Räumen vorgesehen, deren Wände die Ausbreitung des Laserstrahls begrenzen.
- Der Laserbereich ist deutlich und dauerhaft zu kennzeichnen.
- Ab Laserklasse 4 ist eine Laser-Warnleuchte am Raumzugang notwendig.

- Die Geräte sind zur Lehre und Ausbildung in Berufsschulen, Universitäten oder ähnlichen Einrichtungen gedacht.
- Die Geräte nur innerhalb der in den Anleitungen vorgegebenen Betriebsbedingungen betreiben.
- Die Geräte nur von entsprechend unterwiesenen Mitarbeitern und Studierenden benutzen lassen.

Bei Handhabung des Gerätes durch Studenten müssen diese von entsprechend geschultem Personal überwacht werden.

Als praktische Ratschläge:

- Vor dem Einschalten auf Beschädigungen prüfen
- Nicht in den Strahl blicken
- Den Laserstrahl so führen, dass sich keine Personen, Kinder oder Tiere ungewollt im Strahlbereich befinden können
- Den Laserstrahl nicht auf reflektierende Flächen oder in den freien Raum richten
- Nicht mit reflektierenden Gegenständen im Laserstrahl arbeiten
- Armbanduhr, Schmuck und andere reflektierende Gegenstände ablegen.
- Beim Einsetzen optischer Bauteile den Laserstrahl an der Quelle abschalten oder geeignet abdecken, bis die Bauteile positioniert sind
- Teilweise wird mit unsichtbaren Laserstrahlen gearbeitet, deren Verlauf nicht sichtbar ist.
- Falls nötig, Laserschutzbrillen oder Laserjustierbrillen benutzen.

Die Firma LD Didactic GmbH haftet nicht für eine missbräuchliche Verwendung der Geräte durch den Kunden.
Der Kunde verpflichtet sich hiermit die Geräte nur entsprechend der rechtlichen Grenzen einzusetzen und insbesondere den Laserstrahl nicht im Straßenverkehr oder Luftraum zu verwenden oder in anderer Form auf Personen und Tiere zu richten.

Der Kunde bestätigt, das er befugt ist, diesen Laser zu erwerben und zu verwenden.

Laser Safety Notes

LD Didactic GmbH informs the customer this is laser equipment of either class 3A, 3B or 4 according to IEC 60 825. Typically a Nd:YAG Pump Diode is class 4, a HeNe with output coupler class 3A, but a HeNe with two high reflecting is mirrors only class 1. Please see manual or attached labels for the exact specification of the laser.
Special safety precautions are necessary. Please check with local regulations. Typically the use requires a safety sign and a warning lamp that is on when the laser is activated and it might also be necessary to do and document a risk assessment.

Due to product liability, the laser must not be sold to individual persons. Companies, higher schools and universities might use it, but are notified that misuse of the laser poses a health risk, especially for the eyes.

The intended use of this equipment is for lessons, education and research in higher schools, universities or similar institutions.
Do not operate the devices outside parameters specified in the manual.
People using the laser must be properly trained and students must be supervised.

As a general guidance, the user is advised to:
- Check the laser for damages before use
- Not to look into the beam
- Take necessary measures that no people or animals can accidentally enter the beam area
- do not direct the beam on reflecting surfaces or into public areas
- do not work close to the light path with reflecting tools
- take off all jewelry and wristwatches when working with the laser to avoid reflections
- While placing or removing optical parts in the light path, switch off the laser or cover its exit
- Some of the experiments use invisible laser beams, but still might hurt the eye
- use laser protection glasses or laser adjustment glasses where necessary
- supervise students by trained personnel when they work with the laser system
- use the laser system only as described in the instruction manuals

Customer acknowledges the receipt of this information.

The customer indemnifies LD Didactic from liability for any damages that occur because of misuse of the laser.

The customer confirms that he will obey all local regulations and is allowed by law to buy and use the laser system.

Table of Contents

1.0 Introduction

E. Snitzer proposed already in 1961 just one year after the demonstration of the first laser his idea to exploit optical fibres cavities. In the abstract of his publication "E. Snitzer, "Proposed Fiber Cavities for optical masers," Journal of Applied Physics, Vol. 32, No. 1, 36, 1961" we can read:

"The use of dielectric waveguides in the form of small fibers as the mode selector in optical masers is considered. The fibers consist of a core of index of refraction n1 which contains the maser material, surrounded by a cladding of lower index n2. A comparison is made with the Fabry-Perot interferometer used as a cavity. The principal advantages of the fiber for maser applications are the mode selection and the stronger mode coupling. It is shown that for core diameters just small enough to support only the two HE11 modes, the fraction of spontaneous emissions into the waveguide modes is given approximately by 1.4 (n1-n2)/(n1+n2). This could make maser action possible at much lower power levels. The major disadvantage is the difficulty of pumping into the small volume of the fiber. Schemes to overcome this difficulty are discussed."

The difficulty of pumping the such fibre lasers became more feasible due to the invention of the diode laser in 1962. The first devices where available only as pulsed diode laser. E. Snitzer continued his research in this field and published his paper in 1964 about amplification in a fibre laser:
C.J.Koester and E.Snitzer, "Amplification in a fiber laser", Applied Optics, 3, pp.1182-1186, 1964

In the abstract we can read:

"Fiber lasers of neodymium-doped glass have been used on a pulsed basis to amplify 1.06-µ radiation. To prevent oscillation, the ends are polished at an angle such that reflected light is lost from the cavity. With the high inversion which can then be obtained, gains as large as 5×10^4 have been observed in a 1-m long fiber. The gain was measured as a function of pumping energy and as a function of time during the pumping pulse at which the amplification was determined."

However, the achieved output power and the wavelength of 1.06 µm have not been so attractive for technical applications.

The rebirth of this field has been stimulated primarily by the application of optical amplifier and fibre lasers to optical communications. The commercial interest and the availability of high power diode pump laser, low insertion losses optical multiplexer and isolator boosted the research and development. A further important milestone in the development is the realisation of optical amplifiers that have properties which were previously achievable at high cost or did not exist at all in electronic amplifiers. Within a period of only 3 years of research and development, the optical amplifiers have revolutionised the future of glass fibre nets. The main reason for the replacement of the electronic with the optical amplifier lies therein that they can simultaneously amplify any data format and –rates within a comparatively extremely large spectral area. With that, the barrier of the small and limited bandwidth of electronic semiconductor amplifiers was broken. Out of the multitude of concepts for optical Amplifiers, the Erbium doped Fibre Amplifier (EDFA Erbium doped fibre amplifier) has turned out to be especially well suited.

The fundamental principle of this new technology is the use of an amplifying medium through optical pumping. The theory and practice of optical amplifiers is as old as the laser technique itself, since the laser is nothing else but an optical amplifier that amplification is increased to oscillation through feed-back. When one removes the feed-back (i.e. the cavity mirror) in a laser, one gets an optical amplifier which is in a position to amplify a stream of photons if its frequency lies within the amplification band width of the optical amplifier.

The aim of this project is the introduction to the concept of fibre lasers. This project also includes the fundamentals of the production of optical amplification by means of optical pumping which is also the basis for optically pumped laser systems.

The discussion of diode lasers, which are used as pumping light sources, supplements the technical knowledge.

The dependence of emission of laser diodes on the temperature and injection current are constituents of the measurements in the frame-work of the experimental work. For the technical application as well as for the measurements within this project, wavelength dependant multiplexer (WDM), Erbium doped fibre and different kinds of photodetectors are necessary, whose characteristic features will be presented.

Two different laser cavities are discussed and demonstrated. The experiments starts with the linear cavity and it is extended to a ring cavity.

To understand the dynamic behaviour like the spiking of the Erbium doped fibre laser the pump laser is modulated and the effect on the laser output measured.

The lifetime of the excited state is measured and the Einstein coefficient for spontaneous emission is determined.

During the pumping with higher power at 980 nm a green fluorescence emerging the fibre is observed. It can be identified as result of a resonant two photon pump process.

2.0 Basics

2.1 Interaction of light and matter

The saying "to shed light upon a matter" means, more or less, to "illuminate" facts that are unclear. In 1644 Rene Descartes published his metaphysical ideas on the essence of light. Since then, people have been trying to shed light upon "light" itself.

According to his ideas, light consists of scattered particles which have different speeds in different bodies.

In 1667, R. Hooke claimed that this was all nonsense. He was the first person who thought that light consisted of quick oscillations.

Huygens demonstrated light ether in 1690. In 1717 Newton proved that light has a transversal quality. At that time, however, people could only imagine longitudinal waves, so Newton rejected the wave theory of light completely. Newton's authority over the subject prevented the formulation of the wave theory of light for 100 years.

Unaffected by the dispute over the essence of light, James Clerk Maxwell summarised the electrical and magnetic appearances in a system of mathematical equations. In 1856, when Kohlrausch and Weber found out through measurements that the speed of electromagnetic waves was the same as that of light, Maxwell came to the conclusion that light is an electromagnetic oscillation. In 1888 Heinrich Hertz was able to give experimental proof of electromagnetic waves.

As can be easily imagined, due to the various interpretations on the nature of light it took a long time for the electromagnetic theory to be recognised as a basis for the sum of the physical experiences which could not be reduced any further. But, as we now know, even this theory has its limitations. It is possible to explain all appearances which occur in light scattering using this theory. However, it fails in the case of the emission and absorption of light.

Max Planck was able to solve the problems in this area with his formula $E = h\nu$. According to this formula light possesses both properties, i.e. corpuscular as well as wave-like qualities. This paradoxical formula could finally be clarified through quantum mechanics. There was a further change in classic optics in the sixties of this century when lasers were discovered.

For the first time, light was subjected to an unusually high intensity. People observed appearances such as the optical frequency doubling which led to the formulation of non-linear optics.

In classic, i.e. linear optics, the scattering of light in matter is described by both optical constants dependent on the frequency, the refractive number n and the absorption coefficient α. In present linear optics, these variables are independent of the intensity of the light. Reflection, refraction, scattering, speed and absorption of light are therefore constants of the relevant medium and are not dependent on the light intensity. This resulted in two important principles used everywhere in optics: The superimposition principle (interference) and maintaining the frequency. Both these conditions are only valid in relatively small light intensities as can be obtained from normal light sources. Neither the superimposition principle nor the conservation of frequency apply to the high intensities of lasers. Therefore, linear optics is only specifically applicable to small light intensities.

The appearances observed on the basis of the interaction between light and matter can, in principle, be divided into two groups.

A. resonant phenomena
B. non-resonant phenomena

In the case of resonant light the incoming light has an energy of $E = h\nu$, which corresponds to the energetic distance of a transition. Electrons of the atoms or molecules in their initial state are transferred to E_1 which is in an excited state.

In the example of non-resonant light, the energy of the incoming light is much smaller than the energetic interval of the considered transition.

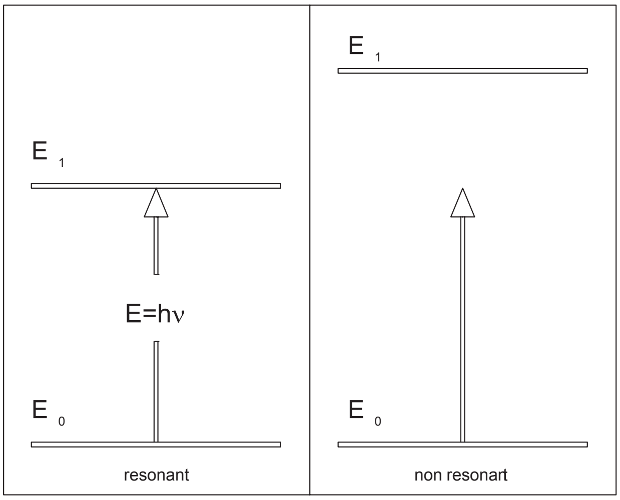


Fig. 1: Incoming light is resonant to a transition of the sample (left) and non-resonant (right) for a material with another transition

There is still an interaction, in which, however, no transition of the electrons takes place. The interaction occurs through the electromagnetic property of light together with the electromagnetic property of matter.

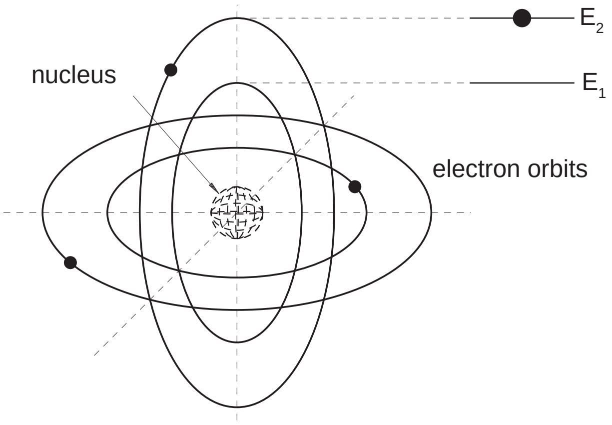


Fig. 2: Bohr's Atom

The work and measurements had proved that discrete energy must be anticipated for both resonant cavities and appearances of atomic emissions. Einstein began looking for a single description for both these sources of light. He was able to solve this problem in 1917 when he derived Planck's hypothesis once more in his own way. He thought of a way of combining both light sources. He put an ensemble of "Bohr's" atoms in a resonant cavity at a temperature T. In thermal equilibrium E(ν,T) will be an energy distribution which must be formative influenced by the properties of the atoms. Einstein's task was to determine this new energy distribution. In a first step he examined the atom ensemble, which we presume has only two energy levels, as shown in chapter Fig. 7. Since the atoms are exposed to a radiation field, they can take up or absorb energy. The absorption is connected to an emission. If we denote the number of electrons in state 1 as n_1, the temporal change of it will be

$$\frac{dn_1}{dt} = -B_{12} \cdot n_1 \cdot u(\nu) \qquad \textbf{(1)}$$

In this case *u(ν)* is the density of energy at the frequency at which the transition from state 1 to state 2 is resonant, i.e. it is the frequency at which E_2-E_1=$h\nu$ is fulfilled. This frequency is called the resonant frequency. It is evident that the temporal change from dn_1/dt is dependent on the number n_1 itself, on one hand, and on the density of energy of the radiation with the frequency ν, on the other.

A constant B_{12} is necessary for a correct equation in terms of dimension. The minus sign is required because the number of electrons in state 1 decreases through the absorption .

The same observation is carried out for state 2. We will call the number of electrons in this state n_2. The electrons return to state 1 from state 2 whilst emitting radiation. The transition from 2 to 1 is released (induced) by the existing radiation field of the resonator and takes also place coincidentally (spontaneously). So, two types of emission are responsible for depopulating state 2, the induced and the spontaneous emission. The temporal change in the number n_2 is

$$\frac{dn_2}{dt} = -B_{21} \cdot n_2 \cdot u(\nu) - A_{21} \cdot n_2 \qquad \textbf{(2)}$$

Nothing has been left out of the last term since the spontaneous emission does not depend on the surrounding radiation field and is of a statistical nature. It takes place even when there is no radiation field. Until the principles of quantum mechanics were defined by Heisenberg and Schroedinger, it was accepted that spontaneous emission was similar to radioactive decay, in that it could not be influenced from the outside. Quantum electrodynamics has shown that a spontaneous emission is an emission induced by zero point energy. So as not to take this too far at this point, the following must be noted with reference to zero point energy. In the cavity there is an average field energy of at least $E_0=1/2\ h\nu$. The spontaneous emission is triggered off by this energy. Let us go back to our resonant cavity-two level atom system. In stationary equilibrium, the same number of electrons must go from state 1 to 2 (with a photon being absorbed from the radiation field) and vice-versa (emission of a photon into the radiation field)

$$\frac{dn_1}{dt} = \frac{dn_2}{dt} \qquad \textbf{(3)}$$

or

$$B_{12} \cdot n_1 \cdot u(\nu) = B_{21} \cdot n_2 \cdot u(\nu) + A_{21} \cdot n_2 \qquad \textbf{(4)}$$

The Boltzmann distribution is also valid in the thermal equilibrium for the population numbers of level 1 and level 2.

$$n_2 = n_1 \cdot e^{-\frac{E_2 - E_1}{k \cdot T}} \text{ or } n_2 = n_1 \cdot e^{-\frac{h \cdot \nu}{k \cdot T}} \qquad \textbf{(5)}$$

By substituting (5) in (4) we get

$$u(\nu, T) = \frac{A_{21}}{B_{12}} \cdot \frac{1}{e^{-\frac{h \cdot \nu}{k \cdot T}} - B_{21} / B_{12}} \qquad \textbf{(6)}$$

$$u(\nu, T) \quad \frac{8\pi}{c^3} \cdot \frac{h \cdot \nu^3}{e^{\frac{h \cdot \nu}{k \cdot T}} \quad 1} \cdot d\nu \qquad \textbf{(7)}$$

Planck's law

Since Planck's law must be valid also in equilibrium we get by comparison of chapter (6) with chapter (7) the meaningful Einstein coefficients:

$$B_{12} = B_{21} \text{ und } \frac{A_{21}}{B_{12}} = 8\pi \cdot \frac{h \cdot \nu^3}{c^3} \qquad \textbf{(8)}$$

2.2 Natural line width

Let's look on Eq. **chapter (1)**:

$$\frac{dn_1}{dt} = -B_{12} \cdot n_1 \cdot u(\nu)$$

B_{12} can be considered as the probability for a transition from level 1 to level 2 by absorption.

This is also analogous to the coefficient B_{21}, which however indicates the probability of the reverse process, i.e. the emission. The coefficient for the spontaneous emission A_{21} gives us another interesting piece of information on the system, which is easy to find.

Let us take, for example, the process of the spontaneous emission by itself.

$$\frac{dn_2}{dt} = -A_{21} \cdot n_2 \qquad \textbf{(9)}$$

This differential equation can be solved using the additional equation

$$n_2(t) = C \cdot e^{-\alpha \cdot t} \qquad \textbf{(10)}$$

$\alpha = A_{21}$ can be found by comparing the two and the solution will then be

$$n_2(t) = n_2(t = 0) \cdot e^{-A_{21} \cdot t} \qquad \textbf{(11)}$$

chapter Fig. 3 shows this function graphically.

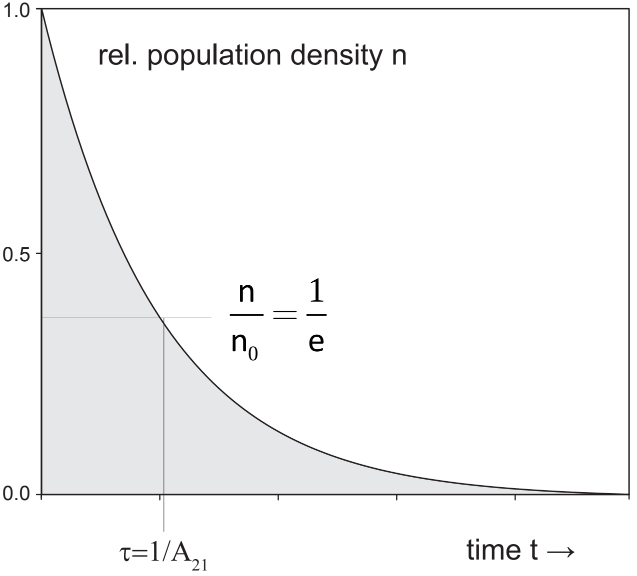


Fig. 3: Population decay curve of a state

This curve and therewith A_{21} can be determined experimentally. The time t which $n_2(t)$ took to reach the value $n_2\ (t=0)\ e^{-1}$ must be deduced. The result will then be $t = 1/A_{21}$.

Obviously the reciprocal value of the Einstein coefficient A_{21} represents a suitable definition for the “life time τ of a state“. More information can be obtained from the decay curve. Photons or a radiation field are produced because of the transition from state 2 to 1.

However, the intensity of the radiation decreases exponentially with the time (chapter Fig. 4). In view of the preceding findings, the frequency of the radiation should be fixed to

$$E_2 - E_1 = h\,\nu_0.$$

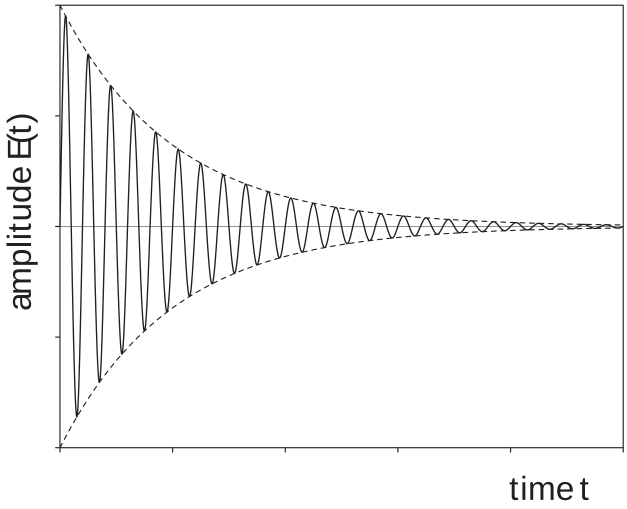


Fig. 4: Spontaneous emission as a damped oscillation

A power spectrum of the spontaneous emission is obtained using a Fourier analysis for non-periodic processes, which has the main frequency ν_0 apart from other frequency parts. The result of this kind of Fourier transformation is illustrated in chapter Fig. 5.

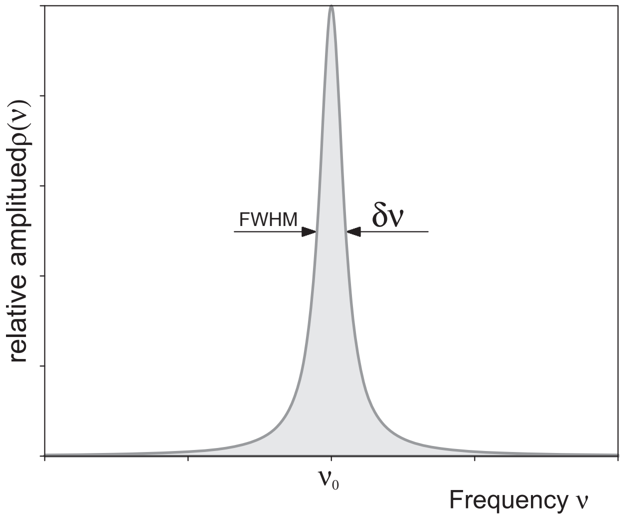


Fig. 5: The Fourier transformation of a damped oscillation as observed for spontaneous emission. It consists of the transition frequency ν_0 and a complete spectrum described by a Lorentz function.

The Fourier transformation of the damped oscillation gives the following result:

$$\rho(\nu) = \frac{1}{4\pi^2 \cdot (\nu - \nu_{21})^2 + (1/2\cdot\tau_s)^2} \qquad \textbf{(12)}$$

This type of curve represents a Lorentz curve. ν_{21} *(or* ν_0*)* is the resonant frequency and

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

the average life time of state 2. The FWHM (Full Width at Half Maximum) of the curve as shown in chapter Fig. 5 is calculated by inserting the value of ρ(ν) = *1/2*. The result is:

$$\delta(\nu)_{nat} = \frac{1}{2\pi}\cdot A_{21} \qquad \textbf{(13)}$$

which is the natural line width of a transition, defined by the Einstein coefficient A_{21} which has a particular value for every transition. The results obtained can also be interpreted as if the state 2 did not have any clearly defined energy, but a broadening with half-width $\Delta E = 2\,\pi\,h\,A_{21}$. This means that the state is somewhat blurred. Quantum mechanics has shown this effect to be extremely important. It is known as the Heisenberg uncertainty principle, after the person who found it. In the case of normal optical transitions the value of τ_s lies between 10^{-8} to 10^{-9} seconds. This life time, determined by spontaneous transitions alone, is crucial for the so called **natural width** of a spectral line. To clarify the ways in which we term things, we must emphasise briefly at this point, that there is a difference between the width of a state and the width of a line, as well as between the terms state and line. There are always states for atoms and it is never stated whether the state is occupied or empty. A line is only formed if an emission is caused by the transition from, for example, state 2 to 1. The line is a word commonly used by spectroscopists. They use their spectroscopes to produce photographic plates, for example, on which fluorescent light is shown according to its wavelengths. The use of slits in the optical beam path makes it easier to evaluate the spectra. A line spectrum of this kind is shown in chapter Fig. 6.

Fig. 6: Recording the emission of a light source with corresponding energy levels results in a line spectrum

Apart from the emission wavelengths, the spectrum in chapter Fig. 6 shows the line widths. It must be noted, in this case, that the measuring apparatus makes the line widths seem wider than they actually are. Naturally, it was the aim of spectroscopists to create instruments which could give the closest reading of the actual line widths.

2.3 Homogeneous line broadening

A line is homogeneously broadened when all the atoms or molecules have the same characteristics and all of them interact with their environment in the same way. The natural broadening is a homogeneous broadening, since it is the same for all atoms and molecules in an ensemble. Homogeneous broadening can be found in solids with regular crystal structure in which the atoms considered are in equivalent lattice sites. The interactions with the crystal lattice lead to a broadening of the states that is far beyond the natural width, but which is homogeneous when the lattice sites are symmetrical and of equal value. Gases are known for their inhomogeneous broadening and this will be discussed in the next section. In this case the absorption and emission lines are no more homogeneously but inhomogeneously broadened.

2.4 Two level system

Now that we have learnt a few aspects of the interaction of light with matter, in the following example of a simple two level system, the description of absorption and emission with the help of the Einstein‘s coefficient shall follow. Finally, we will learn the inverse process of Absorption, the amplification of photons.

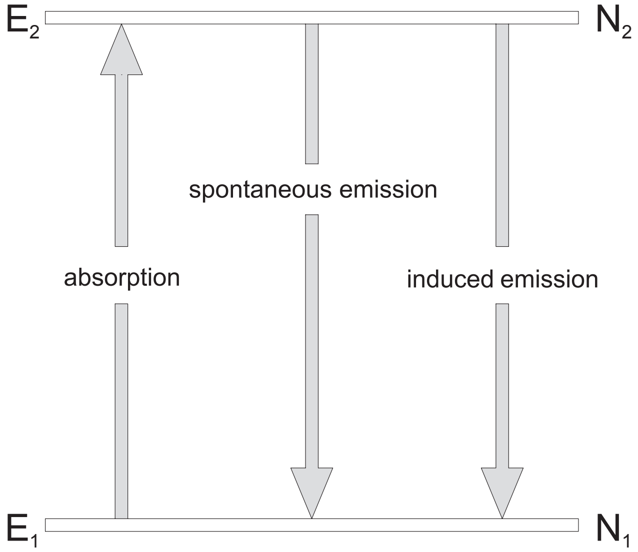


Fig. 7: Two level system

We use the rate equation model, a formalism, whereby the temporal change of the population density can be determined for each of the energy levels involved. For this, let us take a number of atoms *N* or molecules which are presently in the Ground state (E_1). We irradiate this sample now with photons with the spectral energy density *ρ(ν)* i.e. Energy per volume element and per frequency interval *Δν*. Since this concept is used often today, at this stage we will take a closer look at its definition. A photon possesses the energy $E = h\nu$. When, in the volume *dV*, the number of photons is *N*, the energy density is:

$$\frac{N\cdot h\cdot \nu}{dV}$$

Now, not all the photons have necessarily the same frequency, which is why for further classification we require that only those photons whose frequency lies within the interval *Δν* shall be considered. The distribution of the number of photons follows a function which we denote by *f*(ν) without, for the present, defining it any further. We arrive consequently at the expression for the spectral energy density:

$$\rho(\nu)=\frac{N\cdot f(\nu)}{dV}\cdot\frac{h\cdot\nu}{\Delta\nu}$$

The density of photons ρ, its number N per volume element dV is related with the spectral energy density:

$$\rho(\nu)=\rho\cdot h\cdot\nu\cdot\frac{f(\nu)}{\Delta\nu} \qquad \textbf{(14)}$$

Under the influence of the photon field the population numbers N_1 and N_2 would change. Now we consider the temporal changes in the numbers to then determine the stationary state. The population number of the level E_1 diminishes in the absorption process:

$$\left.\frac{dN_1}{dt}\right|_{Absorption}=-B_{12}\cdot\rho(\nu)\cdot N_1$$

Through the absorption process the level E_2 is populated:

$$\left.\frac{dN_2}{dt}\right|_{Absorption}=B_{12}\cdot\rho(\nu)\cdot N_1 \qquad \textbf{(15)}$$

Through spontaneous and induced Emission the level 2 is, however, also depopulated:

$$\left.\frac{dN_2}{dt}\right|_{spontaneous}=-A_{12}\cdot N_2 \qquad \textbf{(16)}$$

$$\left.\frac{dN_2}{dt}\right|_{induced}=-B_{21}\cdot\rho(\nu)\cdot N_2 \qquad \textbf{(17)}$$

The total change in the population of the energy level E_2 is therefore::

$$\frac{dN_2}{dt}=B_{12}\cdot\rho(\nu)\cdot(N_1-N_2)-A_{12}\cdot N_2 \qquad \textbf{(18)}$$

The temporal change in the population density in the state 2 obviously changes the photon density since every absorption process is bound with the destruction of a photon, and every emission process with the production of a photon. The change in the photon density is therefore equal to the difference in the population numbers of the levels considered:

$$\frac{d\rho}{dt}=\frac{dN_1}{dt}-\frac{dN_2}{dt} \qquad \textbf{(19)}$$

with

$$\frac{d\rho}{dt}=\frac{d\rho}{dx}\cdot\frac{dx}{dt}=c\cdot\frac{d\rho}{dx}$$

and equation (13) we get

$$\frac{d\rho}{dx}=B_{12}\cdot\frac{f(\nu)}{\Delta\nu}\cdot h\cdot\frac{\nu}{c}\cdot\rho\cdot(N_1-N_2)$$

we use as the abbreviation

$$\sigma_{12} = B_{12} \cdot \frac{f(\nu)}{\Delta\nu} \cdot h \cdot \frac{\nu}{c}$$

$$\frac{d\rho}{dx} = \sigma_{12} \cdot \rho \cdot (N_1 - N_2)$$

and as a solution of the differential equation we get:

$$I = I_0 \cdot e^{-\sigma_{ik} \cdot (N_1 - N_2) \cdot x} \qquad \textbf{(20)}$$

In that we use the identity for the intensity *I* and the photon density ρ

$$\rho \cdot c = I$$

Amplification then takes place when

$$g = \sigma_{ik} (N_2 - N_1) = \sigma_{ik} \cdot n > 0 \qquad \textbf{(21)}$$

On comparing the result after chapter (20) with that of the famous absorption rule in classical optics by Beer, it is determined that the strength of the absorption does not only present a material constant, but additionally depends on the difference of the population numbers N_1-N_2 and therefore on the intensity of the photon field. This dependence is determined through the solution of the rate equations for the stationary state.

$$\frac{dN_i}{dt} = 0 .$$

From $dN_2 / dt = 0$ we get the expression:

$$\frac{N_2}{N_1} = \frac{B_{12} \cdot \rho(\nu)}{B_{12} \cdot \rho(\nu) + A_{12}}$$

Thereafter for a very large (large ρ(ν)) photon density N_2 / N_1 goes against 1. This means that in this case the population density of both the levels are equally large and according to chapter (20) no more absorption takes place, the medium has become transparent under the influence of strong photon fields.

Obviously in this two level system it is not possible to produce a population number N_2 larger than N_1 since according to equation chapter (20) instead of absorption, amplification takes place.

2.5 Optical Amplifier

The optical amplifiers are characterised by the fact that at their output, the number of photons is larger than at their input. A material that possesses this characteristic, must have a structure of energy levels, in which a population inversion, i.e.

$$N_i > N_f$$

can be created. In this, N_i is the population density of the excited and N_f the lower lying state.

2.6 Three-level system

In the last chapter, we found out, that such a situation cannot be produced in a two level system. Therefore, we shall presently attempt a three-level system chapter Fig. 8.

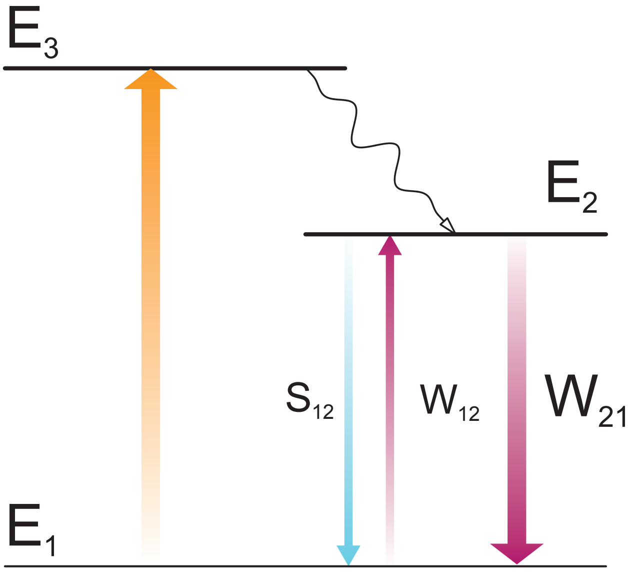


Fig. 8: Three level system

There E_1 is the initial level, mostly also the ground state of the respective atoms or molecules for the pump process. The atoms or molecules of the ground state are excited through the pump process and populate the state E_3 with the population density N_3. We proceed on the assumption that the transfer from E_3 to E_2 occurs very rapidly, so that $N_3 = 0$. The temporal change in the population density of the state E_2 results therefore, directly from the decrease in the population density E_1:

$$\left.\frac{dN_2}{dt}\right|_{Pumpprocess} = \eta \cdot W_{13} \cdot N_1$$

Here W_{13} is the probability that a particle passes from state 1 to state 3 and η for that of the transition from 3 to 2. The product:

$$W_{13} \cdot \eta = W_p$$

represents consequently the pump rate for a particle. The spontaneous Emission affects the state 2 as the second process and leads to a depletion of the state.

$$\left.\frac{dN_2}{dt}\right|_{spontaneous} = -\frac{N2}{\tau_s} = -\Gamma \cdot N_2$$

Here τ_s stands for the life time of the state 2 and Γ as its inverse value. A special feature of the spontaneous emission is that it is not possible to influence it through external fields and depends only on the life time of the levels. In contrast to this, the induced emission depends on the one hand on the existing photon density p and on the difference in population density N_2-N_1.

$$\left.\frac{dN2}{dt}\right|_{induced} = -\sigma \cdot c \cdot p \cdot \left(N_2 - N_1\right)$$

With σ, the cross section for the induced emission is introduced and *c* is the velocity of light. It consequently follows that for the total temporal change in population in state 2:

$$\frac{dN_2}{dt} = \sigma \cdot c \cdot p \cdot \left(N_1 - N_2\right) - \Gamma \cdot N_2 + W_p \cdot N_1$$

Since each process of state 2 leads to an opposite change in population density of state 1 it is valid for the temporal change of state 1 so that

$$\frac{dN_1}{dt} = -\frac{dN_2}{dt}$$

In every induced process one photon is produced or destroyed. Therefore the photon density *p* changes respectively:

$$\frac{dp}{dt} = -\sigma \cdot c \cdot p \cdot \left(N_1 - N_2\right)$$

Photons once produced, however do not stay available for all time. They can be destroyed by other processes and their density decreases with a time constant τ_{ph}. We formulate these losses as loss rate and its temporal change is:

$$\frac{dp}{dt} = -\frac{p}{\tau_{ph}}$$

For the total change in photon density we finally get:

$$\frac{dp}{dt} = p \cdot \left(\sigma \cdot c \cdot \left(N_2 - N_1\right) - \frac{1}{\tau_{ph}}\right)$$

We use the following abbreviations:

$n = N_2 - N_1$ and $n_{tot} = N_1 + N_2$

so we get:

$$\frac{dn}{dt} = -2\sigma cpn - \Gamma\left(n_{tot} + n\right) + W_p \cdot \left(n_{tot} - n\right) \qquad \textbf{(22)}$$

and

$$\frac{dp}{dt} = p \cdot \left(\sigma \cdot c \cdot n - \frac{1}{\tau_{ph}}\right) \qquad \textbf{(23)}$$

The equations chapter (22) and chapter (23) build a couple of simultaneous differential equations, for which no analytical solutions are known. Merely for a few special cases, solutions are possible. For the stationary state, i.e. the temporal change in population inversion is zero, respectively.

$$\frac{dn}{dt} = 0$$

so from chapter (22) we get

$$n = N_2 - N_1 = \frac{n_{tot} \cdot \left(W_p - \Gamma\right)}{W_p + \Gamma + 2\sigma \cdot c \cdot p} \qquad \textbf{(24)}$$

We use eq. chapter (21) for the amplification g and get

$$g = \frac{\sigma \cdot n_{tot} \cdot \left(W_p - \Gamma\right)}{W_p + \Gamma + 2\sigma \cdot c \cdot p}$$

Obviously amplification occurs only when the pump rate is larger than the rate of spontaneous emission. This is achievable when the life time τ_s is very large. Especially suitable are therefore metastable states. We further discover that with increasing photon density the amplification decreases.

Thus, we have been able to show that in a three level system, optical amplification can be achieved.

It shall not pass without mention that four level system show more favourable characteristics in a few respects.

Still the level system of EDFA is a three level system which shall be illustrated in the following. Now the question arises, why this Erbium doped Fibre was chosen as a candidate for this application. The main reason lies therein, that this material shows suitable transition at 1550 nm. This wavelength is of extraordinary importance for the communication technology with glass fibres. This wavelength falls in the so called second absorption window. Now it is not sufficient just to have a suitable transition with this wavelength, but one should be able to excite it with simple means. The first step of the experiment therefore contains the analysis of the absorption- and fluorescence spectrum.

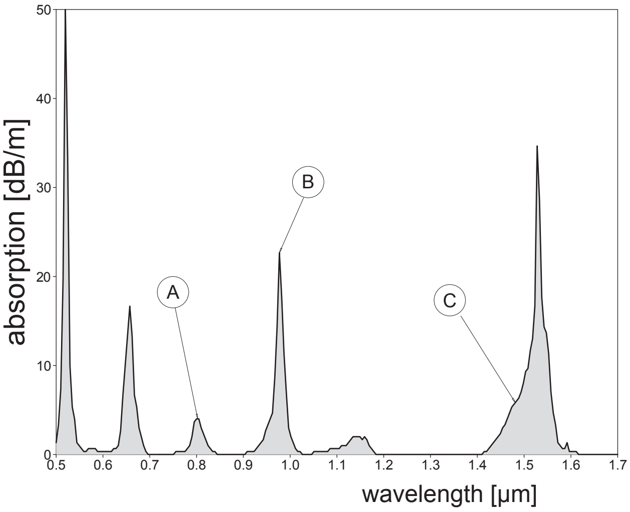


Fig. 9: Absorption spectrum of an Erbium doped fibre, A

Pump band for 800 nm, B 980 nm and C 1480 nm

The areas marked in the chapter Fig. 9 can be pumped with currently available Laser diodes. It has however turned out that the use of transition B is connected with many advantages. A detailed description of the characteristics of all the possible pump configurations is to be found in: „Optical Fiber Amplifiers: Design and System Application“ by Anders Bjarklev published in Artech House Boston London, ISBN 0-89006-659-0.

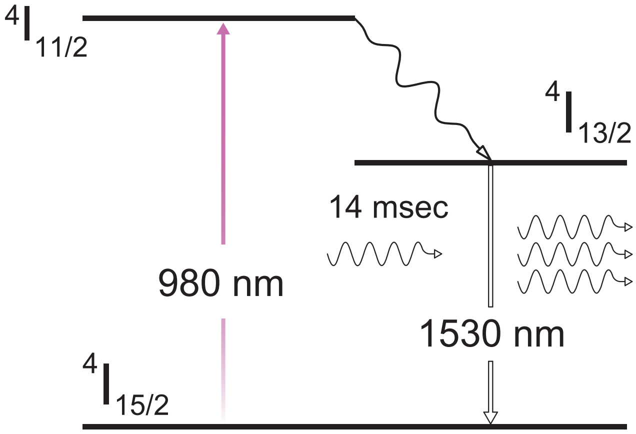


Fig. 10: Three level system of EDFA

In the chapter Fig. 10 we recognise the well known energy level system from the preceding chapter. The pump transition occurs between the states $^4I_{15/2} \rightarrow {}^4I_{11/2}$ followed by a quick transfer of the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ and finally as radiative transition back to the ground state $^4I_{15/2}$. With a comparatively extremely long life time of 14 msec, this system fulfils the requirements for the production of the desired population inversion.
The next step towards the realisation of a laser is the required cavity. Two main concepts, the linear and the ring cavity will be introduced in the next chapter.

2.7 Optical resonator or cavity

2.7.1 Linear Cavity

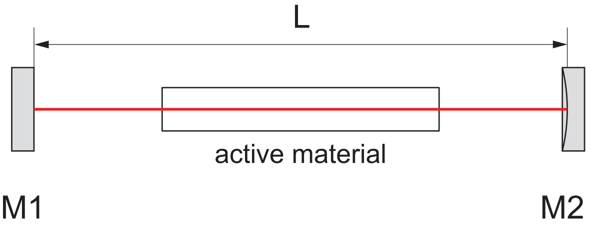


Fig. 11: Two mirror linear cavity with active material

Now we will place an inverted or active ensemble of atoms into an optical cavity, which is formed by two mirrors M1 and M2 having the distance of L. Due to the spontaneous emission photons are generated which will be amplified by the inverted medium and reflected back from the mirrors undergoing a large number of passes through the amplifying medium. If the gain compensates for the losses, a standing laser wave will be built up inside the optical resonator. Such a standing wave is also termed as oscillating mode of the resonator also eigenmode or simply mode. Every mode must fulfil the following condition:

$$L = n\cdot\frac{\lambda}{2} \text{ or } L = n\cdot\frac{c}{2v}$$

L represents the length of the resonator, λ the wavelength, c the speed of light, v the frequency of the generated light and n is an integer number. Thus every mode has its frequency of

$$v(n) = n\cdot\frac{c}{2L}$$

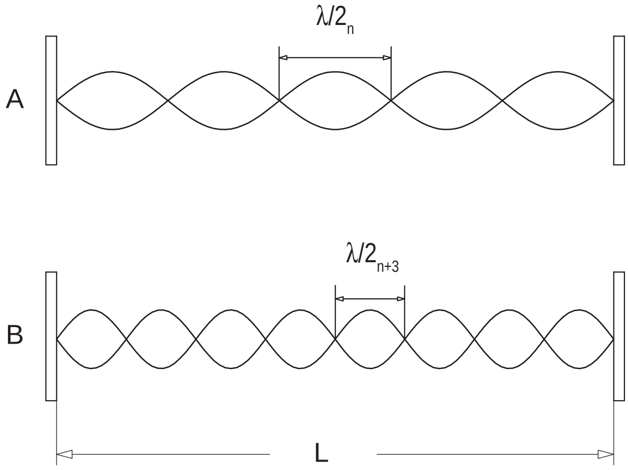


Fig. 12: Standing longitudinal waves in an optical resonator. A with n nodes and B with n+3 nodes

e.g. A laser with a resonator length of 30 cm at an emission wavelength λ of 632.8 nm will have the following value for n:

$$n=\frac{v}{c}\cdot 2\cdot L = 2\cdot\frac{L}{\lambda}=2\cdot\frac{0,3}{632,8\cdot 10^{-8}}=949.167$$

The difference in frequency of two neighboured modes is:

$$\Delta v = v(n+1)-v(n)=(n+1)\cdot\frac{c}{2L}-n\cdot\frac{c}{2L}=\frac{c}{2L}$$

In the above example the distance between modes would be

$$\Delta v=\frac{3\cdot 10^8}{2\cdot 0,3}=5\cdot 10^8\,\text{Hz}=500\text{ MHz}$$

If the active laser material is now brought into the resonator standing waves will be formed due to the continuous emission of the active material in the resonator and energy will be extracted from the material. However, the resonator can only extract energy for which it is resonant. Strictly speaking, a resonator has an indefinite amount of modes, whereas the active material only emits in an area of frequency determined by the emission line width.
chapter Fig. 13 shows the situation in the case of material that is inhomogeneously broadened.

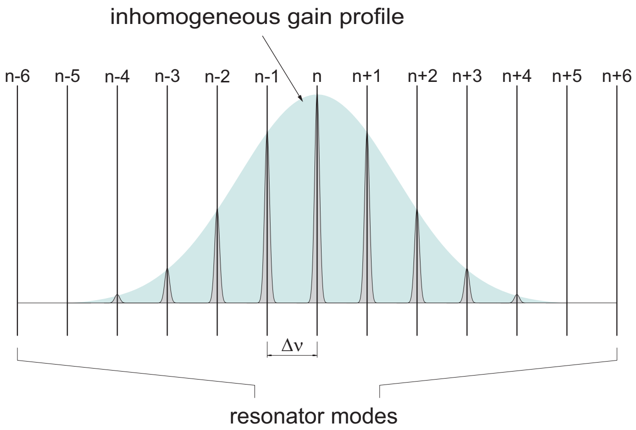


Fig. 13: Inhomogeneously broadened gain profile (Gaussian profile) interacting with an optical resonator

If the laser is operating in a stationary state, we can see that it is emitting several longitudinal modes. These are exactly the same modes that will be found in the emission profile. Since the modes are fed by an inhomogeneous emission profile they can also exist independently.

2.7.2 Ring resonator or cavity

However, the structure of chapter Fig. 11 can be expanded by two more mirrors to get a ring laser, in which no standing waves are generated as in the two-mirror resonator, but instead, gyrating waves.

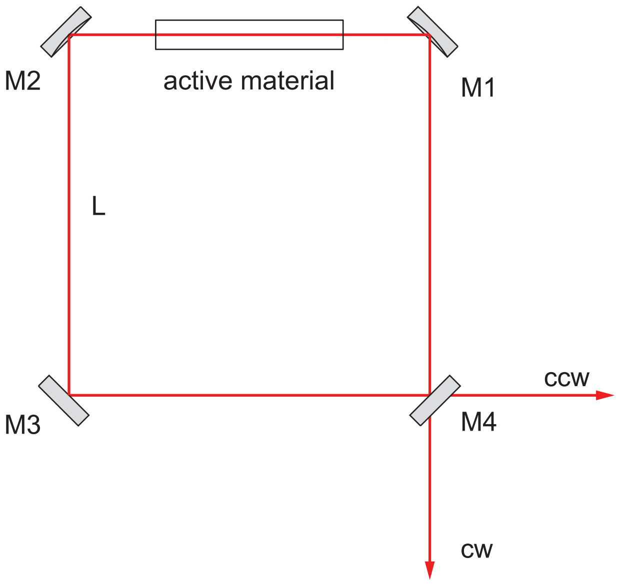


Fig. 14: Ring cavity

Here, one wave runs in the clockwise direction (cw, clockwise) and the other in the counter clockwise direction (ccw, counter clock-wise). In the next section we shall deal with the calculation and the design of such optical resonators.

2.7.3 ABCD Matrices

In the following section, certain basic concepts about the calculation and the description of the optical resonator will be explained. For the resonator type used in the later experiments, the optical stability criteria and the beam radius course has been calculated and discussed. The calculations have been done for an "empty" resonator, since the resonator properties can be especially influenced depending upon the active laser material (e.g. thermal lenses, abnormal refractive index etc.). In this context, the ABCD law will be introduced and used. This type of optical computation is an elegant method for ray tracing in a complex optical system. As shown in the next figure (chapter Fig. 15), an equivalent lens system can be constructed for each optical resonator.

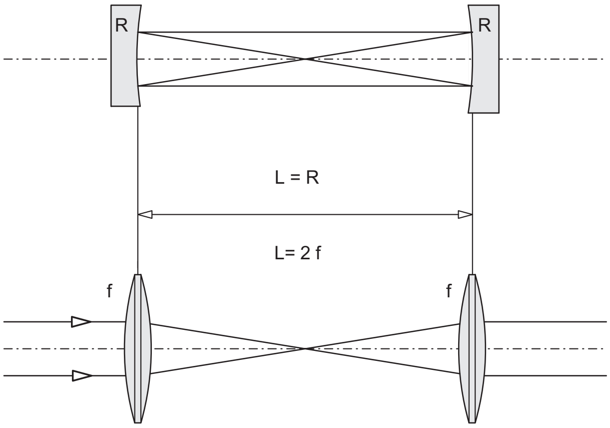


Fig. 15: Spherical resonator with equivalent lens guide

It must be noted here, that the number of gyrations would be endless in a resonator or else one can imagine a system with a number of lenses as shown in chapter Fig. 15.
One gets an *optically stable* resonator only when such optical imaging properties are selected, that after endless passes the ray diameter remains smaller than the mirror diameter. With the help of ABCD or the matrices on one hand the ray path of the resonator can be traced mathematically in its equivalent lens guide, and on the other a criteria can be specified for the distances L of the mirrors used, at which an optical resonator would be "stable".
How does the ABCD law work?
First, we must assume that the following calculations for the limiting case of geometrical optics are correct. This in addition, when the angle of the rays to the optical axis is < 15^0, i.e. $\sin\alpha \approx \alpha$ at a good approximation. This condition is fulfilled for most of the systems, especially for the laser resonator. A light ray is then uniquely defined through its height x to the optical axis and the inclination at this point (chapter Fig. 16).

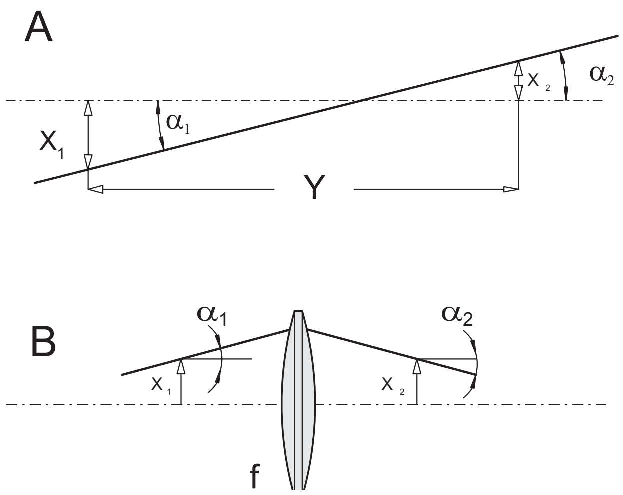


Fig. 16: Characteristic values for A.) Light ray and B.) Thin lens

A matrix is introduced, which when applied to the initial quantities X_1 and α_1 gives the final quantities X_2 and α_2:

$$\begin{pmatrix} X_2 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \cdot \begin{pmatrix} X_1 \\ \alpha_1 \end{pmatrix}$$

The matrix thus introduced is called ray transfer matrix or the ABCD-matrix. From the example given in chapter Fig. 16 A of the free propagation of a ray we can see, that $\alpha_1 = \alpha_2$ and $X_1 = X_2 \cdot Y \cdot \alpha$. The ABCD-matrix for this case will then be

Free ray propagation $$A_1 = \begin{pmatrix} 1 & Y \\ 0 & 1 \end{pmatrix}$$

For the example B of a thin lens, one gets the corresponding matrix from the following:
Just before (1) and after (2) the lens is $X_1 = X_2$

The slope of the ray in area (2) is $\alpha_2 = \frac{X_2}{b}$

With the image equation $\frac{1}{f} = \frac{1}{a} - \frac{1}{b}$ and $a = \frac{X_1}{\alpha_1}$

One thus gets the ABCD - matrix for a thin lens: $$A_2 = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}$$

With this method one can imagine a whole series of ABCD-matrices for different optical elements. However, the above examples suffice fully for the calculation of a cavity.
One can now see, that the combination of example A and B, free ray propagation with subsequent passage through a thin lens occurs as a result of arranging systems A and B one after the other.

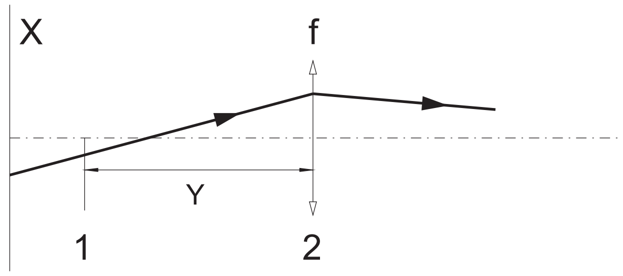


Fig. 17: Passage through a thin lens

At point 1 the ray has the coordinate X_1 and the slope α_1 and in the distance Y from the lens of the focus f (point 2) the desired values are X_2 and α_2.

By applying the ABCD-matrix for the free ray propagation (A_1) and of the thin lens (A_2) on the initial coordinates, we get:

$$\begin{pmatrix} X_2 \\ \alpha_2 \end{pmatrix} = A_2 \cdot A_1 \cdot \begin{pmatrix} X_1 \\ \alpha_1 \end{pmatrix}$$

$$\begin{pmatrix} X_2 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & Y \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} X_1 \\ \alpha_1 \end{pmatrix}$$

$$\begin{pmatrix} X_2 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} 1 & Y \\ -\frac{1}{f} & 1-\frac{y}{f} \end{pmatrix} \cdot \begin{pmatrix} X_1 \\ \alpha_1 \end{pmatrix}$$

In the meantime, we keep the ABCD matrix A_3 fixed, which then describes the path of the ray through a thin lens:

$$A_3 = \begin{pmatrix} 1 & Y \\ -\frac{1}{f} & 1-\frac{y}{f} \end{pmatrix}$$

Finally, we get the following as the result:

$$\begin{pmatrix} X_2 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} X_1 + \alpha_1 Y \\ -\frac{1}{f} X_1 + \alpha_1 \left(1-\frac{y}{f}\right) \end{pmatrix}$$

With these concepts, we are now ready to calculate a lens guide, in order to specify the optical stability criteria of a laser resonator with this knowledge. As already mentioned, the light rays travel infinitely back and forth in an optical resonator. In the case of the equivalent lens guide this implies, that the same optical structure is traversed infinite times. After n passages, the ABCD law becomes the following for any specific place of the lens guide (chapter Fig. 15):

$$\begin{pmatrix} X \\ \alpha \end{pmatrix}^n = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^n \begin{pmatrix} X \\ \alpha \end{pmatrix} \qquad \textbf{(25)}$$

The ABCD matrix thereby is the equivalent lens guide allocated to the resonator. It would now be very cumbersome to solve the above expression for a few thousand values of n. Fortunately; the nth power of a 2x2 matrix can be calculated much more simply:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}^n = \frac{1}{\sin(\theta)} \begin{pmatrix} A\sin(n\theta) - \sin((n-1)\theta) & B\sin(n\theta) \\ C\sin(n\theta) & D\sin(n\theta) - \sin((n-1)\theta) \end{pmatrix}$$

Here $$\theta = \arccos\left(\frac{A+D}{2}\right). \qquad \textbf{(26)}$$

So that the linear system of equations remains solvable, i.e. the rays after infinite passages remain within the lens guide, equation chapter (25) demands:

$$\left|\frac{A+D}{2}\right| \leq 1 \qquad \textbf{(27)}$$

This is now the stability criteria for the lens guide and hence also for the related resonator. Within the scope of this project, we shall be dealing with a special type of resonator, which forms the basis of the ring laser with three mirrors (chapter Fig. 18).

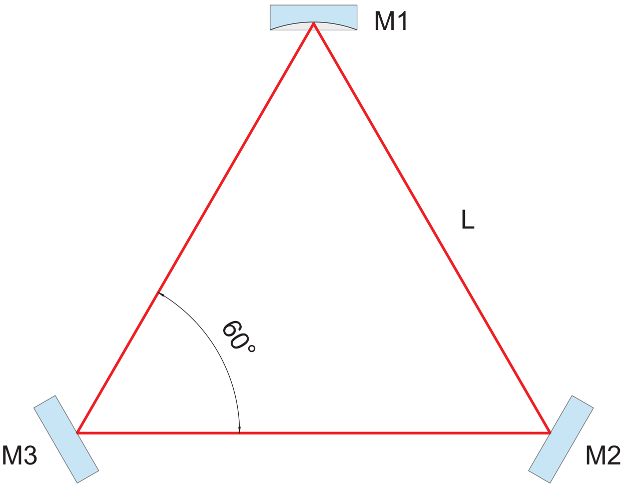


Fig. 18: Ring cavity with three mirrors

The mirror M1 has a radius of curvature R, whereas the mirrors M2 and M3 are flat mirrors. The equivalent lens guide is shown in chapter Fig. 19:

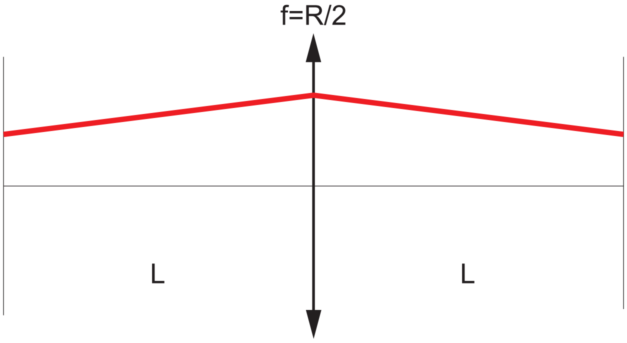


Fig. 19: Equivalent lens guide for the ring resonator as shown in chapter Fig. 18

The equivalent lens guide comprises of three stages (from left to right):

1) Free ray path
2) Passage though a thin lens
3) Free ray path

The related matrices thus become:

$$A=\begin{pmatrix}1 & L\\ 0 & 1\end{pmatrix}\cdot\begin{pmatrix}1 & 0\\ -\frac{1}{f} & 1\end{pmatrix}\cdot\begin{pmatrix}1 & L\\ 0 & 1\end{pmatrix}$$

$$A=\begin{pmatrix}1 & L\\ 0 & 1\end{pmatrix}\cdot\begin{pmatrix}1 & L\\ -\frac{1}{f} & 1-\frac{L}{f}\end{pmatrix}$$

$$A=\begin{pmatrix}1-\frac{L}{f} & L+L\left(1-\frac{L}{f}\right)\\ -\frac{1}{f} & 1-\frac{L}{f}\end{pmatrix}$$

With equation chapter (27) one gets the stability criteria for this arrangement as:

$$\frac{|A+D|}{2}=\left|1-\frac{L}{f}\right|=\left|1-\frac{2L}{R}\right|\leq 1 \qquad \textbf{(28)}$$

Apparently, the resonator is optically stable, when the distance L fulfils the following condition:

$$\frac{R}{2}\leq L\leq R \qquad \textbf{(29)}$$

From the lens guide after chapter Fig. 19 we can conclude that we can combine two or more lens guides to achieve a long cavity.

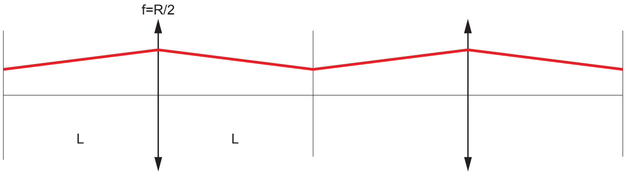


Fig. 20: Principle of a lens guide

In the same way we can argue that also an arrangement of mirrors is suitable do obtain a long cavity. This principle is found in optical fibres where the required cavity mirrors is formed by the end faces of the fibre.

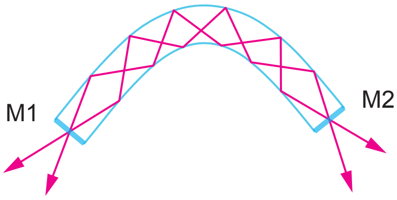


Fig. 21: Reflective light guide

Even without extra coating the end faces have a natural reflectivity of approximately 4%. This is described by the Fresnel equations which we will recall in the following chapter

2.8 Fresnel equations

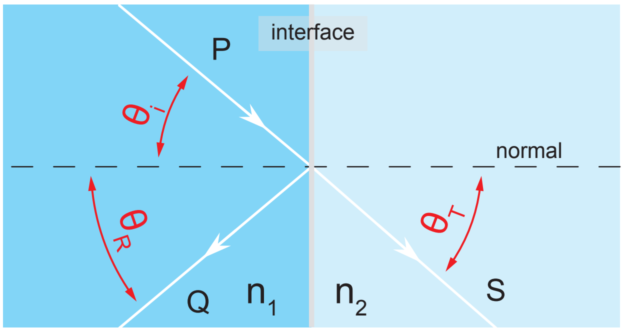


Fig. 22: Definition of terms

We assume that a light ray passes on its way an interface which forms the transition from media 1 with index of refraction n_1 and media 2 with n_2.
The fraction of the incident power P which is reflected from the interface is denoted by R and the fraction which is refracted (S) is denoted by the transmittance.
The calculated values of R and T depend on the polarisation of the incident beam with respect to the interface.
If the electrical field of the incident beam P is perpendicular to the plane of the interface of chapter Fig. 22 the reflectivity is termed as R_S In the case that the polarisation is parallel to the plane of the interface the reflectivity is denoted as R_P.
The angles θ_i, θ_R and θ_T are connected to the law of reflection ($\theta_i=\theta_R$) and the Snell's law $\sin\theta_i/\sin\theta_T=n_2/n_1$.

$$R_s \quad \left(\frac{n_1 \cdot \cos\theta_i \quad n_2 \cdot \cos\theta_T}{n_1 \cdot \cos\theta_i + n_2 \cdot \cos\theta_T} \right)^2$$

$$\left[\frac{n_1 \cdot \cos\theta_i \quad n_2 \sqrt{1 \quad \left(\frac{n_1}{n_2} \cdot \sin\theta_i \right)^2}}{n_1 \cdot \cos\theta_i + n_2 \sqrt{1 \quad \left(\frac{n_1}{n_2} \cdot \sin\theta_i \right)^2}} \right]^2 \qquad \textbf{(30)}$$

$$R_P \quad \left(\frac{n_1 \cdot \cos\theta_T \quad n_2 \cdot \cos\theta_i}{n_1 \cdot \cos\theta_T + n_2 \cdot \cos\theta_i} \right)^2$$

$$\left[\frac{n_1 \sqrt{1 \quad \left(\frac{n_1}{n_2} \cdot \sin\theta_i \right)^2} \quad n_2 \cdot \cos\theta_i}{n_1 \sqrt{1 \quad \left(\frac{n_1}{n_2} \cdot \sin\theta_i \right)^2} + n_2 \cdot \cos\theta_i} \right]^2 \qquad \textbf{(31)}$$

The numerical results of equations chapter (30) and chapter (31) are shown in chapter Fig. 23 and chapter Fig. 31 as function of the incident angle θ_i in the range of 0 to 90°.

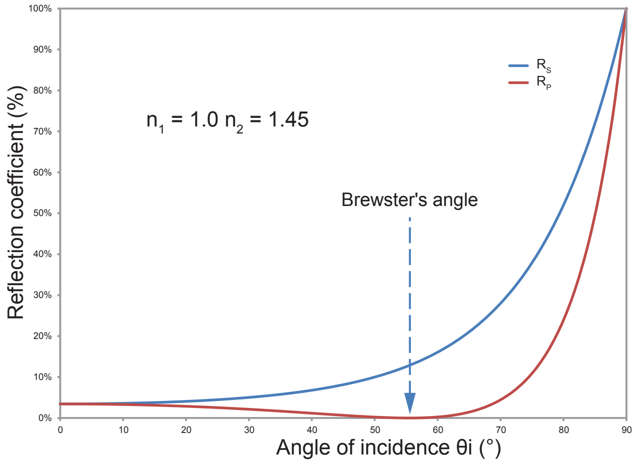


Fig. 23: Calculation for $n_1 < n_2$

The chapter Fig. 23 shows the results for RS and RP for an interface air to glass. It is notable that the reflection for the s polarized light becomes zero around 56°. This well known effect named after his discoverer Brewster occurs at the "Brewster's angle which depends on the index of refraction of the media

$$\tan\theta_{Brewster} \quad n$$

Another remarkable result is the fact that for perpendicular incidence (θ_i=0) the reflectivity of both polarisation states s or p the reflectivity is almost 4%.

If we are calculating the same equations however now with n_1=1.45 and n_2=0 we will get the curves as shown in chapter Fig. 24. These results describes the situation when light rays travelling inside an optical fibre are striking the end face of the fibre. Generally speaking a transition from glass to air takes place.

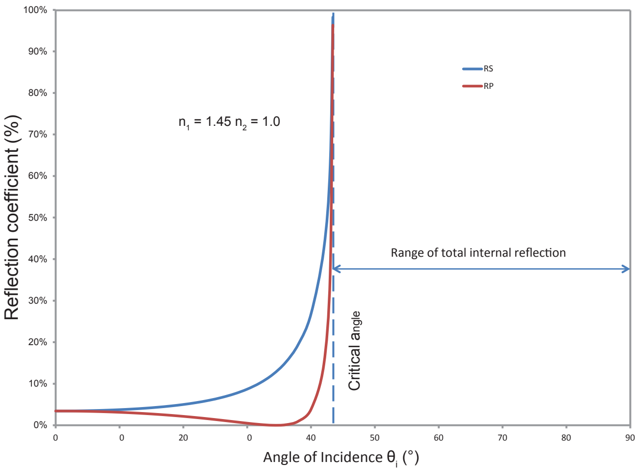


Fig. 24: Calculation for $n_1 > n_2$

Also this calculations show that for perpendicular incidence (θ_i=0) the reflectivity of both polarisation states s or p has the same values as for a transition from air into media. This conclusion is important to understand the operation of a fibre laser without extra mirrors. The natural reflectivity is sufficient to create stable laser oscillation.

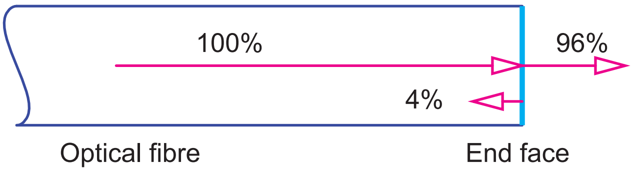


Fig. 25: Power balance at the fibre end face

2.9 *Fibre laser*

Each doped optical fibre can form a laser without extra mirror due to the natural Fresnel reflection, the high gain and the high gain length.

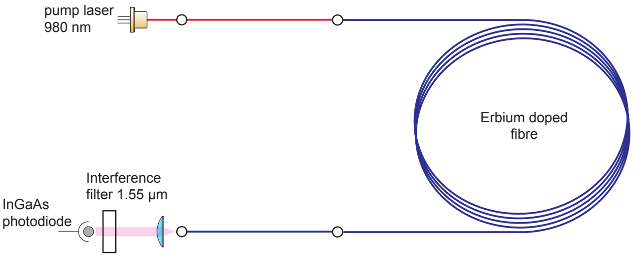


Fig. 26: A practical layout of a linear fibre laser

The active media as well as optical cavity is formed by an Erbium doped fibre. The optical pumping is achieved by means of a diode laser emitting at 980 nm. To verify the laser oscillation or just to measure the fluorescence an interference filter is used which completely blocks non absorbed pump power.

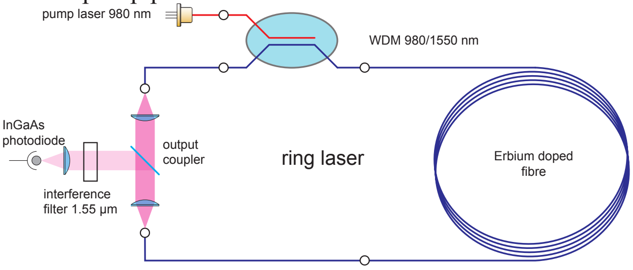


Fig. 27: Fibre ring laser

2.10 Wavelength division multiplexer (WDM)

In practice a fibre ring laser is a closed loop. To inject the necessary pump power a so called wavelength division multiplexer (WDM) is used. In principle two kinds of such units are used. The chapter Fig. 28 shows the most common one for optical pumping.

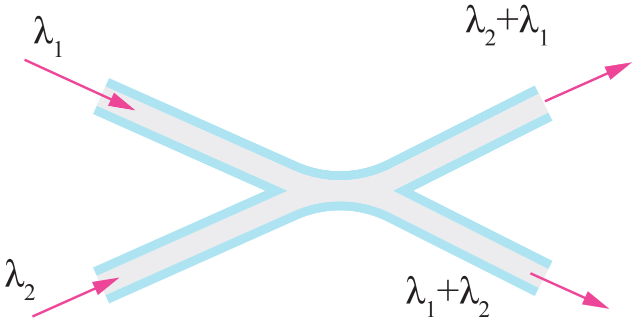


Fig. 28: Fused fibre coupler

Two fibres are bend and ground to half of its diameter. After that they are fused together to form a structure as shown in the chapter Fig. 28.

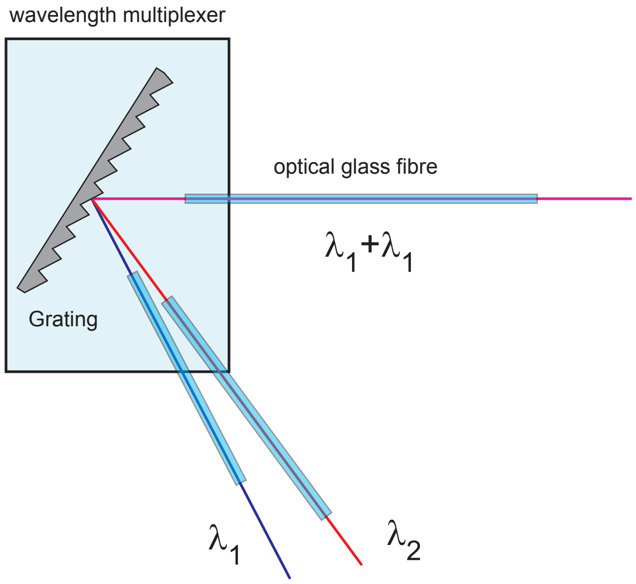


Fig. 29: Grating wavelength division multiplexer

Basically also a grating WDM can be used, however such devices are suited for less power for telecommunication devices. Even much more wavelength can be combined to one beam.

2.11 Resonant two photon absorption

This phenomenon occurs in energy level as shown in chapter Fig. 30. The pump process populates the $^4I_{11/2}$ state. From here are two possible transitions possible. The most probable is the radiationless decay to the $^4I_{13/2}$ state from where the laser transition starts. If the pump rate is strong enough to keep some photons in the $^4I_{11/2}$ state before they leave the can absorb another pump photon and excited to the next higher $^4F_{7/2}$ state.

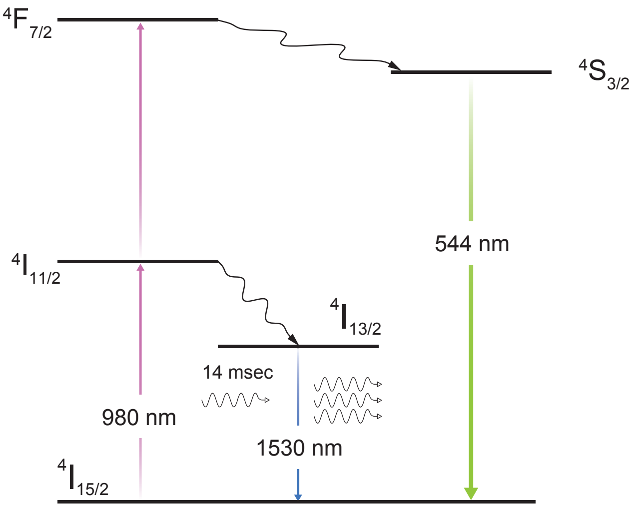


Fig. 30: Energy level diagram of Erbium doped glass fibre

Because the second absorption of a pump photon starts from a resonant transition, which means that the photon energy equals the energy difference of the excited to the ground state (see also chapter Fig. 1). Furthermore the second photon populates directly a resonant state. From here a radiationless transfer to the $^4S_{3/2}$ state takes place. The subsequent transition to the ground state yields “green” photons having a wavelength of 544 nm.
This is very exciting process to see the production of invisible to visible photons and will be demonstrated during the experimental work.

3.0 Experiments

3.1 Experimental set-up

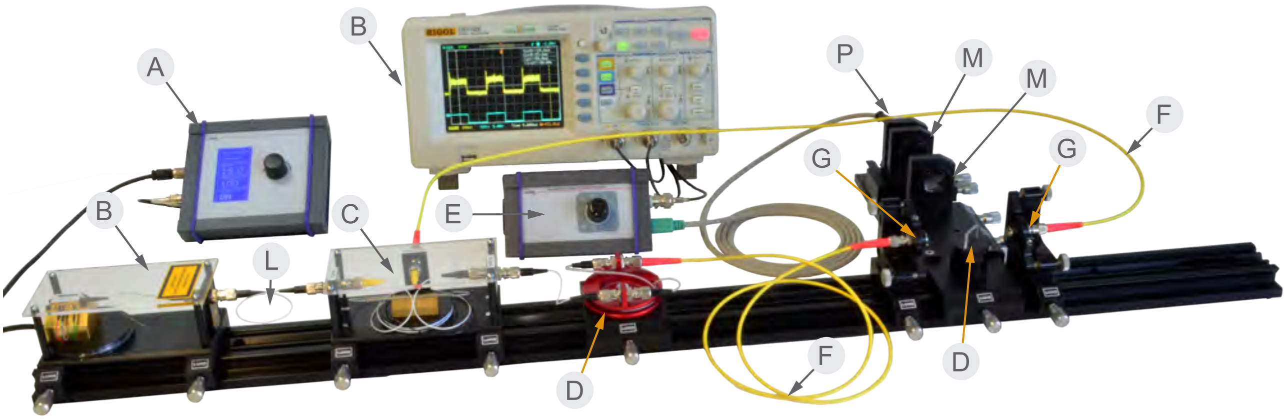


Fig. 31: Experimental set-up of the fibre ring laser

3.2 Description of the components

3.2.1 Module A Digital Laser Diode

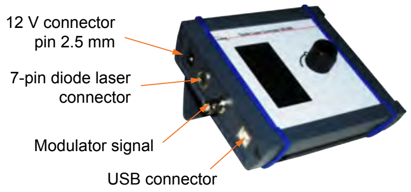
and Peltier's Element Controller ED-020

This fully digital operating device controls the injection current as well as the temperature of the diode laser head. By means of a one knob interaction all parameters can be set and displayed. By turning the knob a specific menu item is selected. Pressing the knob acts as enter key.

The diode laser head is connected via a multi-pin connector to the device. A BNC jacket provides a synchronisation signal of the modulation frequency when the diode laser is electronically switched on and off. The ED-020 device provides an integrated USB interface which enables full remote control by an optional computer or laptop.

Specifications:

Injection current	1000 mA maximum, selectable in steps of 10 mA
Temperature	15 - 40 ° C in steps of 1°
Modulation	10 to 1000 Hz in steps of 10 Hz
Operating Voltage	12 VDC, by means of an extra wall plug power supply
Inputs	Diode laser connection
Outputs	Modulation signal as TTL trigger signal via BNC jacket
Dimensions	115 x 130 x 38 mm



On the left side of the ED-020 the connectors are located. A 12 V connection with 2.5 mm pin is provided. A simple wall plug power supply is attached to here. The diode laser connection requires a 7 pin connector and is suited for the DIMO laser head with integrated Peltier's element and NTC temperature sensor. However also other laser heads may be connected, please feel free to ask for our support. A BNC jack is provided to deliver a monitor signal for the internal modulator. This signal can be used as trigger. The USB connector is provided for future expansions to control the unit by external software.

Laser ON / OFF

Turning the central knob highlights sequentially the selected item. To switch the laser on, turn the knob until the "Laser" menu is highlighted as shown in the figure on the left side. Pressing the central knob shortly (less one second) switches the laser on or off. If a previous value of the current has been set and the laser is switched of, the processor provides a soft shut down of the laser diode.

Injection current

Select the "Current" menu and press the central knob down for 2 seconds until the "Current" item starts to blink. By turning the knob the current is selected which is set to the laser diode from the processor with soft steps of 10 mA in 100 ms. This assures a safe and lifetime extending operation for the laser diode. Pressing again the central knob leaves and closes the current menu.

Current
10
Temp.
23
Modulator
OFF
Laser
ON

Temperature

Select the “Temp.” menu and press the central knob down for 2 seconds until the “Temp.” item starts to blink. By turning the knob the temperature set point is selected. To take over the value the central knob must be pressed as long as the menu item “Temp.” stops blinking.
The temperature range can be set in from 15° up to 35° C. In highlighted mode the value of the temperature is the temperature set point. In non highlighted mode the actual temperature is displayed.
It may take a moment before the system reaches the stable temperature.

Current
10
Temp.
15
Modulator
300
Laser
ON

Modulator

The injection current can be switched periodically on and off. In this mode the output power of the laser diode is modulated as well. This is of interest, when time dependant measurements shall be carried out. The modulation frequency can be set from 0 to 1000 Hz. The duty cycle is fixed to 50%.
A monitor signal of this modulation signal is present as TTL signal at the BNC jack as shown in the illustration of the left page.

3.2.2 Module B Fibre coupled diode laser

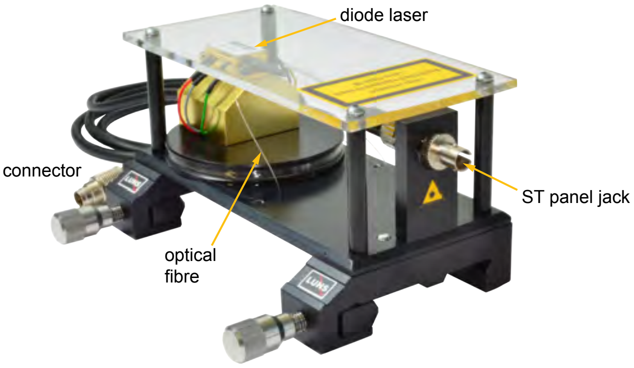


Fig. 32: Module B: Fibre coupled pump diode laser

The module B contains a diode laser integrated into a butterfly housing. The laser emission is available via an optical monomode fibre terminated with a ST fibre connector which is attached to the ST panel jack. The maximum output power at the fibre connector is 275 mW at a wavelength of 980 nm and belongs to the laser class 3B.

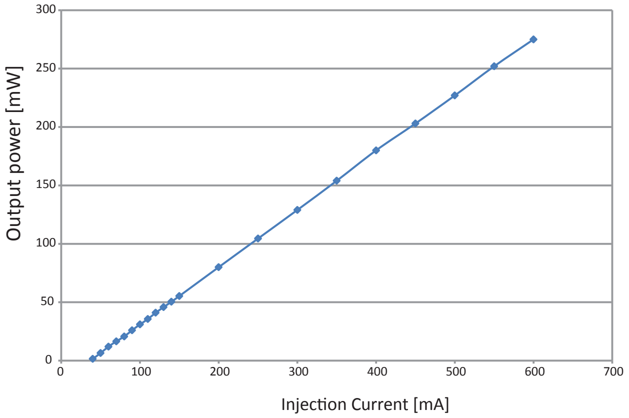


Fig. 33: Output power at 980 nm and diode laser temperature of 20°C

3.2.3 Module D Erbium doped fibre

Fig. 34: Module H Erbium doped fibre, 8 m

This module is the centre piece of the set-up and is one of the most valuable components. It consists of 8 m Erbium doped fibre, which is coiled up on a drum (1). The fibre ends are connected to ST connectors (2) which are connected to the fibre socket (3). The data of the fibres is summarised in the following table

Core diameter	2.2	µm
Cladding diameter	125	µm
Total diameter	250	µm
Length	17	m
Refractive index difference between cladding and core	$30\ 10^{-3}$	
Numerical Aperture	0.3	
Mode Field diameter 980 nm	2.7	µm
Mode Field diameter 1550 nm	5.6	µm
Cut-off wavelength	840	Nm
Attenuation at 980 nm	2.6	dB/m
Attenuation at 1532 nm	3.4	dB/m

Erbium Concentration	442	ppm weight
Permitted bending radius	30	mm

The specification of attenuation in dB can be re-written with (24) in the conventional Beer's Absorption Rule.

$$\alpha_{dB/m} = 10 \cdot \log\left(\frac{I}{I_0}\right) = 10 \cdot \log e^{-\alpha} \qquad (24)$$

$$\alpha = -\ln\left(10^{\frac{1}{10}\alpha_{dB/m}}\right)$$

Consequently we get for the attenuation at 980 nm:

$$\alpha = -\ln\left(10^{\frac{1}{10}\cdot 2\ 6}\right) = -\ln\left(10^{0\ 26}\right) = -0.6\,/\,m$$

$$I = I_0 \cdot e^{-0\ 6 \cdot L}$$

where L is the Fibre length.
When for e.g. 50 mW is launched in the fibre having a length of 8 metres, then at the output

$$I = 50 \cdot e^{-0\ 6*8} = 0.4\,mW$$

is expected. This result is more easily calculated by those who are used to dealing with dB, namely:

$$I = I_0 \cdot 10^{-\alpha_{dB/m} \cdot}$$

As can be shown with later measurements, a substantially greater output is measurable at the fibre end, since the specified relationships are valid only for pump outputs which are very small compared to the saturated intensity of the absorbing transition

Fig. 35: Erbium doped fibre 1.5 m

For some experiments a shorter Erbium doped fibre is required to prevent laser oscillation and to demonstrate the effect of a feed back mirror.

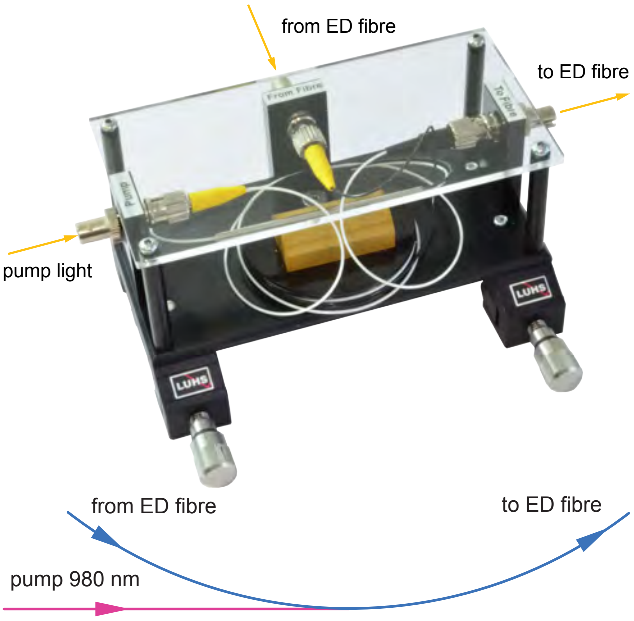


Fig. 36: WDM (Wavelength Division Multiplexer)

3.2.4 Module G Fibre Collimator

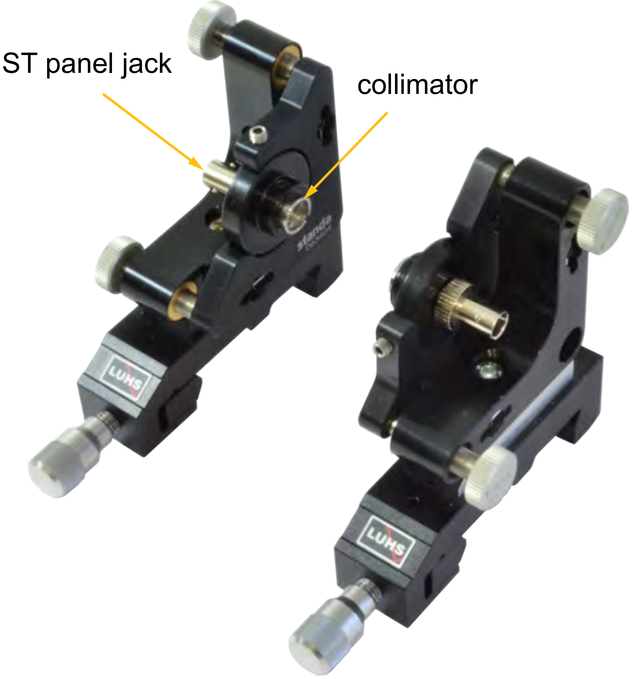


Fig. 37: Fibre collimator

The fibre collimator is used to collimate the divergent radiation emerging from the fibre into a parallel beam. A second collimator is used to couple the parallel beam back to the fibre.

3.2.5 Module B Beam splitter unit

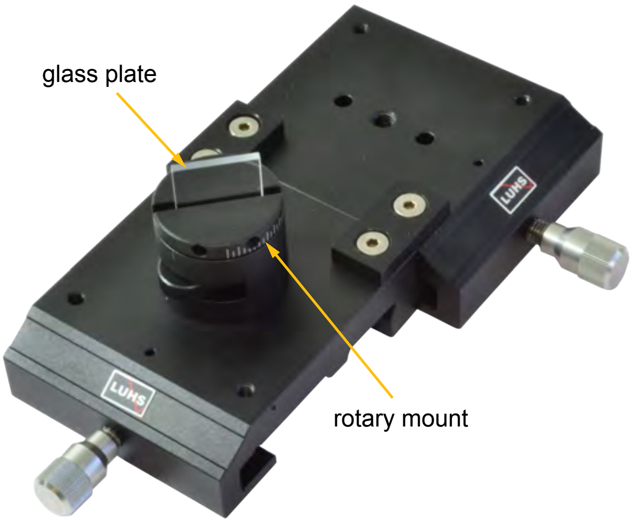


Fig. 38: Beam splitter unit

The beam splitter is used between the two fibre collimators. A fraction of the passing light is diverted according to the Fresnel reflection for a given angle of incidence. The diverted light is guided to the photodetector to measure static as well as dynamic properties of the ring laser emission.

3.2.6 Module P Photodetector

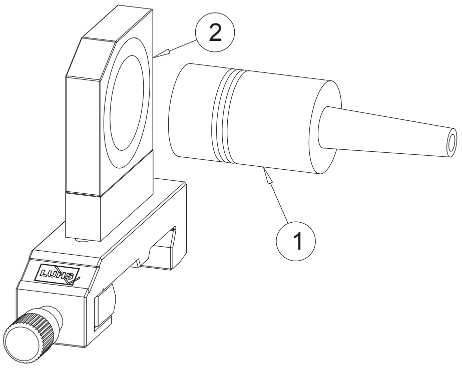


Fig. 39: Module P photodetector

Either the Si PIN or the inGaAs photodetector (1) is set into the mounting plate (2). Three spring loaded steel balls are keeping the detector in position.

Fig. 40: InGaAs photodetector with mini DIN connection cable

For the detection of radiation at 980 and 1550 nm, two different photodetectors are used, as there are no photodiode which possess sufficient intensity and speed required for both wavelengths. The respective photodiode is mounted in a housing (1), which can easily be installed in the mounting plate (2) by a click-mechanism. The signal produced is available at a mini DIN cable which is connected to the signal conditioning box. The module is fixed on the optical rails with the help of carrier.

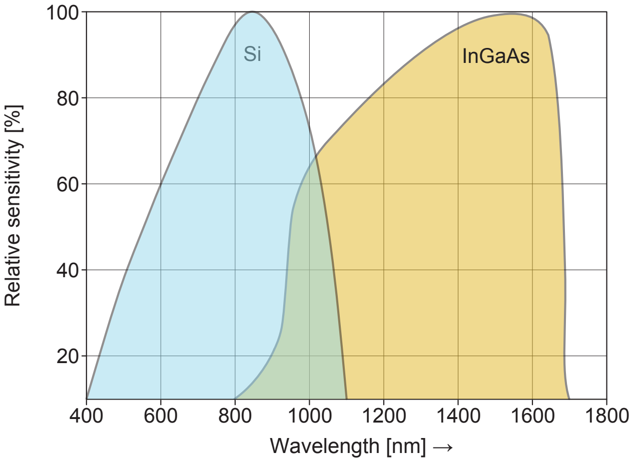


Fig. 41: Relative sensitivity of Si and InGaAs photodiode as a function of the wavelength

For the detection of radiation of 980 nm a PIN Si and of 1550 nm a InGaAs (Indium Gallium Arsenic) photodetector is used, which possesses similar spectral characteristics as the classical Ge photodiode. These data are arranged in the following table.

	Si	InGaAs
Quantum efficiency η	90 % 850 nm	95% 1550 nm
Rise time τ_R=2.2 $R_L C_j$ at 10%-90% R_L= 50 Ω and U_d= 10V (5V InGaAs)	1.7 nsec	0.1 nsec
Capacitance C_j at U_d=		
0 V	73 pF	
1 V	38 pF	
5 V		1 pF
10 V	15 pF	
Dark current i_d at U_d= 10V (5V InGaAs)	2 nA	1.0 nA

Fig. 42: IR sensor card

Since the radiation at 980 nm and also that at 1550 nm is not visible to human eyes, a few aids are used to achieve reproducible fine adjustment. With the help of an infrared display card the invisible radiation can be illustrated as luminescent green or red speckles.

3.2.7 Module E Signal conditioning box

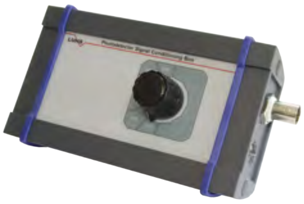


Fig. 43: Module P - Photodetector signal conditioning box

This device allows the connection of the photodetector to an oscilloscope. For this purpose the photoelectric current which is proportional to the number of incident photons needs to be converted into a voltage. This is done by the simple however very effective by the circuit as shown in the chapter Fig. 44.

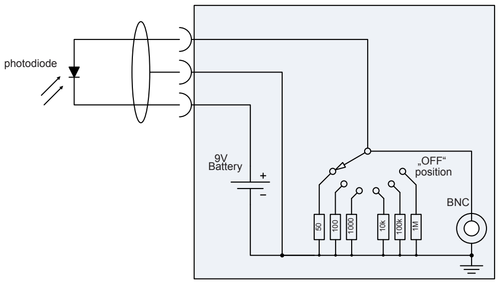


Fig. 44: Signal conditioning circuit

The circuit is driven by a 9 V battery which lasts almost one year under regular operation. The impedance of the output can be adjusted from 50 Ω to 100 kΩ. The “OFF” position still provides via an 1 MΩ shunt a signal with a very high sensitivity which sometimes is useful.
For fast signals the lower shunt resistors are used. Rise times of 1 ns can be measured in the 50 and 100 Ω position.

3.2.8 Feed back mirror and interference filter

Fig. 45: Mounted feed back mirror

An interference filter having a transmission maximum at 1550 nm with a bandwidth of 40 nm. The overall transmission is 60% resulting in a reflectivity of 40%. This element is dually used once as feed back laser and secondly as blocking filter for the pump radiation at 980 nm. When it is used as feed back mirror the element is mounted into the adjustment holder. For this purpose the fibre collimator is removed from the holder (chapter Fig. 48) and the mirror inserted.

Fig. 46: Removing a component from the adjustment holder

3.2.9 Fibre patch cable

Fig. 47: Single mode fibre patch cable

For the setup of the different arrangements fibre patch cables are used to connect and distribute the laser radiation to the individual components. Once the connector are placed into the connecting jacks the fibre end faces are in spring loaded close contact. Each dust particle may scratch the fibre surface and leaves it unusable.

Fig. 48: Cleaning the front face of an optical fibre

To avoid this, the fibre faces must be cleaned for each use with the provided optics cleaning set.

Fig. 49: ST jack mounted in a click 25 mount

A useful aid to perform measurements at the fibre out the fibre adapter as shown in chapter Fig. 49 is provided. it will set into a mounting plate and the fibre to be testes is connected to the holder. The emerging light is measured by one of the two photodetectors.

4.0 Experimental tasks

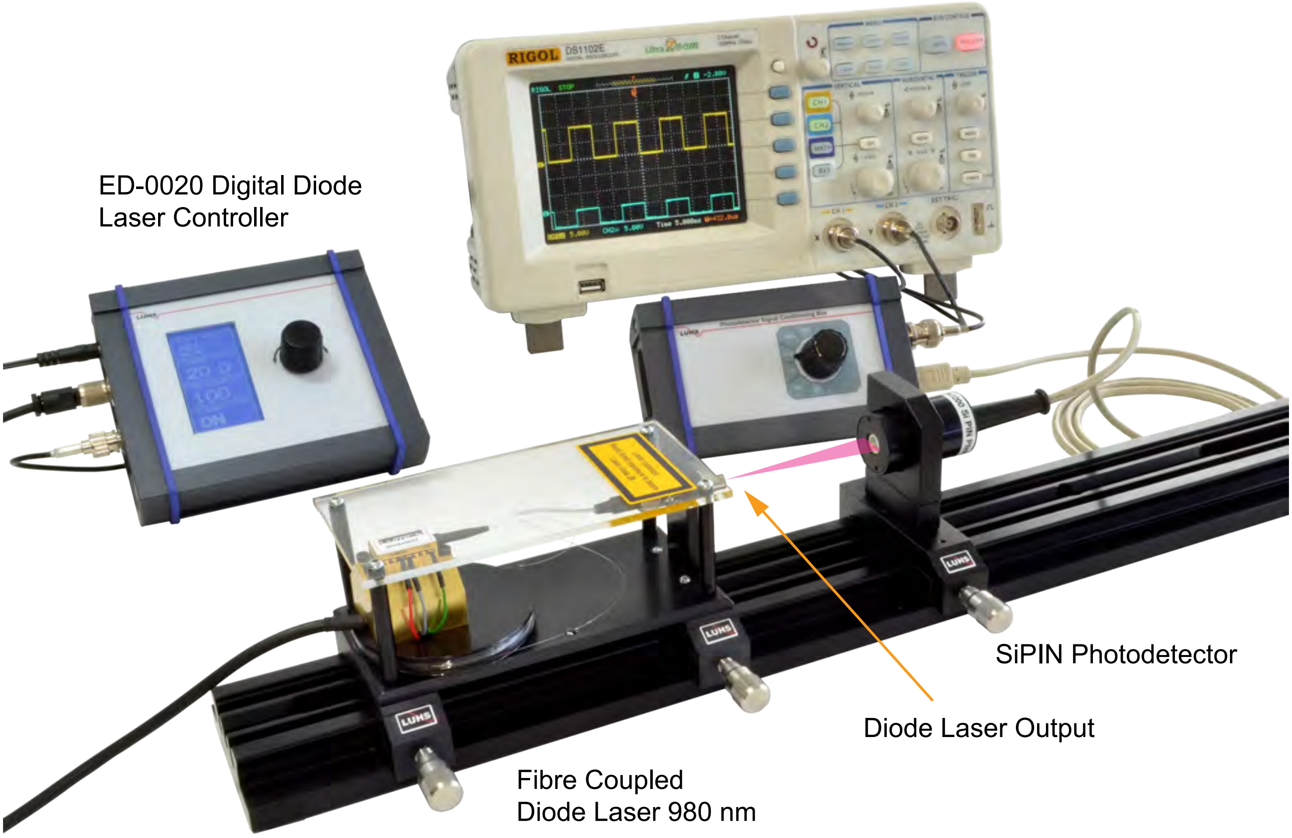


Fig. 50: Setup for characterising the diode laser

4.1 Characterizing the diode laser.

In this first experiment the relative output power of the diode laser is measured as function of the injection current and the temperature as parameter.

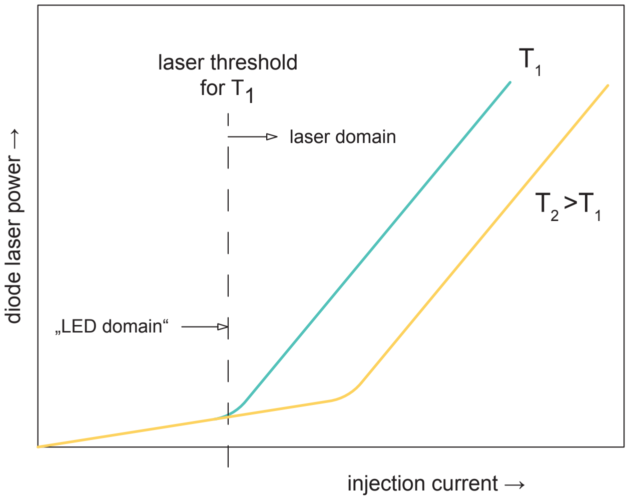


Fig. 51: Output power of the diode laser

The characteristic data of the diode laser can be measured in relative units. If a laser power meter is available this can also be done in absolute units. From the plot of chapter Fig. 51 the output power as a function of injection current, the slope efficiency and the laser threshold injection current are determined.

4.2 Measuring the Einstein coefficient for spontaneous emission

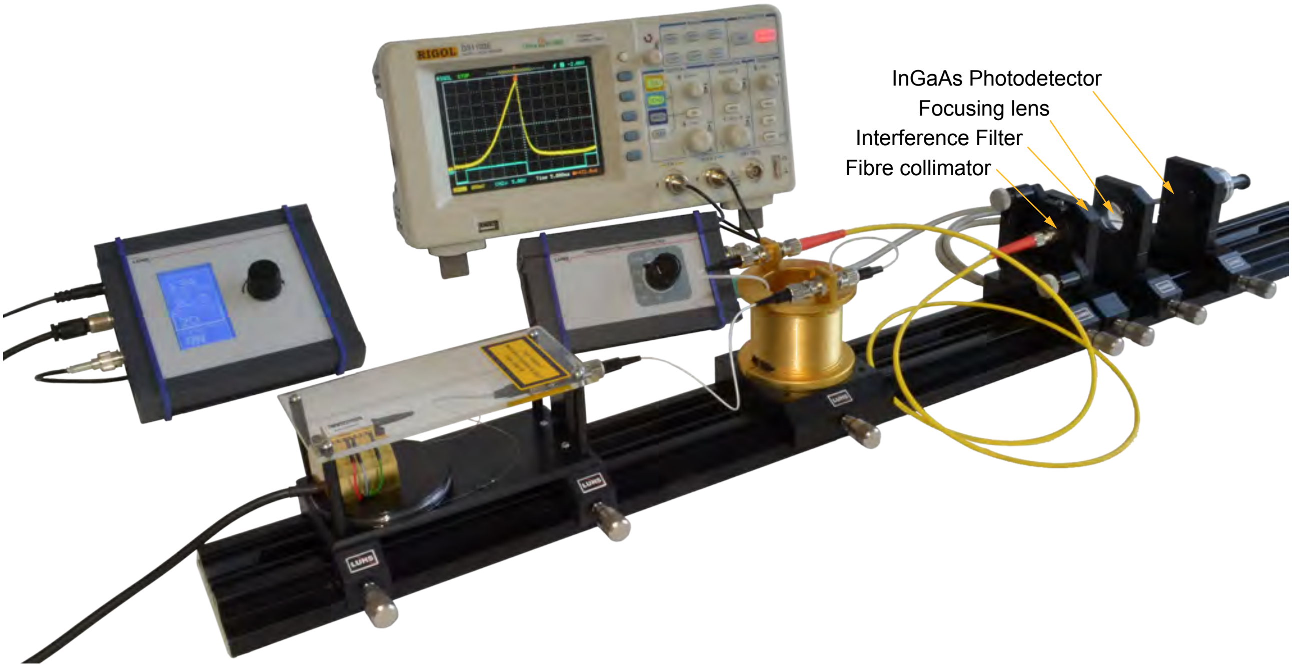


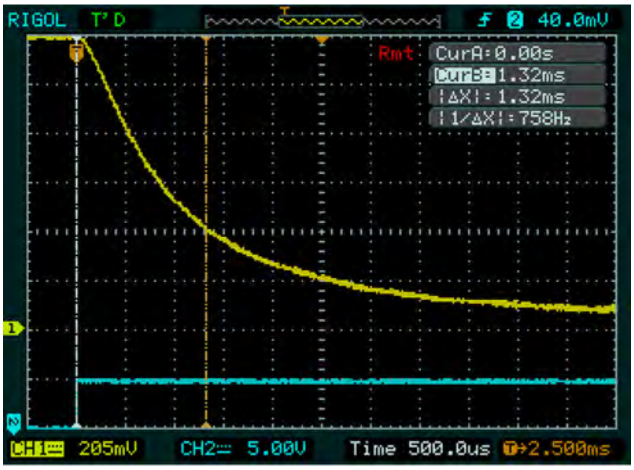
Fig. 52: Setup for measuring the lifetime of the fluorescent

In this setup the 8 m long Erbium doped fibre (EDF) is directly connected to the diode laser. The output power of the diode laser is reduced in such a way that the 1.5 µm laser does not oscillate.

The end of the EDF is connect via a fibre patch cable to the fibre collimator. Directly behind the collimator the interference filter is placed. Since the sensitive area of the InGaAs is small compared to the fluorescence cross section a focusing lens is used to image the almost entire fluorescence light to the detector.

The modulator of the diode controller is activated and the modulation frequency is chosen in such a way that the almost full decay of the fluorescent light is shown on an oscilloscope. As trigger the reference signal from the diode laser controller is use. The trigger mode is set to falling edge. Please note that the reference signal is inverted and the respective channel of the oscilloscope needs to be inverted.

The corresponding screen shot of an oscilloscope is shown in chapter Fig. 53. The lifetime is taken at the point where the initial intensity drops to 1/e.



CurA:0.00s
CurB:1.32ms
|ΔX|:1.32ms
|1/ΔX|:758Hz

CH1 205mV CH2 5.00V Time 500.0us T→2.500ms

Fig. 53: Decay of fluorescence light

4.3 Linear fibre laser

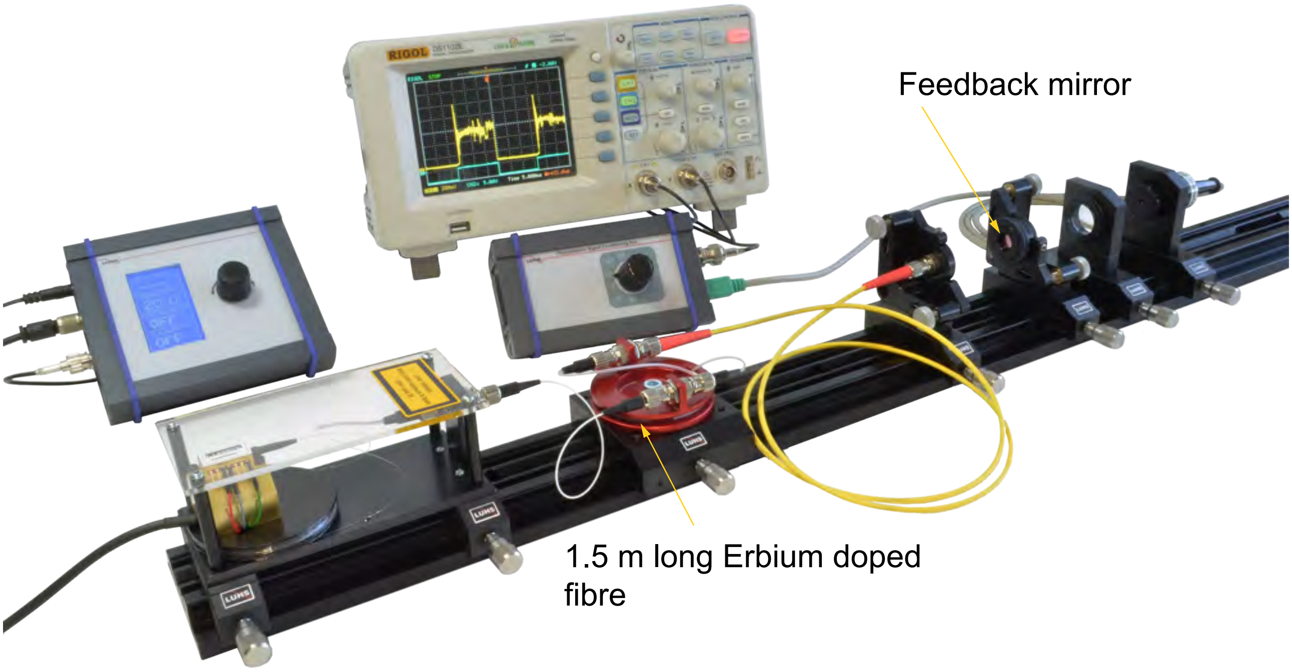


Fig. 54: Setup with feedback mirror

4.3.1 Feed back mirror

For this experiment the 8 m long Erbium doped fibre (EDF) is replaced by a 1.5 m long one to avoid that the fibre laser starts already at low pump powers. The aim of this experiment is to show the effect of a feedback mirror which provides a much higher reflectivity as the natural reflection of the fibre end face.
As feedback mirror we are using the flat interference filter which is set into an adjustment holder.

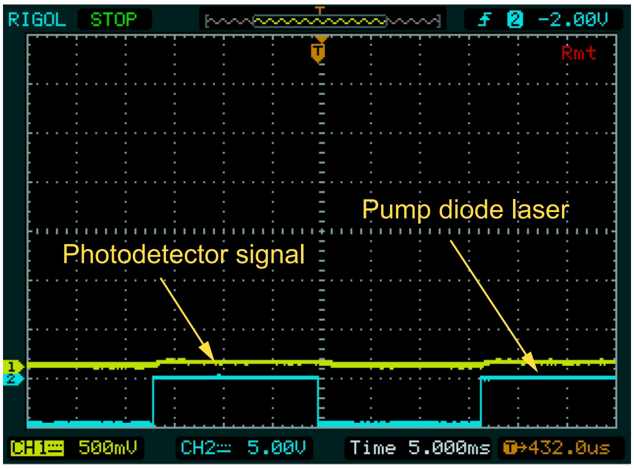


Fig. 55: Linear fibre laser with misaligned feedback mirror

Behind the feedback mirror a focusing lens and the InGaAs photodetector is placed to verify the occurrence of fibre laser oscillation. The chapter Fig. 55 shows the screen shot of an oscilloscope. The lower track corresponds to the modulation signal of the pump diode laser. With completely misaligned feed back mirror a weak oscillation can be observed (upper track).
To align the mirror we are using the infrared converter card and adjusting the not absorbed pump power back to the fibre collimator while observing the signals of the oscilloscope.

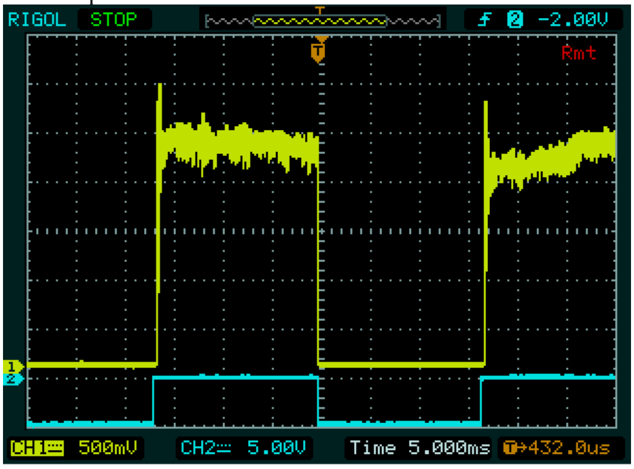


Fig. 56: Linear fibre laser with aligned feedback mirror

Once the mirror has been aligned a much stronger fibre laser oscillation can be observed.

4.3.2 Dynamic behaviour

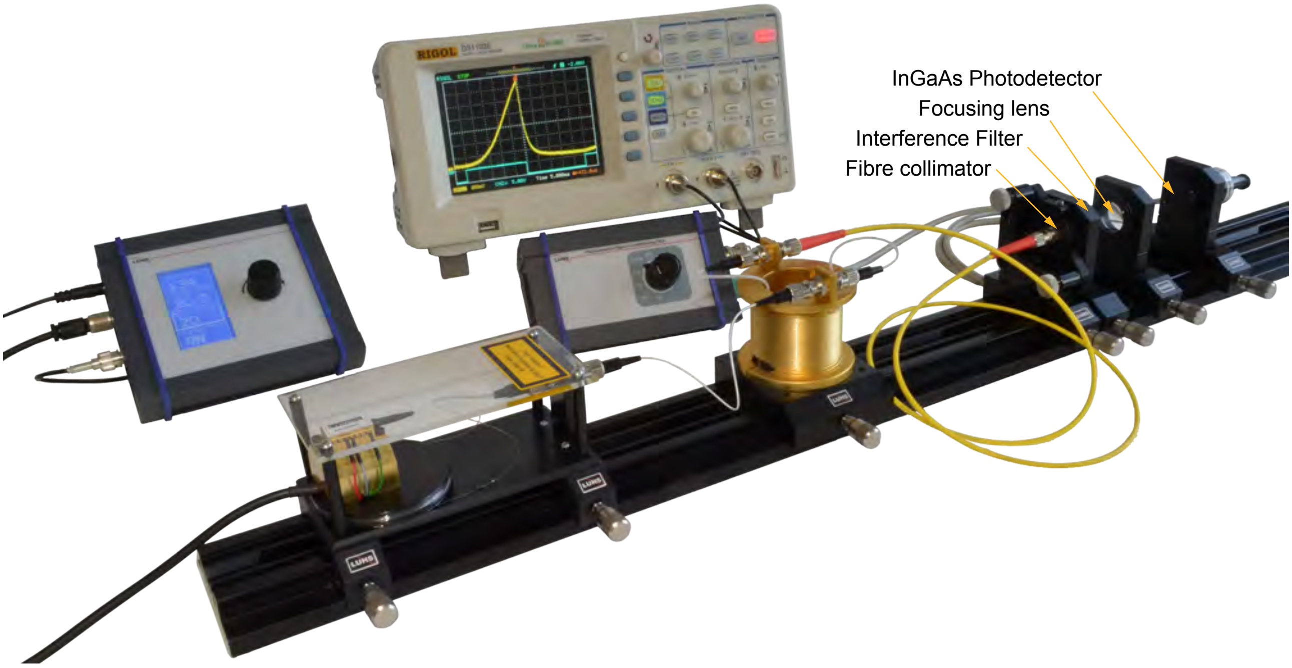


Fig. 57: Linear fibre laser to study the dynamic behaviour

To study the dynamic behaviour of the fibre laser we modulate the pump power and observing the time resolved response of the fibre laser. For this purpose the photodetector is used as shown in the chapter Fig. 57 and the signals displayed on the scope.

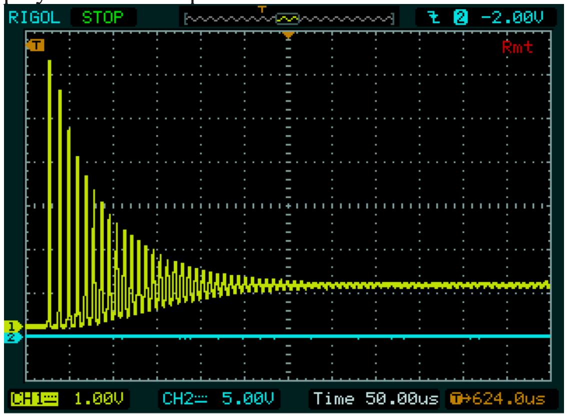


Fig. 58: Spiking when the fibre laser starts

The screen shot of the scope shown in chapter Fig. 58 shows the typical behaviour. The fibre laser response starts with a series of single pulses which amplitude is exponentially decreasing in time and converges a steady power level. The amplitude as well as pulse periodicity depend on the pump power itself.

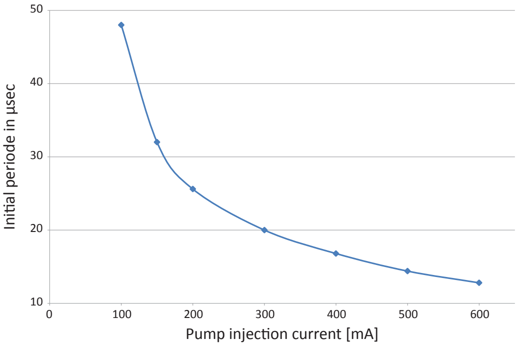


Fig. 59: Pulse period as function of the pump power

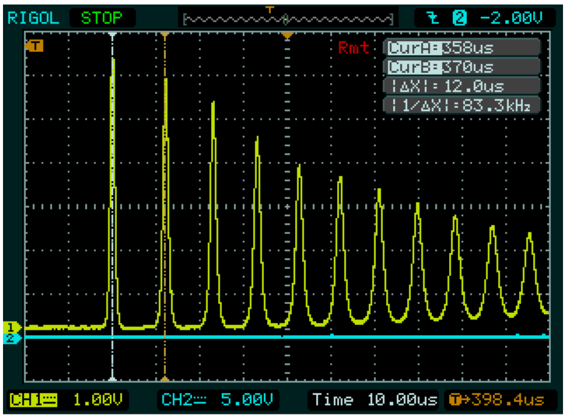


Fig. 60: Spiking at 600 mA injection current

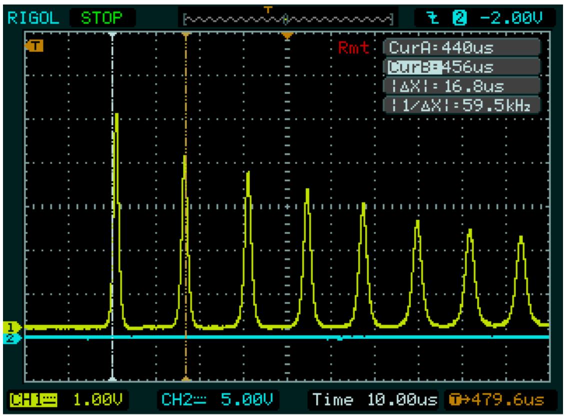


Fig. 61: Spiking at 400 mA injection current

The chapter Fig. 59 shows a sample measurement of the periodicity of the first two spiking pulses as function of the pump power (injection current of the diode laser). The nonlinear function decreases and converges to value which is related to the lifetime of the excited state. By mathematical extrapolation this value can be determined and compared to the results of chapter 4.2.

4.4 Ring fibre laser

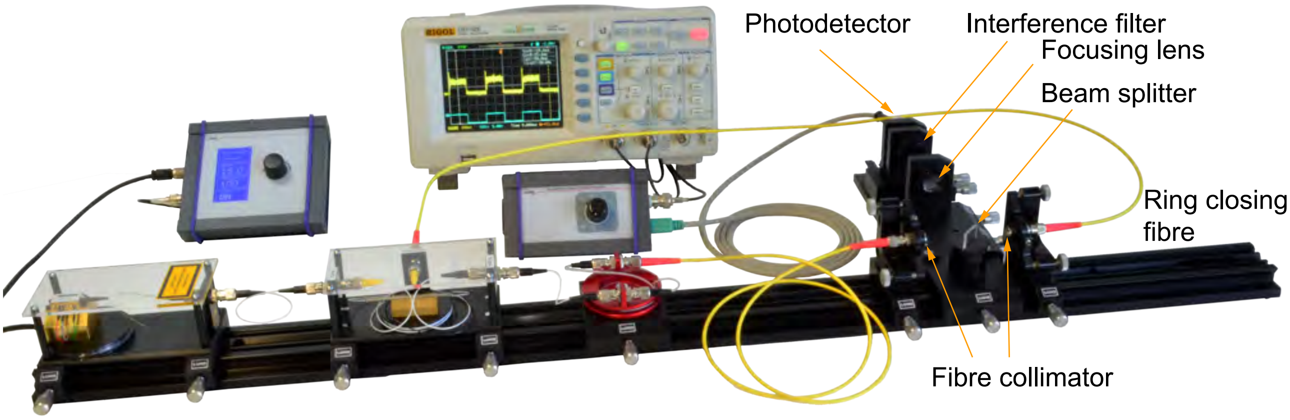


Fig. 62: Setup of the fibre ring laser

To achieve fibre ring laser operation the fibre collimator need to be aligned in such a way that the emerging light from one fibre end enters the opposite fibre without almost no losses. For this purpose we are using the fibre adapter which is set into a mounting plate in front of the SiPIN photodetector.

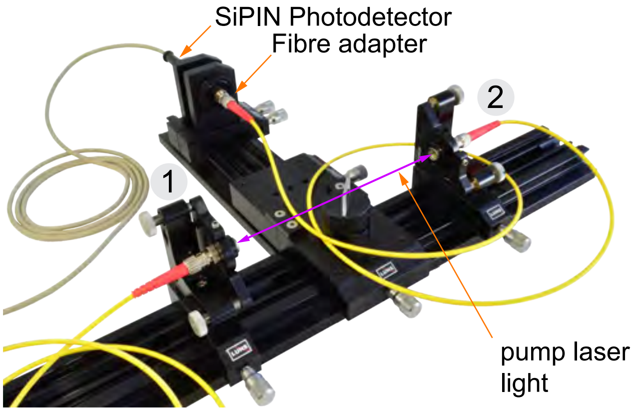


Fig. 63: Alignment of fibre collimators

The pump light which is emerging from the left fibre collimator (1) is adjusted in such a way that it hits the centre of the right (2) fibre collimator. The alignment is done by using an oscilloscope showing the signal of the SiPIN photodetector. Both adjustment holders are aligned for maximum intensity of the transferred pump radiation.

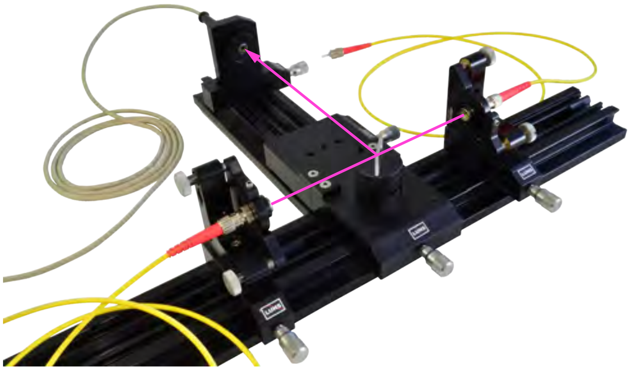


Fig. 64: Setting the beam splitter

Within the next alignment step the beam splitter is slightly rotated for maximum signal on the photodetector.

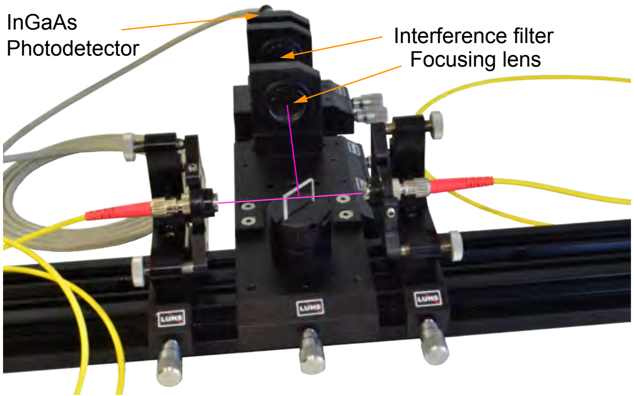


Fig. 65: Inserting the focusing lens and interference filter

Within the next step the focusing lens as well as the interference filter is placed onto the rail. The SiPIN detector is replaced by the InGaAs type to be able to detect laser emission at 1.5 µm.

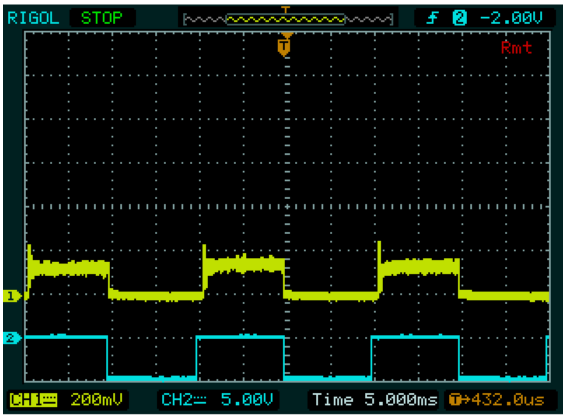


Fig. 66: Laser oscillation of the linear part of the setup

Although the ring is not closed, laser oscillation may occur, however this is due to the linear cavity. In the next step the ring will be closed by connecting the closing patch cable to the WDM.

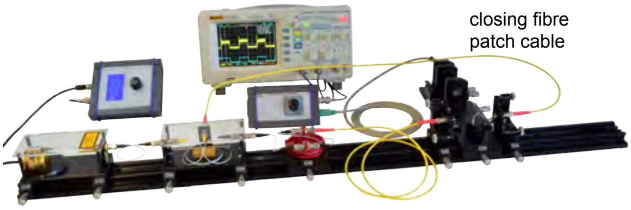


Fig. 67: Closed fibre ring laser

Once the ring is closed and eventually realigned the signal will increase as shown in the chapter Fig. 68.

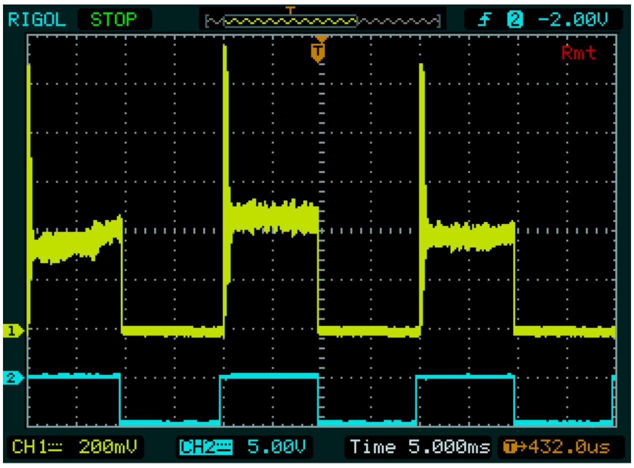


Fig. 68: Increased signal when ring is closed

The ring laser experiments should be carried out with the 1.5 m long Erbium doped fibre. Otherwise oscillation at the end face as linear cavity is dominant.

4.5 Demonstration of resonant two photon excitation

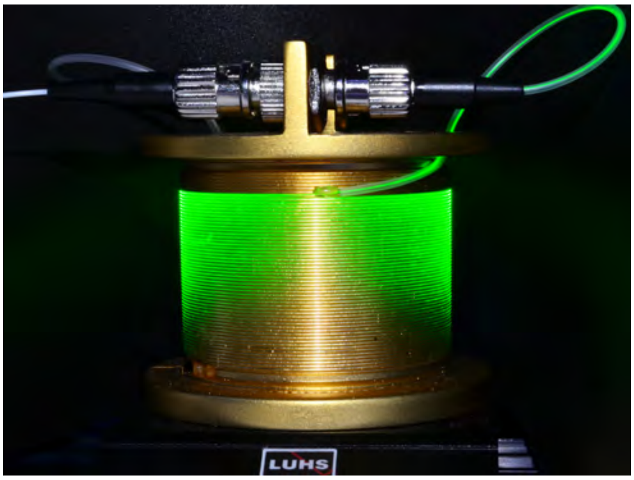
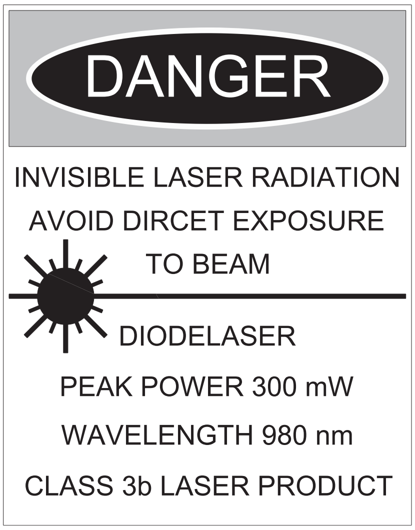


Fig. 69: Green emission at 544 nm due to two photon processes

A very exciting green fluorescence can be observed when the 8 m long Erbium doped fibre is pumped with the maximum available power. This fluorescence shows up very impressive in a darkened room. The origin of this radiation is due to a resonant two photon absorption with a subsequent creation of a “green” photon.

5.0 Laser Safety



DANGER

INVISIBLE LASER RADIATION
AVOID DIRCET EXPOSURE
TO BEAM

DIODELASER
PEAK POWER 300 mW
WAVELENGTH 980 nm
CLASS 3b LASER PRODUCT

The XP-10 contains diode laser which is only suitable for laboratory applications.

With the individual modules in the assembled state, laser radiation (semiconductor laser) can be produced at 980 nm with a maximum power of 300 mW and 5 mW at 1550 nm.

The complete assembled laser is therefore a product which exhibits the power characteristics of a Class 3B laser. Since the XP-10 is a laser system formed from combined modular elements and can therefore be modified in a number of different ways, the operator of this system must ensure that the safety requirements are met.

The manufacturer only provides a guarantee for the individual modules, but does not accept any responsibility for cases of damage which arise due to the combination of the modules. The user must observe the laser safety regulations, e.g. **DIN VDE0837 or IEC 0837**.

In these guidelines of February 1986 the following points are listed for the operation of laser equipment in laboratories and places of work.

Laser equipment in laboratories and places of work

Class 3B laser equipment

Class 3B lasers are potentially hazardous, because a direct beam or a beam reflected by a mirror can enter the unprotected eye (direct viewing into the beam). The following precautions should be made to prevent direct viewing into the beam and to avoid uncontrolled reflections from mirrors:

a.) The laser should only be operated in a supervised laser area.
b.) Special care should be taken to avoid unintentional reflections from mirrors
c.) Where possible the laser beam should terminate on a material which scatters the light diffusely after the beam has passed along its intended path. The colour and reflection properties of the material should enable the beam to be diffused, so keeping the hazards due to reflection as low as possible.
d.) Note: Conditions for safely observing a diffuse reflection of a Class 3B laser which emits in the visible range are : Minimum distance of 13 cm between screen and cornea of the eye and a maximum observation time of 10s. Other observation conditions require comparison of the radiation density of the diffused reflection with the MZB value.
e.) Eye protection is necessary if there is a possibility of either direct or reflected radiation entering the eye or diffuse reflections can be seen which do not fulfil the conditions in c.).
f.) The entrances to supervised laser areas should be identified with the laser warning symbol

MZB means Maximum Permissible Radiation and it is defined in section 13 of DIN/VDE 0837.

Special attention is drawn to point 12.4 of DIN VDE0837:

Laser equipment for demonstration, display and exhibition purposes

Only Class 1 and Class 2 lasers should be used for demonstrations, displays and exhibitions in unsupervised areas. Lasers of a higher class should then only be permitted if the operation of the laser is controlled by an experienced and well trained operator and/or the spectators are protected from radiation exposure values which does not exceed the applicable MZB values.

Each laser system, which is used in schools for training etc. should fulfil all the applicable requirements placed on class 1 and class 2 laser equipment; also, it should not grant persons access to radiation which exceeds the applicable limits in Class 1 or Class 2.

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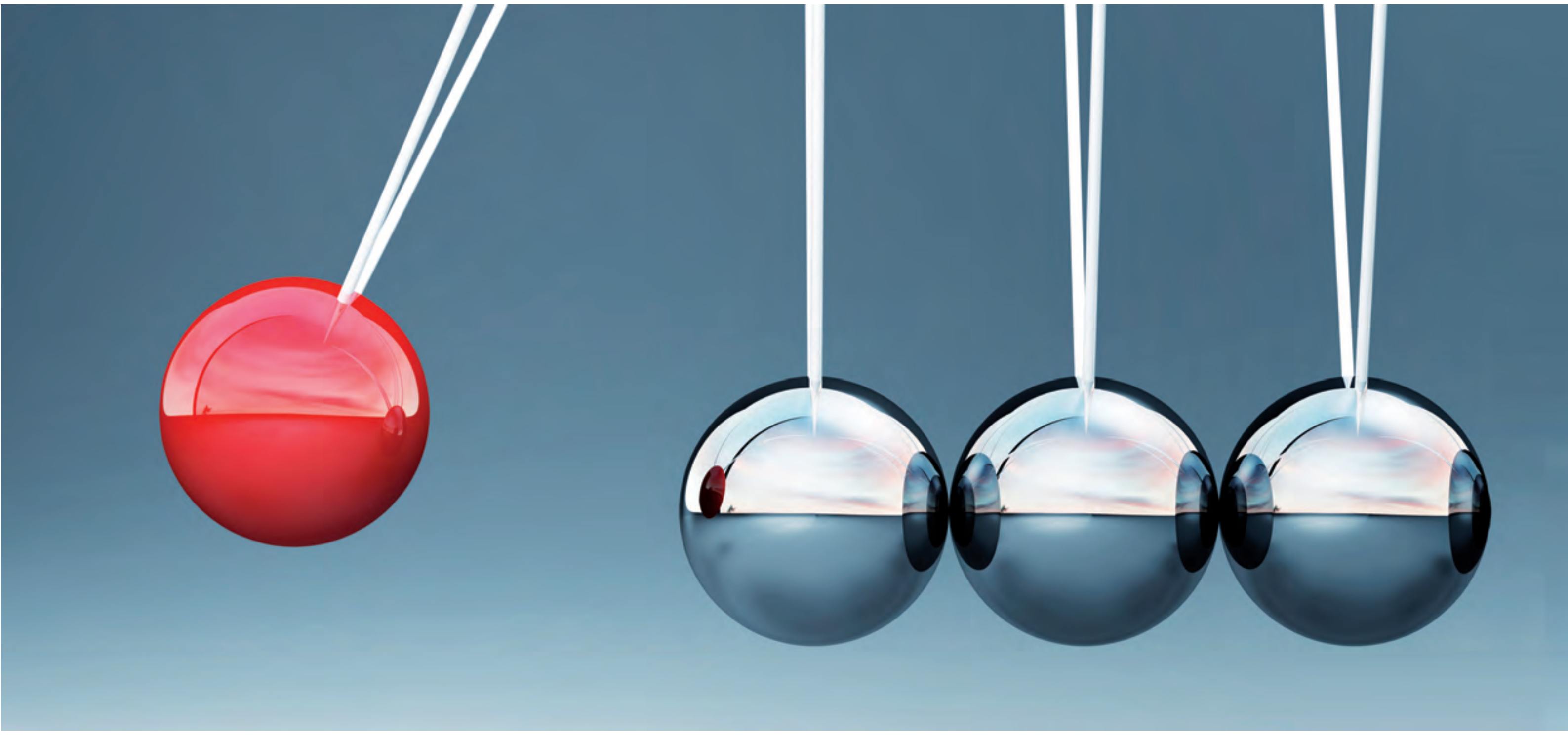

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