Photonik
Ingenieurbüro
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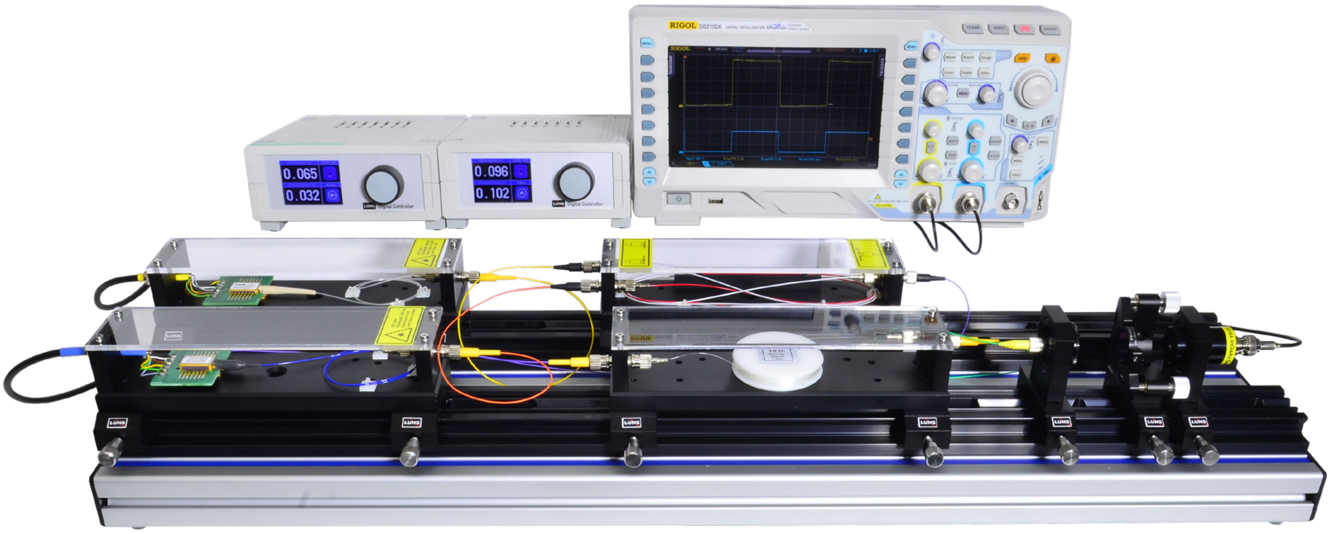
EDFA Fibre Laser and Amplifier



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1.0 Introduction

These days as one reaches out for the phone to call somebody up, one hardly realises the great technological change that has taken place during the past decade in the field of Telecommunications. This is also a characteristic of the epochal change from an industrial society to a communication society.

The globalization of the world markets requires essentially more information on the one hand, for the development and production and on the other, more communication with distant markets. There is also a steady increase in communication requirements even in the private areas due to the possibility of being part of world-wide Data-nets for e.g. the Internet with the help of a simple PC. All this led to a rapid increase in the number of subscribers to the Telecommunication network and that necessitated a markedly bigger transmission bandwidth. The transmission speed had to be likewise drastically increased since the largest part of communication occurred between computers.

The copper cables that were used up to now, however are overtaxed in the face of this challenge. It is true that special cables with the required bandwidths can be produced, but due to the cost involved they are not an economical alternative to the optical waveguides which are replacing copper cables to an increasing degree, so much so that even newly laid down Nets are being equipped with them.

The idea of sending light signals by waveguides and making use of it in Data Transmission was predicted in 1939 by H. Buchholz in his publication “The Quasioptic of Ultrashortwave conductor“. However it was only in the year 1962 with the development of the first semiconductor laser, that the serious technical realisation of Data transmission began, using this laser and glass fibre through which laser light was conducted. Thus, simple sources of light production and modulation, became available.

Today, information transmissions through laser diodes and glass fibres are the order of the day and the developments in this area belong to the most important ones in this century. This technology is based on the already known fundamentals so that no new understanding needs to be imparted. In practice, technically, however it means new challenges.

In the fibres used today, light is conducted within a core diameter of only 5 µm and for that on the one hand the fibre production and on the other, the fine mechanical components which are necessary for the launching of the light and for the installation of the fibres, needs to be developed. Further aims are the reduction in the transmission losses, internal fibre optical amplifiers should further reduce the number of electronic relays; and even laser diodes with smaller bandwidth that increase the transmission speed, to name a few.

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 production of an amplifying medium through optical pumping. The transport of information through electrical conductors results from a temporal change in a flow of electrons. Due to losses in the conductors, it become necessary to insert an amplifier after a specific conductor length in order to increase the electron count again. In Glass Fibres, the information transmission results through the temporal change in a flow of photons, whose count has to be likewise increased after a specific transport length.

Till now, this was done through the conversion of a stream of photons into a stream of electrons with the help of photodiodes with connected electronic amplification and the re-conversion of electrons into photons with laserdiodes. In optical amplifiers, however, this intermediate step is dropped; here the photon count is directly increased.

The theory and practice of optical amplifiers is as old as the laser technique itself, since Laser is nothing else but an optical amplifier that is increased as 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 optical amplification as they are employed for modern Telecommunication. 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 on the one hand as photon sources for information production and on the other as pumping light sources, supplements the technical knowledge.

The dependence of emission of Laserdiodes on the temperature and injection current are constituents of the measurements in the frame-work of the testing method. For the technical application as well as for the measurements within this project, photodiodes are necessary, whose characteristic features will be presented.

The fundamentals of optical wave guides, the launching of light and its transport are the more important constituents of the fundamentals, even more than the subject of the experiments. The application of fibre couplers will be avoided due to didactic reasons and dichroic elements will be used instead.

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 wavelike 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.

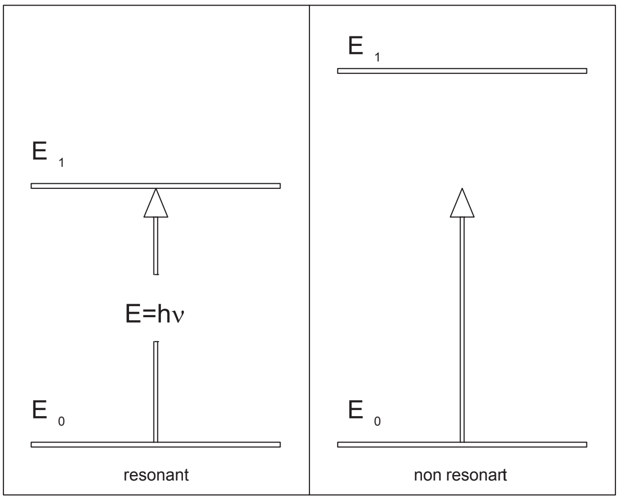


Fig. 1: Incoming light is resonant to a transition of the sample (left) and non-resonant (right) for a material with another transition

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.

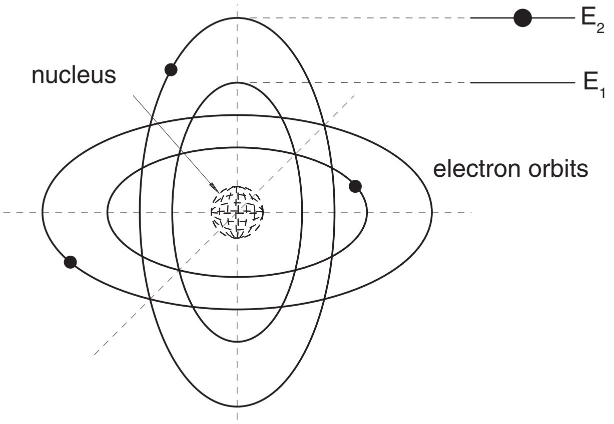


Fig. 2: Bohr's Atom

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(n,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 Fig. 2. 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

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

In this case $u(\nu)$ 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

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

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)

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

or

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

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

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

By substituting (5) in (4) we get

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

Since Planck's law must be valid also in equilibrium we get by comparison of (1.3.33) with (1.4.6) the meaningful Einstein coefficients:

$$B_{12} = B_{21} \text{ und } \frac{A_{21}}{B_{12}} = 8\pi\cdot\frac{h\cdot\nu^3}{c^3} \qquad (7)$$

2.1.1 Natural line width

Let's look on Eq. **(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.

$$\frac{dn_2}{dt} = -A_{21}\cdot n_2 \qquad (8)$$

This differential equation can be solved using the additional equation

$$n_2(t) = C\cdot e^{-\alpha\cdot t} \qquad (9)$$

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

$$n_2(t) = n_2(t=0)\cdot e^{-A_{21}\cdot t} \qquad (10)$$

Fig. 3 this function graphically. 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".

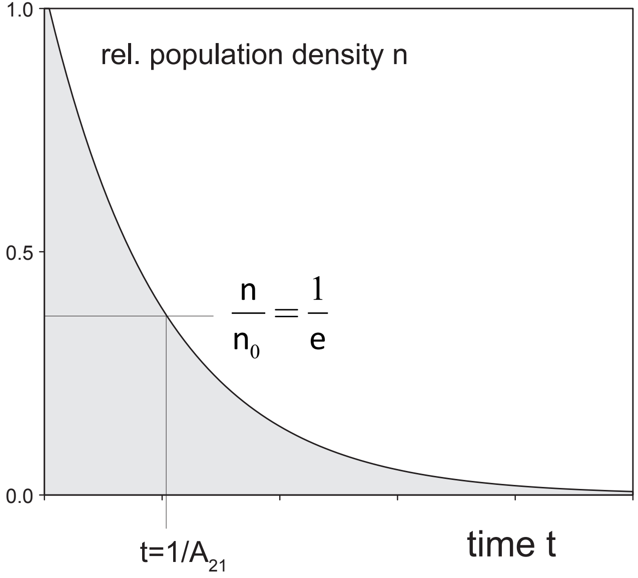


Fig. 3: Population decay curve of a state

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 (Fig. 4). In view of the preceding findings, the frequency of the radiation should be fixed to

$$E_2\text{-}E_1 = h\,\nu_0.$$

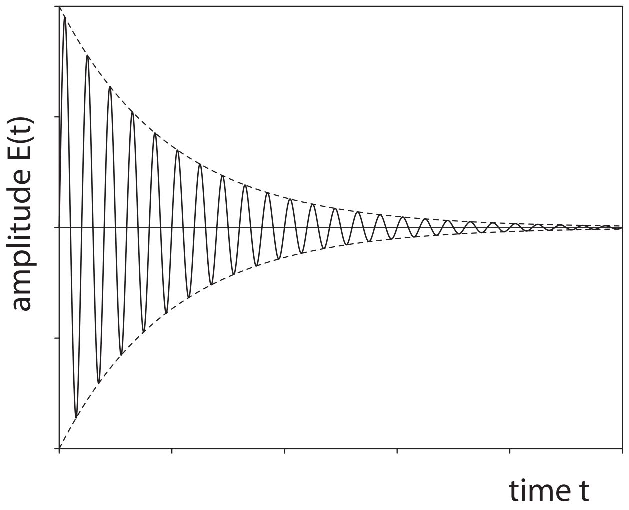


Fig. 4: Spontaneous emission as a damped oscillation

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 Fig. 5.

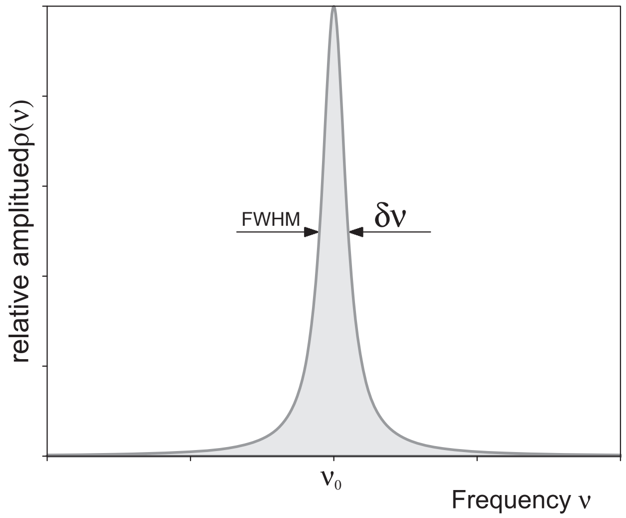


Fig. 5: The Fourier transformation of a damped oscillation as observed for spontaneous emission. It consists of the transition frequency ν_0 and a complete spectrum described by a Lorentz function.

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

$$\rho(\nu) = \frac{1}{4\pi^2 \cdot (\nu - \nu_{21})^2 + (1/2 \cdot \tau_s)^2} \qquad (11)$$

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 Fig. 5 is calculated by inserting the value of $\rho(\nu) = 1/2$. The result is:

$$\delta(\nu)_{nat} = \frac{1}{2\pi} \cdot A_{21} \qquad (12)$$

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 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 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.

2.2 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.

2.3 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.

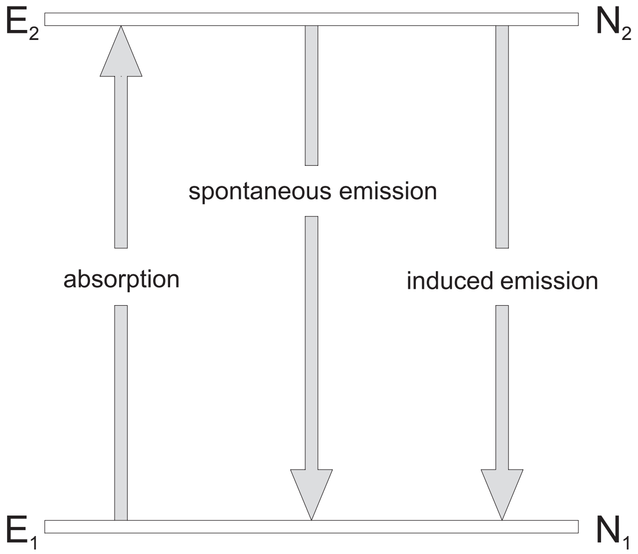


Fig. 7: Two level system

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 $\Delta\nu$. 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 $\Delta\nu$ 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:

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

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

$$\rho(\upsilon) = \rho \cdot h \cdot \nu \cdot \frac{f(\nu)}{\Delta\nu} \qquad (13)$$

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:

$$\left.\frac{dN_2}{dt}\right|_{Absorption} = B_{12} \cdot \rho(\nu) \cdot N_1 \qquad (14)$$

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

$$\left.\frac{dN_2}{dt}\right|_{spontaneous} = -A_{12} \cdot N_2 \qquad (15)$$

$$\left.\frac{dN_2}{dt}\right|_{induced} = -B_{21} \cdot \rho(\nu) \cdot N_2 \qquad (16)$$

The total change in the population of the energy level E$_2$ is therefore::

$$\frac{dN_2}{dt} = B_{12} \cdot \rho(\nu) \cdot (N_1 - N_2) - A_{12} \cdot N_2 \qquad (17)$$

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:

$$\frac{d\rho}{dt} = \frac{dN_1}{dt} - \frac{dN_2}{dt} \qquad (18)$$

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:

$$I = I_0 \cdot e^{-\sigma_{ik}\cdot(N_1-N_2)\cdot x} \qquad (19)$$

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

$$\rho \cdot c = I$$

Amplification then takes place when

$$g = \sigma_{ik}\left(N_2 - N_1\right) = \sigma_{ik} \cdot n > 0 \qquad (20)$$

On comparing the result after (19) 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 (19) 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 (19) instead of absorption, amplification takes place.

2.4 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 produced. In this, N_i is the population density of the excited and N_f the lower lying state.

2.5 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 (Fig. 8).

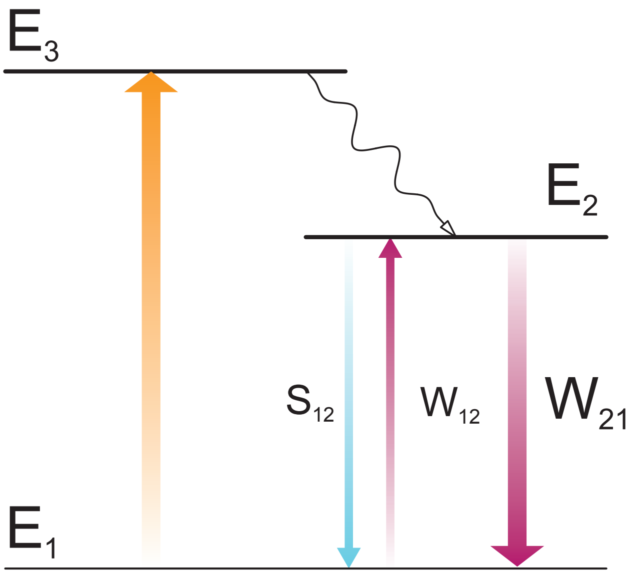


Fig. 8: Three level system

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:

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

photon 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:

$$\frac{dn}{dt} = -2\sigma cpn - \Gamma\left(n_{tot} + n\right) + W_p \cdot \left(n_{tot} - n\right) \qquad (21)$$

and

$$\frac{dp}{dt} = p \cdot \left(\sigma \cdot c \cdot n - \frac{1}{\tau_{ph}} \right) \qquad (22)$$

The equations (21) and (22) 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 (21)we get

$$n = N_2 - N_1 = \frac{n_{tot} \cdot \left(W_p - \Gamma\right)}{W_p + \Gamma + 2\sigma \cdot c \cdot p} \qquad (23)$$

We use eq. (20) for the amplification, and get (23)

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

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.

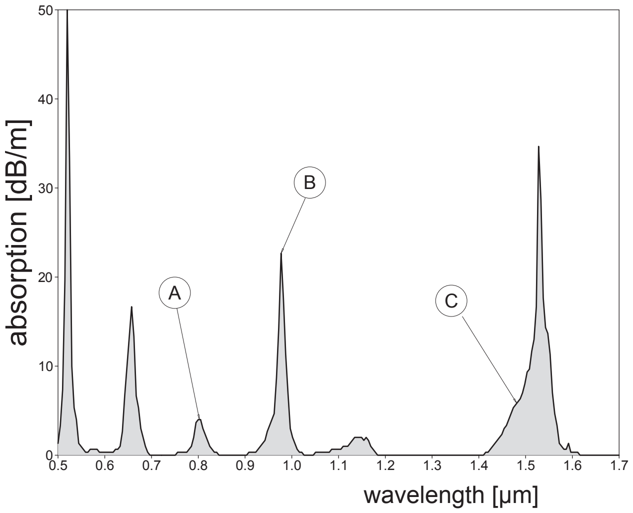


Fig. 9: Absorption spectrum of an Erbium doped fibre, A Pump band for 800 nm, B 980 nm and C 1480 nm

The areas marked in the 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.

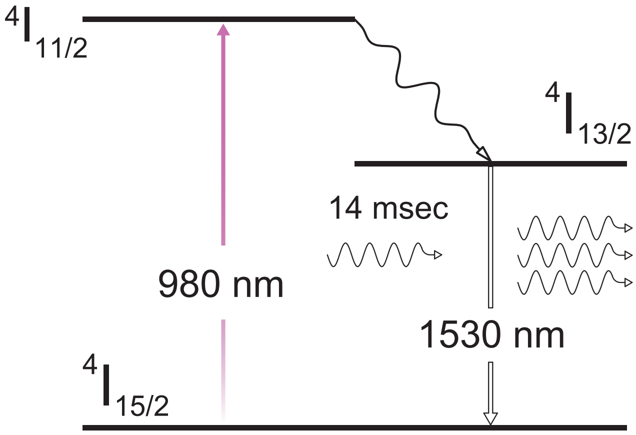


Fig. 10: Three level system of EDFA

In the Fig. 10 we recognise the well known 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 $^4I_{11/2} \rightarrow {}^4I_{31/2}$ 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.

3.0 Experimental set-up

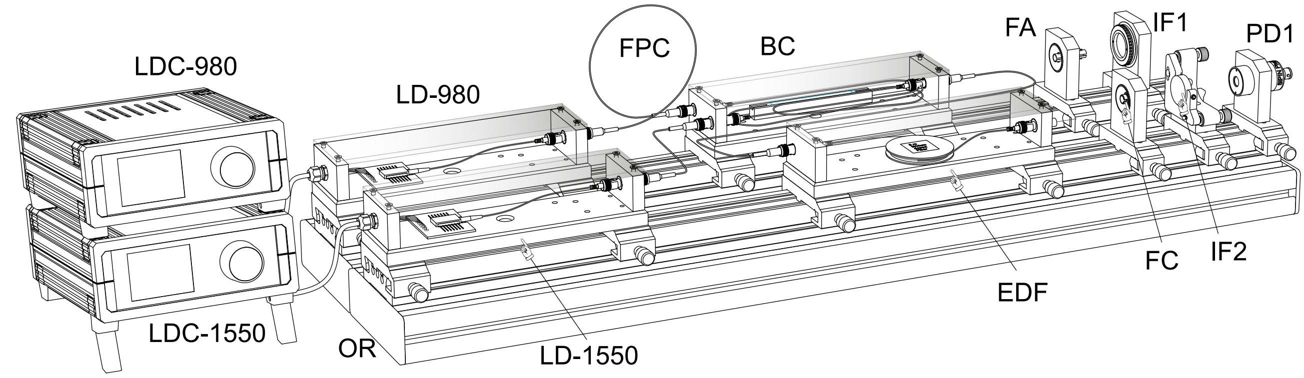
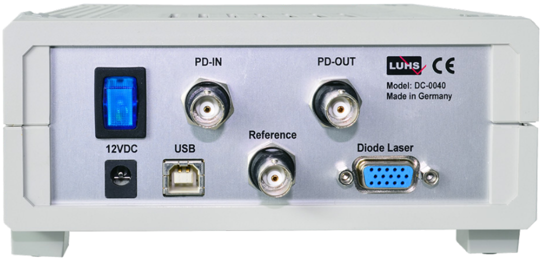


Fig. 11: Experimental set-up

3.1 Description of the modules

3.1.1 Laser Diode Controller (LDC)

The controller is operated by a touch screen and a digital potentiometer with a knob.
The laser diode module is connected via the 15 pin HD SubD jacket (LD). The controller reads the EEPROM of the laser diode and sets the required parameter accordingly. The MK1 is powered by an external 12V/ 1.5 A wall plug supply. A USB bus allows the connection to a computer for remote control. Furthermore, firmware updates can be applied simply by using the same USB bus.
The MK1 provides an internal modulator which allows the periodic switch on and off the diode laser. A buffered synchronisation signal is available via the BNC jacket (MOD). Furthermore, the duty cycle of the modulation signal can be varied in a range of 1...100 % to enable the measurement of thermal sensitivity of the optically pumped laser crystal.
The controller is equipped with industrial highly integrated circuits for the bipolar Peltier cooler (Maxim, MAX 1978) as well as for the injection current and modulation control (iC Haus, iC-HG) of the attached laser diode. Further detailed specifications are given in the following section of the operation software.



The back side of the controller contains the connector for power (12V 1A, a power supply is provided), the Reference modulation signal, the 15 pin HD SubD connector for the laser diode and the In and Out BNC for the photodetector.

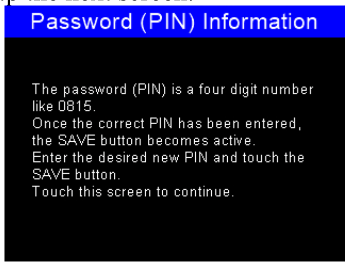
When the external 12 V is applied, the controller starts displaying the screen as shown in the figure below.


LUHS

Digital Controller DC-0048
Touch screen to continue.

The first interactive screen requires the log in to the device since due to laser safety regulations unauthorized operation must be prevented.

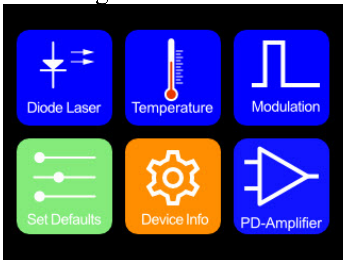
In general, this is accomplished by using a mechanical key switch. However, this microprocessor operated device provides a better protection by requesting the entry of a PIN. After entering the proper PIN, the next screen is displayed, and the system is ready for operation. Touching the “HOW TO?” brings up the next screen.


Password (PIN) Information

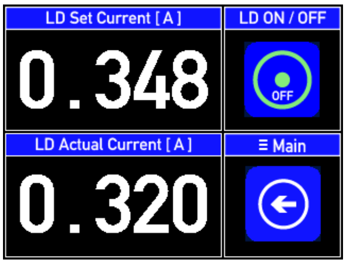
The password (PIN) is a four digit number like 0815.
Once the correct PIN has been entered, the SAVE button becomes active.
Enter the desired new PIN and touch the SAVE button.
Touch this screen to continue.

The appearing text explains how to change the default password.

After the correct password has been entered, the main screen is activated. It shows the buttons for the current settings of the attached diode laser, its temperature and modulation. Furthermore, the photodiode amplifier, the device info, and a Set to Defaults” button. The individual functions are explained in the following.

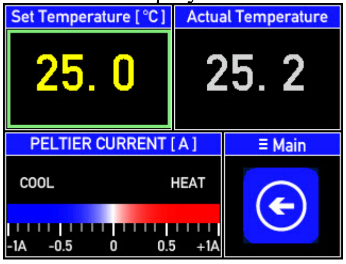


The current settings screen shows the set current as well as the actual current.


LD Set Current [A]: 0.348

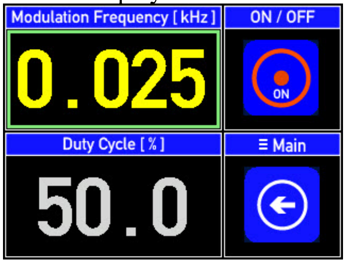
LD Actual Current [A]: 0.320

With the LD ON/OFF touch button the laser is switched on or off. The ≡Main touch button switches back to the main page. By turning the knob, the value of the injection current can be set and is immediately applied, provided the LED ON/OFF touch button is activated. Touching the LED ON/OFF button switches the LED ON or OFF. When switched ON, the actual current is displayed in addition.


Set Temperature [°C]: 25. 0

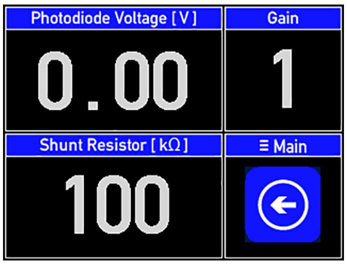
Actual Temperature: 25. 2

“Set Temperature” section. When in operation and connected to the laser diode the actual temperature is shown in the “Actual Temperature °C section. Furthermore, the actual current of the Peltier element is shown in such a way, that cooling, or heating of the element can be observed. By touching the “Set Temperature display field it is highlighted. By turning the knob now, the value of the temperature can be set and is immediately applied. However, it may take some minutes before the stable value is reached. The diode laser module used here has no Peltier element and only the actual temperature is displayed.


Modulation Frequency [kHz]: 0.025

Duty Cycle [%]: 50.0

The LED or laser can be switched periodically on and off. This is for a couple of experiments of interest. By tapping the display of the modulation frequency, the entry is activated. Turning the settings knob will set the desired frequency value. The modulation becomes active when the Modulator ON/OFF button is tapped. For some experiments it is important to keep the thermal load on the optically pumped object as low as possible or to simulate a flash lamp like pumping. For this reason, the duty cycle of the injection current modulation can be changed in a range of 1...100 %. A duty cycle of 50% means that the OFF and ON period has the same length. The set duty cycle is applied instantly to the injection current controller.


Photodiode Voltage [V]: 0.00

Gain: 1

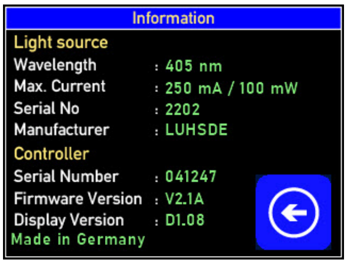
Shunt Resistor [kΩ]: 100

The photodiode page displays the measured photo voltage, the selected shunt resistor and the chosen gain. Tapping the gain display field switches the gain from 1, 2, 4 and 8. Activating the shunt resistor display field lets one set the shunt resistor by turning the digital knob.


Missing Laser Diode or LED

We could not detect a LIGHT SOURCE. Please switch of the controller connect one and restart.

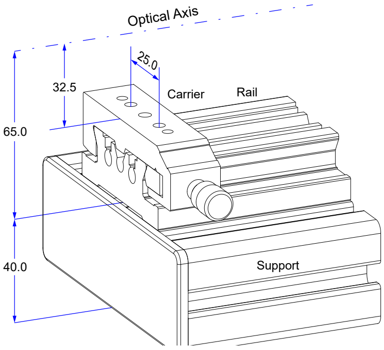
This screen is self-explanatory and appears either when no laser diode is connected or the data reading from the EEPROM is erroneous.


Information

Light source
Wavelength : 405 nm
Max. Current : 250 mA / 100 mW
Serial No : 2202
Manufacturer : LUHSDE
Controller
Serial Number : 041247
Firmware Version : V2.1A
Display Version : D1.08
Made in Germany

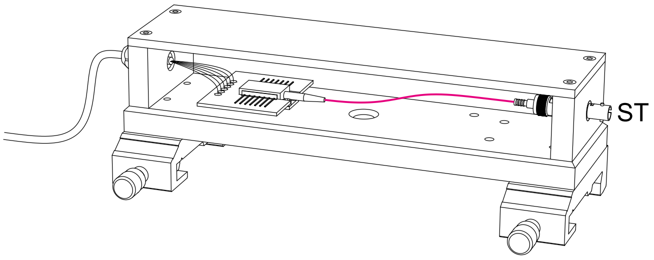
The diode laser module is connected via the 15 pin HD SubD jacket at the rear of the controller. The controller reads the EEPROM of the laser diode and sets the required parameter accordingly. This information and some more information about the controller are shown on the info screen.

3.1.2 Optical rails (OR)



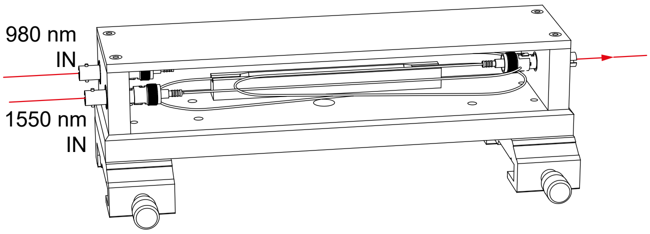
The rail and carrier system provides a high degree of integral structural stiffness and accuracy. Due to this structure, it is a further development optimized for daily laboratory use. The optical height of the optical axis is chosen to be 65/105 mm above the table surface. The optical height of 32.5 mm above the carrier surface is compatible with all other systems like from MEOS, LUHS, MICOS, OWIS and LD Didactic. Consequently, a high degree of system compatibility is achieved. The attached support elevates the working height above the table and significantly improves the handling of the components.

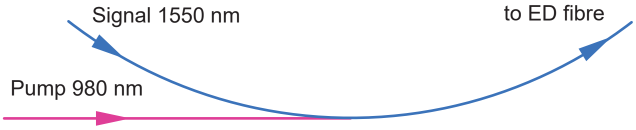
3.1.3 Laser Diode Module



The laser diode module contains a diode laser integrated into a butterfly housing. The laser emission is available via an optical singlemode fibre terminated with a ST fibre connector which is attached to the ST panel jack. The maximum output power at the fibre connector is 350 mW at a wavelength of 980 nm and belongs to the laser class 3B. The module for 1150 nm emits 5 mW and belongs to the laser class 3A.

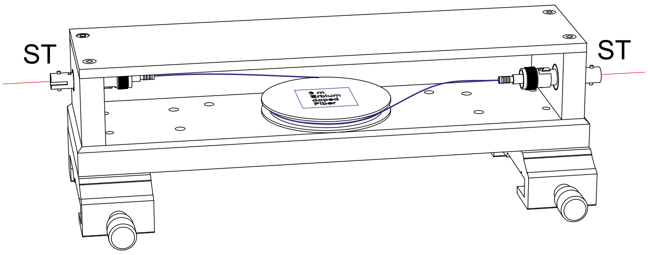
3.1.4 Single Mode Beam Combiner (BC)





Two single mode fibre are merged such that the arrangement has two inputs and one output. This is used to pump the connected Erbium doped fibre and feed the signal at 1550 nm simultaneously into the Erbium dope fibre.

3.1.5 Erbium doped Fibre (EDF)



3.1.6 Single Mode Fibre Patch Cable (FPC)

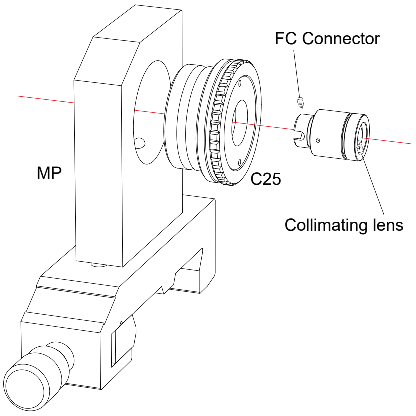
Fig. 12: Single mode fibre patch cable

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. 13: 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.

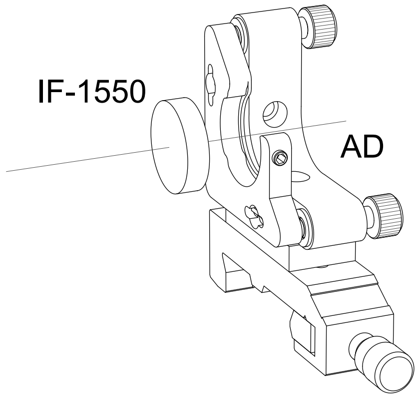
3.1.7 Fibre Collimator FC



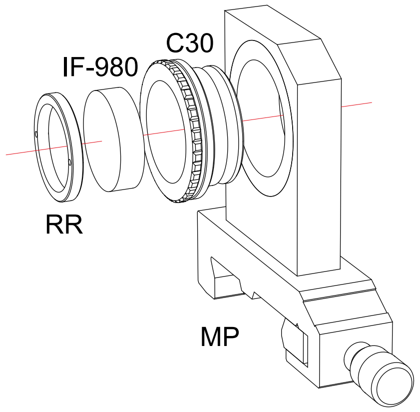
The fibre collimator is used to collimate the divergent radiation emerging from the fibre into a parallel beam. A collimating lens with a short focal length (6 mm) is integrated into a FC fibre receptacle. The collimator is fixed to a click mount (C25) which itself is placed into the mounting plate (MP).

3.1.8 Interference Filter (IF1 and IF2)

Two interference filter are used, one with a centre wavelength of 980 nm (FWHM = 10 ± 2 nm, transmission 50%) and one for 1550 nm (FWHM = 12 ± 2.4 nm, transmission 50%).

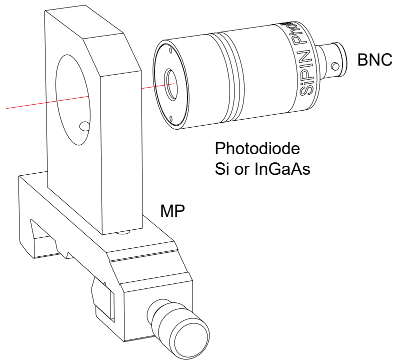


The IF-1550 filter has a diameter of 25.4 mm and is mounted into an adjustment holder (AD) since it will be also used as a back reflecting mirror.



The IF-980 filter also has a diameter of 24.5 mm and is placed and fixed with a retaining ring (RR) into a C30 click mount holder. The C30 mount is placed into a mounting plate (MP) with 30 mm opening.

3.1.9 Si-PIN and InGaAs Photodetector (PD1)



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

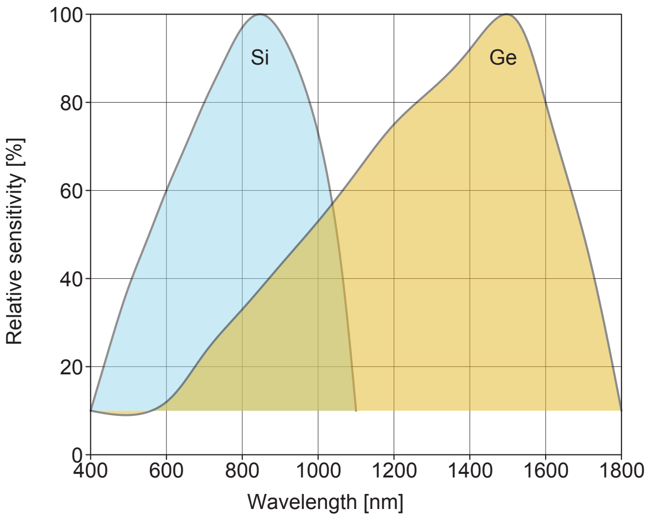
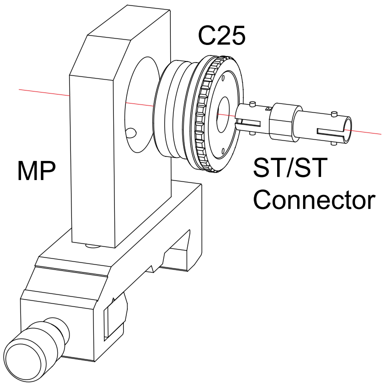


Fig. 14: Relative sensitivity of Si and Ge photodiodes as a function of the wavelength

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 $\tau_r = 2.2 \cdot R_L C_j$ at 10%-90% $R_L = 50\Omega$ 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

3.1.10 ST Fibre Adapter (FA)



This adapter is used to connect a fibre patch cable with ST connector. The ST/ST connector is fixed to a C25 click mount which itself is placed into the mounting plate (MP).

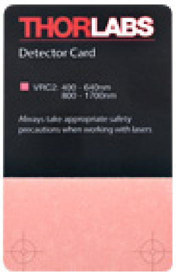


Fig. 15: Accessories for the photodetectors, Thorlab's VRC2

The VRC2 is a credit-card-sized detector card for viewing light in the 400 to 640 nm or the 800 to 1700 nm wavelength range. The lower front surface of this durable plastic card is photosensitive and enables the easy location of visible or near-infrared (NIR) light beams and focal points. Before using the card, it is necessary to charge the active region with visible light. As a consequence of the card needing to be charged to generate emission, during operation the user must move the position of the incident light spot around the active region to maintain the intensity of the excited emission.

To facilitate the use of the card during alignment procedures, the detection region extends all the way to the edge of the card and includes two engraved reticles for use in laser beam collimation.

4.0 Experiments and Measurements

4.1 Characterize the Pump and Signal Laser nm

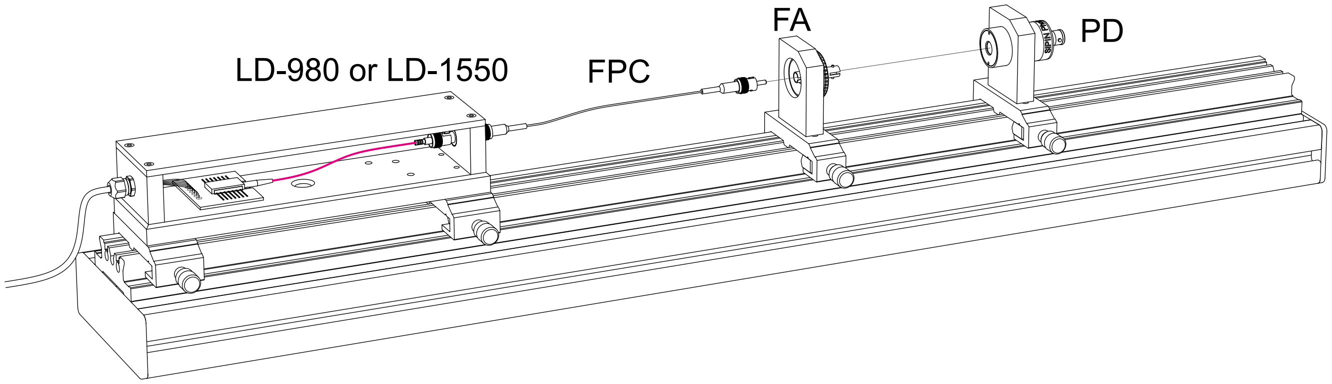


Fig. 16: Setup to characterize the 980 nm or 1550 nm single mode diode laser

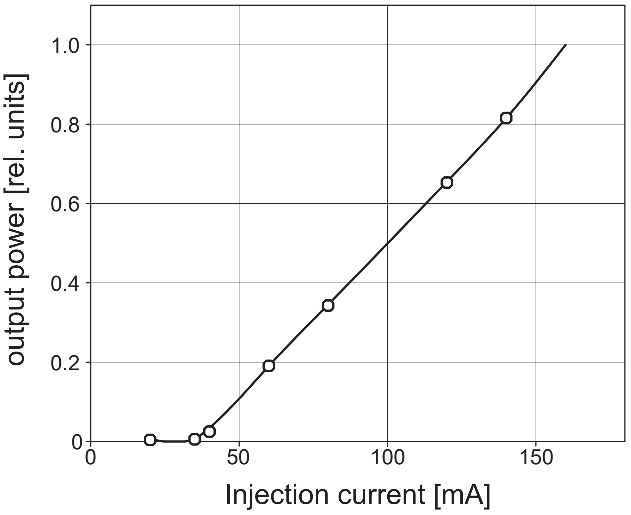


Fig. 17: Sample graph for a measurement of the laser power versus injection current.

The diode laser module 980 or 1550 nm is placed onto the rail. A fibre patch cable connects the module with the fibre adapter (FA). The emerging light hits the photodetector (PD). which is connected via a BNC cable to one of the controller. It must be made sure, that for the maximum diode laser power the photodetector is not saturated or overloaded indicated by a red “OVER” display of the photo voltage.
The measurements will be carried out for the 980 nm and 1550 nm module with the respective photodetectors.
Since each laser is temperature controlled, the curves can also be taken by different temperatures.

4.2 Pumping the Erbium doped Fibre

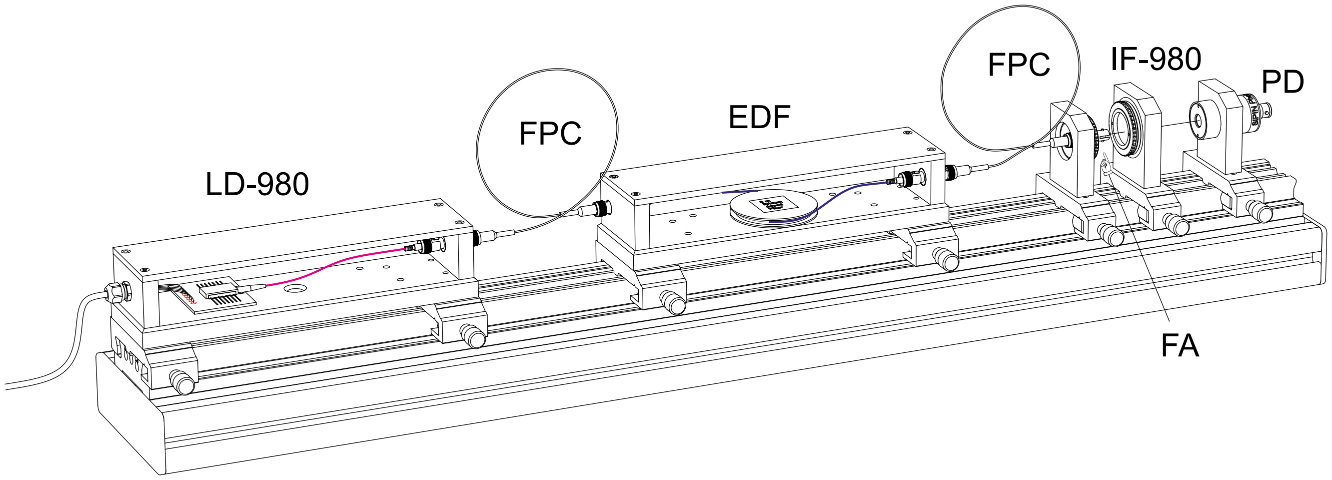


Fig. 18: Setup with an 3 and 16 metre long Erbium doped Fibre

The pump laser module LD-980 and the Erbium doped fiber (EDF) (either the 3 metre or 16 metre long one). The output of the EDF is connected with a fibre patch cable (FPC) to the fibre adapter (FA). To measure only the 980 nm radiation the IF-980 Filter is placed in front of the detector. With this setup the absorption of the 980 nm radiation is measured for different pump powers (injection current). It makes sense to measure the input power to the EDF (has been done in the previous task) and normalize the absorption by this values.

4.3 Measure the lifetime of the excited state.

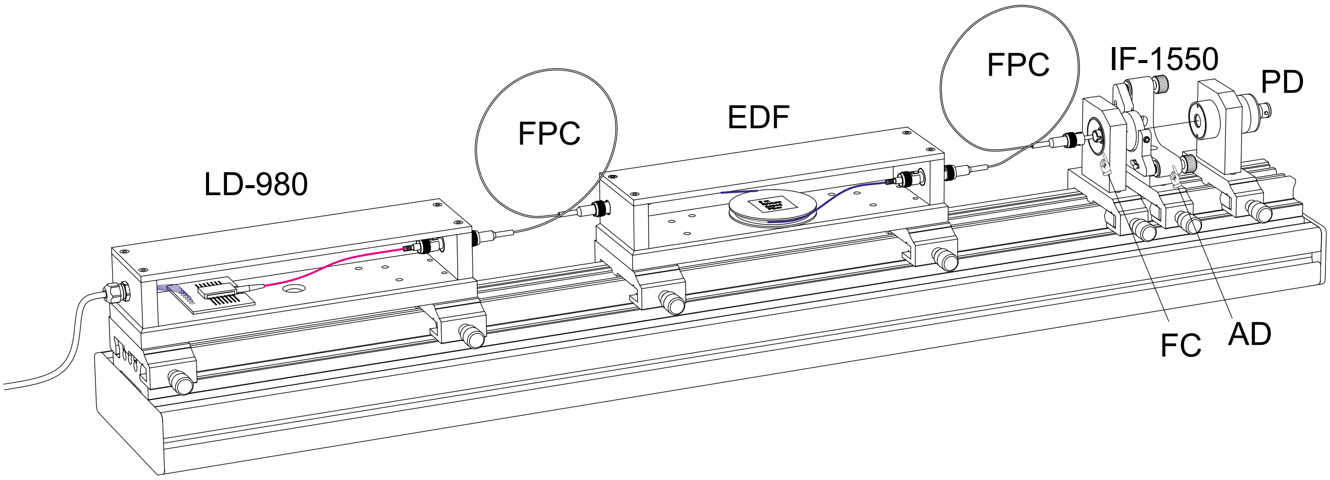


Fig. 19: Setup to measure the fluorescence response at 1550 nm

In this setup, the IF-980 filter is replaced by the IF-1550 and the SiPIN PD detector against the InGaAs one for 1550 nm. It is recommended to start with the 3 m long EDF.
The modulation of the LD-980 is activated with a frequency of about 40 Hz.

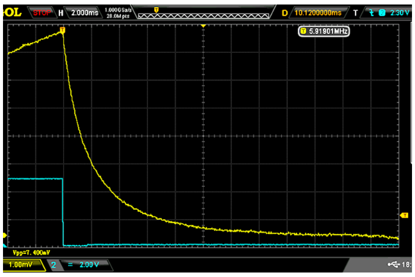


Fig. 20: Fluorescence decay of the 1550 nm radiation

The signal of the photodiode coming from the controller is connected to an oscilloscope (yellow track). The modulation reference signal is connected to the second channel and serves as trigger with falling edge (blue track). The pump power should not too high to prevent amplified spontaneous emission (ASE) or even laser oscillation which will falsify the decay.

4.4 Laser Operation at 1550 nm

We are using the same setup and increasing the pump power.

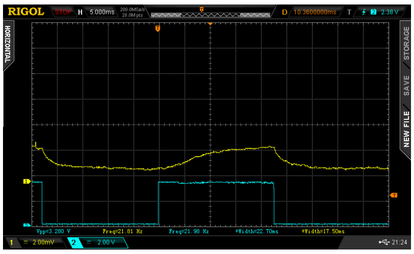


Fig. 21: Operation below the threshold

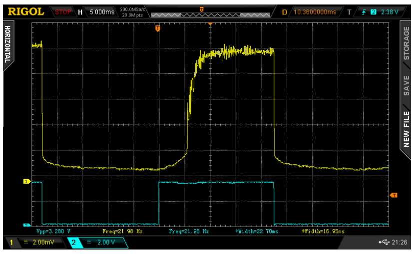


Fig. 22: Operation above the threshold

the output shows the typical spiking of a solid state laser.

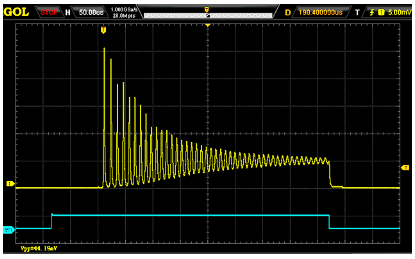


Fig. 23: Spiking of the Fibre laser

After tweaking the pump power and modulation frequency a clear spiking signal can be recorded.

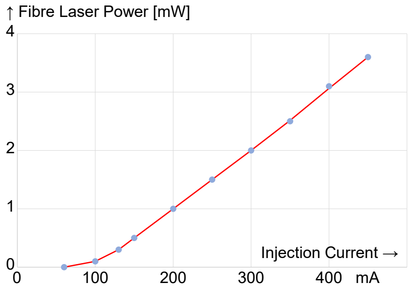


Fig. 24: Example measurement of the fibre laser power versus injection current of the pump laser

If an electronic spectrum analyser is available, the mode spectra of the fibre laser can be recorded.

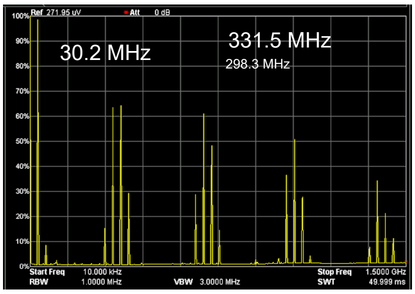


Fig. 25: Example measurement of the beat frequency spectrum

One cavity of the fibre laser used here has a length L of 16 metre. The free spectral range (FSR) is thus c/2L and yields a value of 9.4 MHz only and can be measured with standard analyser easily. The fibre laser with a length of 3 metre has a FSR of 50 MHz.

4.5 Measuring the Gain of the Erbium doped Fibre Amplifier (EDFA)

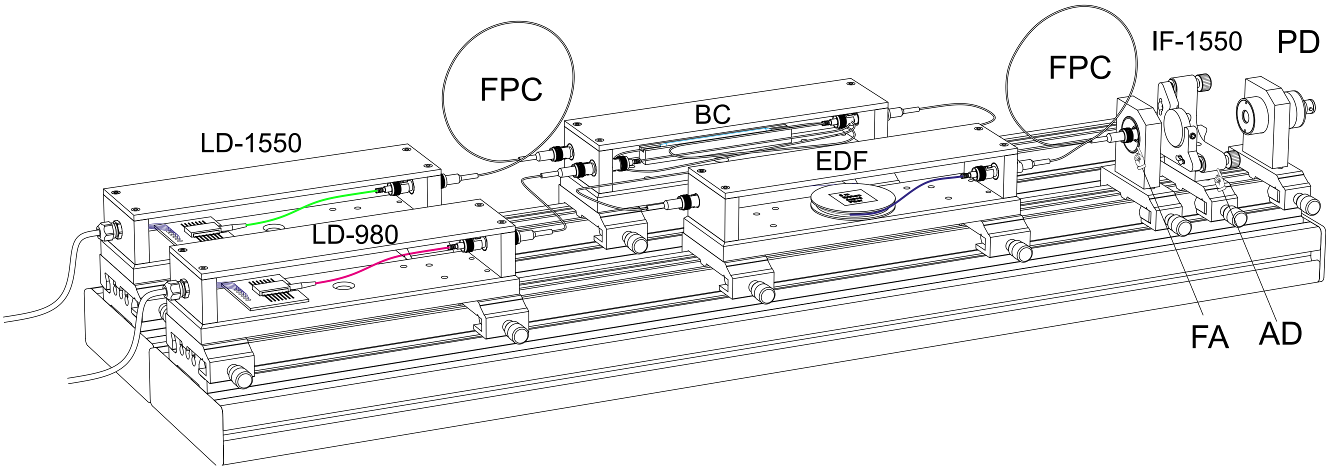


Fig. 26: Setup to measure the gain of the EDFA

The beam combiner (BC) is used to combine both the signal wave generated by LD-1550 and the pump radiation created by the pump module LD-980. The combined radiation is guided into the EDF with a length of either 3 metre or 16 metre.

To measure the gain, the signal radiation at 1550 nm is modulated. The modulation reference is also connected to the oscilloscope and serves as trigger (blue track). The InGaAs photodetector is connected via a BNC cable to the controller and the output signal is connected to the first channel of the oscilloscope (yellow track).

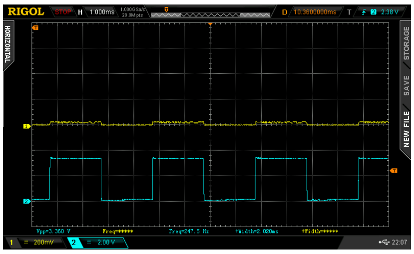


Fig. 27: Signal radiation when the pump laser is switched off

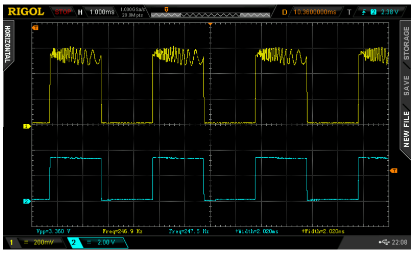


Fig. 28: Signal radiation when the pump laser is switched on

When the pump laser is switched ON the amplitude of the 1550 nm signal increases. Compared to Fig. 27 the amplitude is 18.7 larger or the gain is 12.7 dB (power).

$$V_{dB} = 10 \cdot \log\left(\frac{U}{U_0}\right)$$

Injection current mA 980 nm	Signal strength U at 1550 nm in mV at fibre output for values of injection current of signal Laser of: 15, 20, 30 and 40 mA			
0	0.3	3.0	13	36
32	0.3	3.5	20	60
34	0.3	5.0	28	82
36	0.4	7.0	38	110
38	0.5	10.0	55	160
40	0.6	14.0	82	220
45	1.0	34.0	175	430
50	2.0	76.0	370	840
55	3.5	170	750	1450
60	7.5	360	1300	2300
65	20	700	2000	3200
70	100	1200	2800	4100
72	240	1500	3200	4500
74	400	1800	3600	4900
76	690	2000	4000	
78	900	2300	4400	
80	1050	2500	4600	
82	1200			
84	1600			

Table 1: Measured data, lasing already for higher values of Injection current (example)

The interpretation of the above crude data results in the following figure:

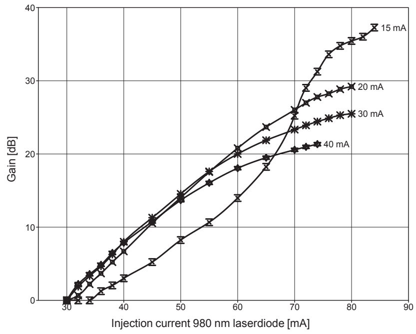


Fig. 29: Gain versus pump power (injection current 980 nm) with signal strength (injection current 1550nm) as parameter

The measurements shown here represent an example. Different values can be determined for other adjustment states of the set up or for other laser diodes.

5.0 Laser Safety

The LE-0320 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 LE-0320 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.