IAP - Lab Course in Modern Physics

Lab Manual

Diode-pumped Nd:YAG laser

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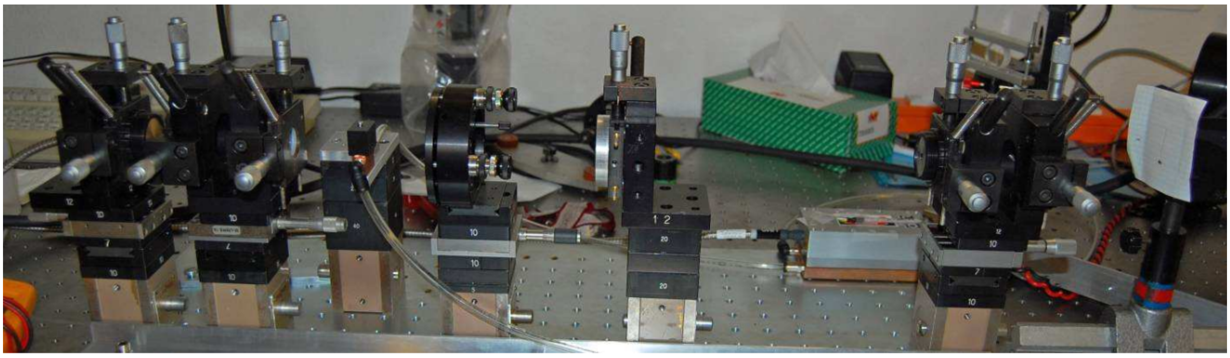
Abstract

In the first part of the experiment, the laser will be set up and adjusted. You practise the handling of modern laser components and learn the basic stability conditions of a laser. In the second part of the experiment, you perform several different experiments by using the laser setup. You will measure the laser efficiency, the lasing threshold, the divergence as well as the thermal lens of the crystal.



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1 Index of the Experiment

This experiment is aimed at practicing the handling of a modern laser and its components.

The following working schedule is recommended:

1. Study the theoretical background of a laser (3-level & 4-level lasers, basic principles of a laser, diode pump-laser, propagation of a gaussian beam, thermal lens, divergence of a laser beam). Additional literature is given in the reference part. Solve the theoretical exercises.

2. Read the safety instructions and memorize it well. Always wear laser safety glasses!

3. The next step is the setup of the laser. Before you build up the laser completely, you already have to do the first measurement! After that, adjust the setup with the He-Ne-laser as good as possible.

4. Put the laser into operation for the first time together with your advisor.

5. Measure the efficiency of the laser with the powermeter and determine the lasing threshold.

6. Measure the divergence of the laser beam for different power and end mirrors.

7. Expand the laser setup to measure the thermal lens.

8. Measure the thermal lens. Please note: This measurement needs to be performed very accurate in order to achieve reasonable results!

9. Perform one of the extra experiments given to you by the advisor.

10. Calculate the efficiency, the divergence and the thermal lens out of your data and compare your results with the theoretical values.

11. Dismount the laser and store it in a professional way.

12. Write your lab report.

2 Safety instructions

2.1 Laser safety glasses

The laser safety glasses have to be worn, when the laser is in operation. In this lab course you're working with laser beams at wavelengths 808 nm (pump laser) and 1064 nm (Nd:YAG), which can't be seen by the human eye. Nevertheless, the radiation can cause serious damage on your eyes, which in the worst case causes blindness. Make certain to wear the laser safety glasses for the correct wavelengths! In addition, you work with a He-Ne-laser, which is used as an adjustment laser. Do not look directly into this laser beam as well. If you have the feeling that your eyes got some laser radiation, immediately visit a eye specialist, preferably at the Inselspital. Your brain will computationally eliminate a possible damage in a few minutes, which will make it impossible for you to notice it anymore. Simultaneously, the damage on your retina will constantly grow.

2.2 Working with a laser

In order to minimize the risks, it is common to limit the laser radiation tightly atop of the laser table. This is the case for the present laser setup. To avoid reflections to other directions, please take off all pieces of jewellery (watches, rings, bracelets etc.). In addition, you should close your eyes when you are in the range of the laser beam (i.e. if you bend down). Be aware, that even if the laser power is small, it is still powerful enough to melt plastic, cause burns and to set things on fire.
The mirrors, the lenses and the laser crystal are easily soiled and touch-sensitive. This means mainly: hands off! You destroy the coatings if you touch the mirrors, lenses or the laser crystal. In addition it is important that the components are clean and dust-free. Check if any of the components is dirty and if this dirt can't be removed by compressed-air, please contact your advisor to clean the component. Don't try to clean it by yourself. The pump laser beam is coupled out by a glass-fiber, which can break easily if you bend it too much.

2.3 Operation of the diode pump-laser

In the experiment, you use a 808 nm diode-laser from Limo to pump the Nd:YAG crystal. Diode-lasers are very sensitive to current peaks or faulty polarization. Already the electrostatic charge of a human has the potential to damage the diode. Never touch the diode-laser without being grounded! Do not connect the laser-diode to the power source by yourself if it is disconnected. Ask your advisor to do it for you! The pump-laser as well as the laser crystal are temperature-sensitive. Don't forget to turn on the water-cooling before turning on the laser.
To turn on/off the diode-laser the following sequence must be strictly adhered to:

Turn on:

1. Turn on the water-cooling.
2. Check if the diode-laser is shortcut (small plug-wire at the bus bar)
3. Turn on the power source with a current of approximately 0.2 A.
4. Remove the shortcut-wire.

Now, you can change the current as you want (but not to 0 A)

Turn off:

1. Set the power source to approximately 0.2 A (not to 0 A).
2. Shorcut the diode-laser with the plug-wire.
3. Turn off the power source.
4. Turn of the water-cooling.

3 Theory

The entire theory is taken from Koechner [1] and Neuenschwander [2].

3.1 Stability of a laser resonator

If an oscillation in a laser resonator will build up without major losses, can be verified by a simple calculation.

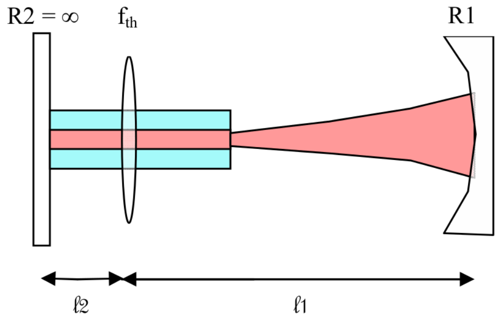

Figure 1: Laser resonator with thermal lens

As the laser used in the experiment forms a thermal lens, the stability criterion looks as follows:

$$0 < g_1 * g_2 < 1 \tag{1}$$

Where g_1 and g_2 are the so called g-parameter of the laser-resonator, which can be calculated as follows:

$$g_1 = 1 - \frac{L'}{R_1} - \frac{\ell_2}{f_{th}} \tag{2}$$

$$g_2 = 1 - \frac{L'}{R_2} - \frac{\ell_1}{f_{th}} \tag{3}$$

The length of the resonator modified by the thermal lens is denoted as L' and can be calculated using the following formula:

$$L' = \ell_1 + \ell_2 - \frac{\ell_1 * \ell_2}{f_{th}} \tag{4}$$

The R_1 denotes the radius of the spherical end mirror, R_2 is the radius of the plane mirror ($R_2 = \infty$) and f_{th} corresponds to the focal length of the thermal lens. The two lengths ℓ_1 and ℓ_2 are specified in figure 3.1.

If the stability criterion (eq. 1) is not fulfilled by the laser setup, the laser won't run or runs with huge losses.

3.2 Beam divergence

The divergence is defined as the angle between the asymptote to the farfield originating at the beam waist.

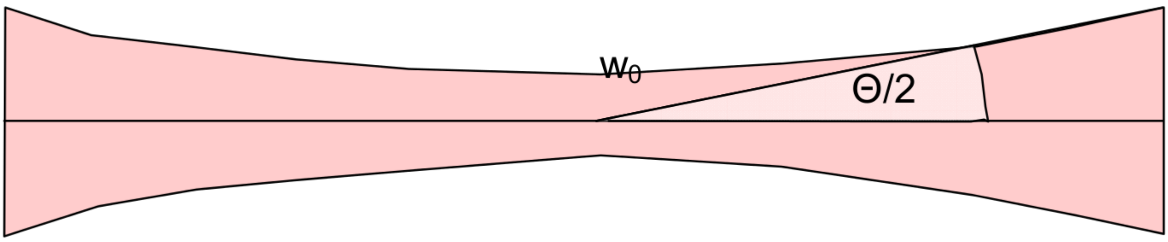

Figure 2: Definition of the divergence

The divergence can be calculated theoretically with the formula:

$$\Theta = \frac{2 * \lambda}{\pi * w_0} \tag{5}$$

Where λ denotes the wavelength of the laser and w_0 the radius of the beam waist. For w_0 one can calculate a theoretical value by using the following formula:

$$w_0 = \sqrt{(\frac{\lambda}{\pi}) * \sqrt{L * (R_1 - L)}} \tag{6}$$

Here L denotes the length of the resonator.

To compare the measured divegence with the theoretical value, the measurement needs to be extrapolated to a point, where no power hits the laser crystal. At this point the thermal lens is zero.

3.3 Thermal lens

In consequence of the temperature distribution in a laser crystal caused by the diode-laser pumping a thermal lens is formed. The thermal lens is a convex lens with a focal length, which can be calculated using the following formula:

$$f_{th} = \frac{\pi * K * w_p^2}{P_h(\frac{dn}{dt}) * (1 - e^{(-\alpha_0 * \ell)})} \tag{7}$$

Here K is the thermal conductivity of the laser crystal (0.13 $\frac{W}{cm \cdot K}$), w_p the radius of the pump beam (100 μm), P_h the fraction of the pumping power converted to heat (approximately 1/3 of the pumping power), $\frac{dn}{dT}$ the change of the refractive index by a change in temperature (7.3*10¯6 W^{-1}), α_0 the linear absorption coefficient of the laser crystal (4.1 cm^{-1}) and finally ℓ is the length of the laser crystal (1 cm).

To calculate the thermal lens from your measurement you need to use the method of Beat Neuenschwander. The derivation of the equation is beyond the scope of this lab course. If you are interested in this derivation have a look on the corresponding paper [2].

$$w_M^2 = \frac{\lambda * L'}{\pi} * \sqrt{\frac{g_2}{g_1 * (1 - g_1 * g_2)}} \tag{8}$$

With your measurements you can determine w_0, which is the radius of the laser beam behind a lens with known focal length. The lens is placed behind the end mirror in a distance of one focal length. Subsequently, the beam diameter is measured in a distance $d_2 = f_3 * (1 + \frac{f_3}{R})$ behind the lens. From this one gets the radius of the beam w_0 and is able to calculate the radius of the beam at the end mirror by using:

$$w_0 = \frac{f_1 * \lambda}{w_M * \pi} \tag{9}$$

Using the equations 2-4 and 8 one can now calculate the focal length of the thermal lens. As equation 8 can't be solved analytically for f_{th}, you need to use a math-software (i.e. Mathematica).

3.4 Theoretical exercises

- Familiarize yourself with the principles of a laser especially with the Nd:YAG solid-state laser, you'll use in the lab course. Have a look on the literature given in the references.
- Prepare a diagram of the g-factors for both end mirrors with variable resonator length. Check if your resonator setup is within the stable region by using the stability criterion (eq. 1).
- Once you've set up the laser and the length of your resonator is determined, calculate theoretical values for the divergence of both end mirrors. Include these values in the diagram of your results and extrapolate your measurement data to zero power to be able to compare measurement and theory.
- Determine the theoretical value of the thermal lens of the Nd:YAG laser for a power range of 0-3 W.

4 The laser: components and setup

4.1 Theoretical setup

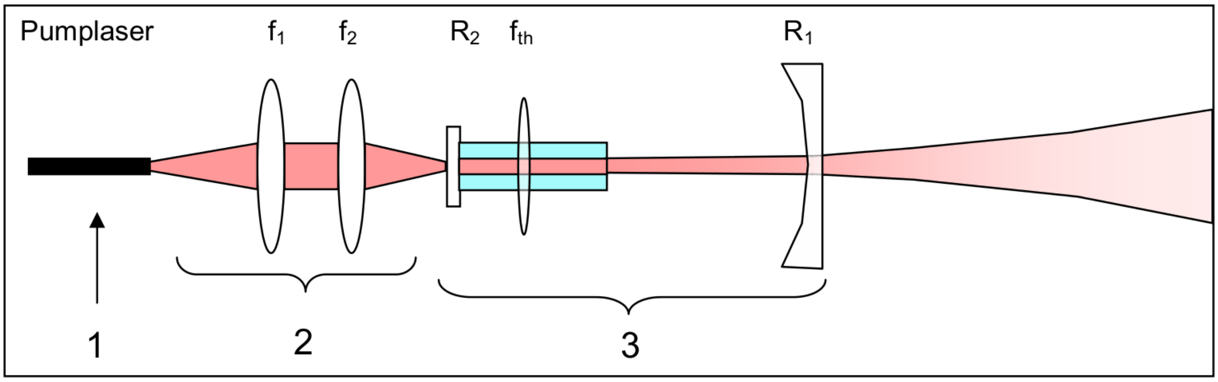

Figure 3: Schematic setup of the laser

1. **Pump laser**
2. **Focusing tower**
   As the pump laser-beam has a large divergence when exiting the outcoupling fiber, it is inevitable to focus the beam into the Nd:YAG crystal by using a 2-lens-system. Here we use a lenses with a focal length f_1=25 mm and f_2=50 mm. The lens with with the smaller focal length is placed closer to the pump laser.
3. **Resonator**
   This is the real laser. In this lab course a crystal and a end mirror holder is provided. In order to act simultaneously as the incoupling mirror and the plane mirror for the resonator, the crystal is coated such that it is AR (anti-reflective) for 808 nm and HR (highly-reflective) for 1064 nm. The other end of the crystal is coated with a AR-Coating at 1064 nm. Two outcoupling mirrors with a reflectivity of 98% are provided (R=750 mm and R=500 mm). These mirrors can be mounted in the lens holder. Ask your advisor to mount them for you. The mirrors are very sensitive and expensive due to their coating. Finger prints and dust need to be avoided.

Every laser is essentially a simple arrangement of lenses, mirror and crystals. The difficulty lies within the adjustment of the components to get a laser.

4.2 Components

A list of needed components:

- Pump-laser with glassfiber
- Tower with fiber-mount
- Tower with focusing lenses
- Crystal mount
- Mount for the end mirror
- Two end mirrors
- Tower with a f=100 mm lens
- Diagnostic tower with a quadratic aperture and a diverging lens
- CCD-camera, screen and filter
- Two paper-screens
- Triangle-bar
- Two towerbases for the triagle-bar
- Powermeter
- Powersource for the pump laser
- Water-cooling for the pump laser and the Nd:YAG crystal
- Optics table with guidebar
- He-Ne-laser
- Screwdriver
- RG 850 Edgepassfilter, Newport

Check if all components exist and identify them.

4.3 Setup and Adjustment

Look for the following components:

- Tower with fiber-mount
- Tower with focusing lenses
- Crystal mount
- Mount for the end mirror
- He-Ne-laser for adjustment

Hint: The following steps for the adjustment are fundamental for the succesful operation of the laser. The laser is very delicate and works only if it is adjusted precisely. Perform the following steps very accurate and fix the components such that they don't move undesiredly. With experience one can set up the laser in about one hour. You probably need more time. Be patient if it doesn't work at the first time.

1. **Before setting up the system**
   The fiber should already be adjusted in the tower. If this isn't the case ask your advisor to mount it. (Ask for his office and his mobile number, you probably need help several times). Ask the advisor to mount the end mirror at the same time.

2. **Fundamentals**
   Check if the guidebar is screwed tightly on the optics table and is oriented parallel to the screw holes. The more reference points you have for setting up the laser, the easier it gets. Now, put the He-Ne laser as far to the right as possible and align it with the guidebar. The He-Ne-laser will be the adjustment aid. Turn it on. Align the laser to be parallel to the guidebar. You can check it with a paper screen. If the He-Ne-laser points a bit up or down this should not be a problem for now. Be aware that the orientation of the He-Ne-laser determines the position of all the other components. A tilted He-Ne-laser beam will cause your laser setup to be tilted as well.

3. **Adjustment of the crystal**
   Next you'll place the laser crystal. As the space on the optics table is limited and each movement of the laser causes a extensive adjustment, you should think in advance how far to the left you can place the laser crystal. On the left hand side of the crystal needs to be space for the fiber-mount and the focusing tower. In addition, the three components need to have a particular distance to each other. This distance is determined by the focal length of the lenses on the focusing tower. Now place the laser crystal in the He-Ne-laser beam. For the exact adjustment use the reflection of the adjustment laser on its own pinhole as well as the point on the crystal mount. The adjustment laser needs to point directly to the crystal and the reflection should point

towards the origin of the He-Ne-laser. Align the crystal mount such that the crystal lies vertically above or below the He-Ne-laser spot. The side of the crystal with the label HR needs to point towards left. Now adjust the height (only the height) of the He-Ne-laser such that it points directly on the crystal. As a next step turn the tower with the crystal such that the reflection of the adjustment laser is vertically below or above its origin. Presumably, this reflection doesn't point exactly to the origin and needs to be adjusted again for its height until it points to the origin. Now the He-Ne-laser should point parallel to the guidebar into the crystal. In addition, the reflection should point exactly to the origin of the He-Ne laser.

4. **Adjustment of the focusing tower**
   Before you place the focusing tower on the optics table and align it with the guidebar, have a look on the micrometer table. It should be in middle position. Afterwards, place the tower such that the right lens has the correct distance to the Nd:YAG crystal. The lenses cause reflections on the crystal mount, which can be used to adjust the focusing tower. First adjust the right lens and therefore put a paper-screen between the two lenses in order to block the reflections of the left lens. Now move the micrometer table/screws such that both reflections point back to the crystal. If this is the case, remove the paper-screen and repeat the adjustment with the left lens.

5. **Adjustment of the fiber**
   Before you set up the fiber for the laser system, you should perform the first measurement for the laser efficiency (see chapter 5.1)

   By using the He-Ne-laser the fiber adjustment is vague. Place the tower with the fiber mount in the correct distance to the focusing tower. It should be located at the left end of the guidebar and the optics table. Check before if the horizontal micrometer table is in the middle position. Then adjust the fiber such that the He-Ne-laser points exactly into the fiber.

6. **Adjustment of the end mirror**
   In the theoretical exercises, you already calculated the distance region, which is beneficial for placing the end mirror. Now you place it. Block the He-Ne-laser after the end mirror with a paper-screen. The end mirror can be adjusted 2-dimensionally by the two screws. The back reflections from the end mirror should point back into the origin of the He-Ne-laser.

Now your laser should look like this:

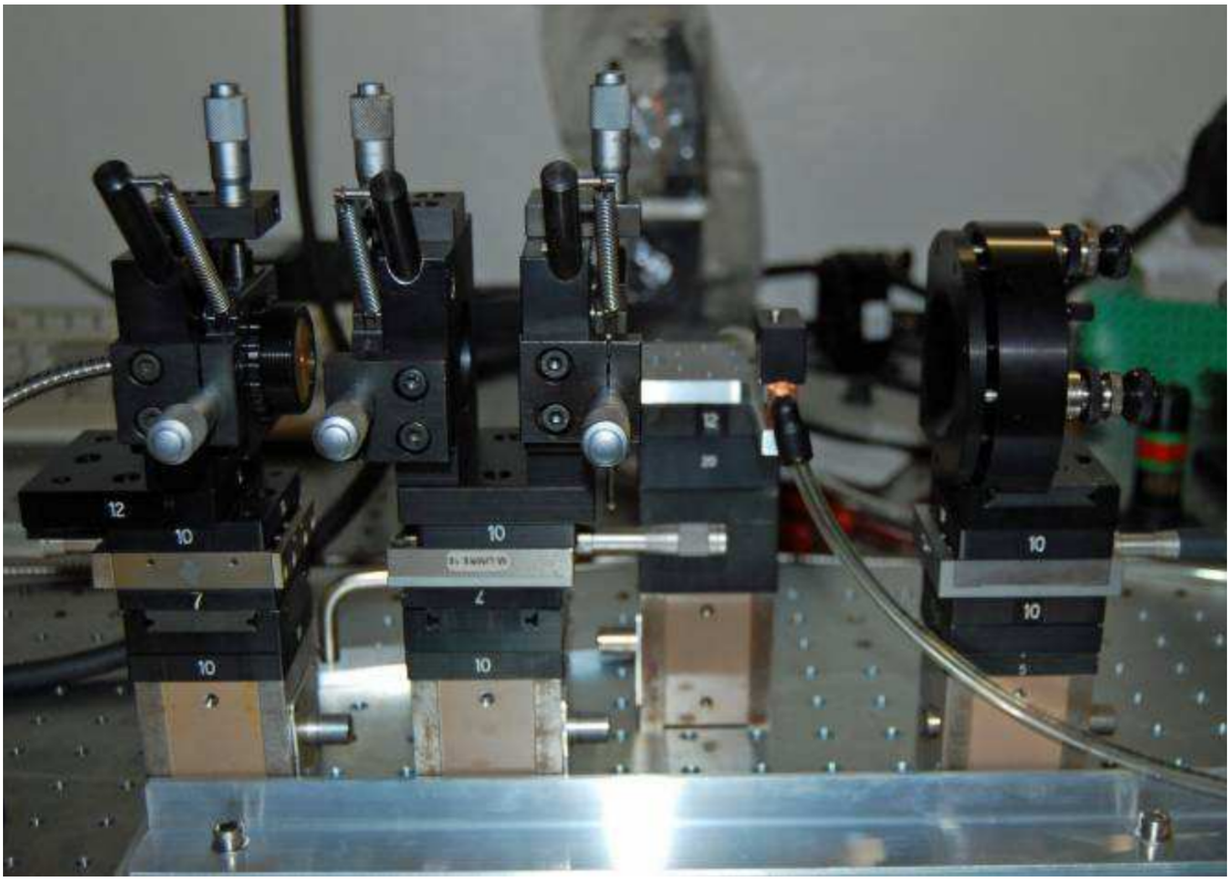

Figure 4: Photo of the laser setup

Now all the requirements are fulfilled and you can bring the laser into service. Ask your advisor for assistance, he will check if your setup is correct. Now the He-Ne-laser should be blocked from the radiation of the Nd:YAG laser, which could possibly damage it. Read again the safety instructions.

4.4 Bringing the laser into service

Before turning on the laser, put on the laser safety glasses!

The easiest way to check if the laser is operating is to observe it with a CCD camera. The laser beam is invisible for our eye. Bring the CCD-camera into service:

The CCD-camera allows you to see the different laser beams. You can use it to observe the pump laser as well as your laser. Be aware that too much radiation damages the camera. There should be no halo otherwise it is overexposed. Always stop down the camera and open the diaphragm slowly until you can see the laser beam. There should be no bright radiation effects. Never put the camera directly into the laser beam, it should always be used to observe the laser indirectly. If you don't need to do precise measurements use a filter.

First you need to place a paper-screen between the Nd:YAG crystal and the end mirror. Then turn on the pump laser as described in section 2.3. Increase the current slowly up to two Ampere. At this current the pump laser should already be clearly visible on the CCD-camera. By adjusting the vertical micrometer table of the focusing lenses the direction of the pump laser can be influenced. Watch the paper-screen. The pump laser should irradiate a circular area as intense as possible, which is an indication that you point straight through the crystal.

After this adjustment, place the paper-screen behind the end mirror and observe it with the camera. Take care that the laser beam is always captured by a paper-screen or a measurement device. The laser starts to oscillate above approximately 5.5 A. To be certain, you increase the current up to approx. 6.75 A. Presumably, your laser is not lasing yet and you only see the big circular illuminated area of the pump laser. You can place the filter in front of the camera in order to filter the pump light out. By carefully adjusting the end mirror you can try to make the laser working. Keep watching the camera screen. If you see a spot of one or two milimeter diameter your laser is running. Congratulation!

It is possible that you won't make it the first time. If you tried for a while, the position of the end mirror is so wrong that you'll never get back to the correct position. In that case, lower the power of the pump laser to 0.5 A and place the paper screen between the crystal and the end mirror. Then use the He-Ne-laser again to adjust the end mirror. Now block the He-Ne-laser again and try to bring the laser to work again.

4.5 Optimization of performance

If your laser is working, you need to do some fine-adjustment. For this, you need to expand your laser setup. Turn off your laser (Don't be afraid, if you don't move any lens or mirror you laser will restart its operation). Remove the He-Ne-laser. If you need it again you can still adjust it by using the crystal. Instead of the adjustment laser you place now the measurement tower with the quadratic aperture and the diverging lens.

The measurement tower

The measurement tower serves as mount for two micrometer tables. On the front one a quadratic aperture to measure the laser beam is mounted. On the back a diverging lens is mounted, which is used to increase the beam diameter and make the measurement easier. In addition, it protects the powermeter from getting damaged.

The quadratic aperture can be removed for the moment (declamp the spring and then it is just hold by magnets and can be removed). Please ensure, that really the diverging lens is in the beam. The power of your laser is enough to damage the mount of the lens (plastic) and in consequence damage the lens.

The powermeter
The powermeter has a relatively large measurement area. It can absorb plenty of power (more power than your laser), as long as most of the area is used. For this reason, the diverging lens is used to irradiate a large area of the powermeter.

Turn on the laser again and check if the laser beam hits the powermeter and irradiates as much area as possible.

Now you can measure the power of your laser. Vary the adjustment of different components starting with the end mirror and move on to the fiber. Try to get the maximum power. Tests with the components you are using showed that one can get approximately 40% of the pump power.

5 Experiments

5.1 Measurement of the efficiency and determination of the laser threshold

For your laser setup, we are not interested in the total efficiency of the laser as we have no influence on the performance of the pump laser. The measurement of the efficiency laser power vs. pump laser power shows nicely the efficiency of the laser resonator. First, measure the power of the pump laser against the current by using the powermeter. Second, you do the same for your laser and use the RG 850 Filter to filter out the pump laser. Consider a 4% loss at each glass surface in your system. Simultaneously, you can measure the laser treshold. Decrease the laser power slowly to zero and record the curve. Interpolate the data to get the intersection with the axis.

5.2 Measurement of the divergence

To measure the divergence (for different power) of your laser you extend your measurement tower by adding again the quadratic aperture (side length: 5 mm). Subsequently, you measure the diameter of the laser beam at two different distances to the end mirror by using the quadratic aperture. The precision improves with increasing distance to the end mirror and by maximizing the distance between the two measurement points. As the space on the optics table is not enough your going to use the triangle-bar. For this reason you need to modify the measurement tower. The measurement should be performed as follows: The laser beam hits first the quadratic aperture, which is moved up and down to measure the diameter at each distance and power. The values you can read from the micrometer screw. From the two values one can calculate the diameter and by doing the measurement at two positions you get the divergence. After the aperture, the laser hits the diverging lens, which is used to increase the laser beam. Then the beam is projected on a paper-screen, which you observe by using the CCD-camera. Ensure the diaphragm is fully opened. Measure the divergence at different power for both of the end mirrors.

5.3 Measurement of the thermal lens

To measure the thermal lens a quite simple method has been developed by Beat Neuenschwander. To perform the measurement, the setup needs to be extended again. Behind the end mirror you place a lens with f_3=100 mm in a distance of 100 mm. Afterwards, you measure the beam diameter at the distance $d_2 = f_3(1 + \frac{f_3}{R_1}$. By using the equations 8 and 9 one can calculate the thermal lens.

For this part of the experiment you don't need to do a error calculation as the error will be much larger than the focal length of the thermal lens. However, the measurement should confirm the theoretical values quite well.

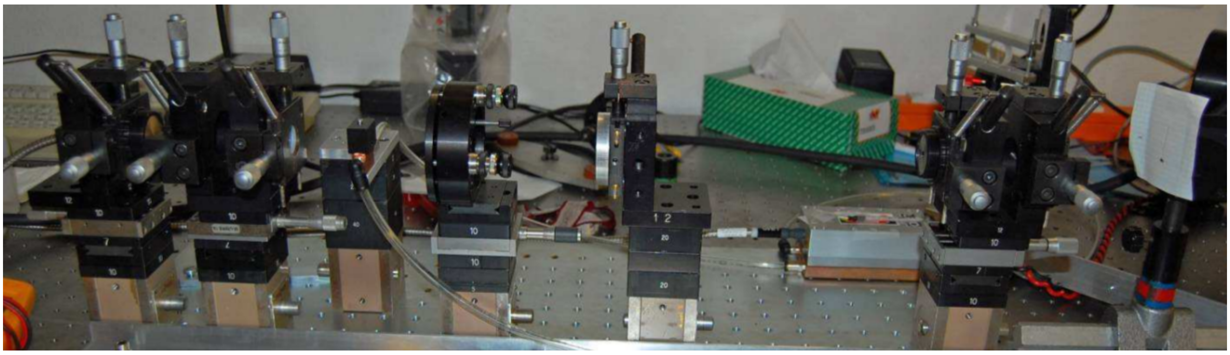

Figure 5: Setup to measure the thermal lens

A Transmission curve RG 850 filter Newport

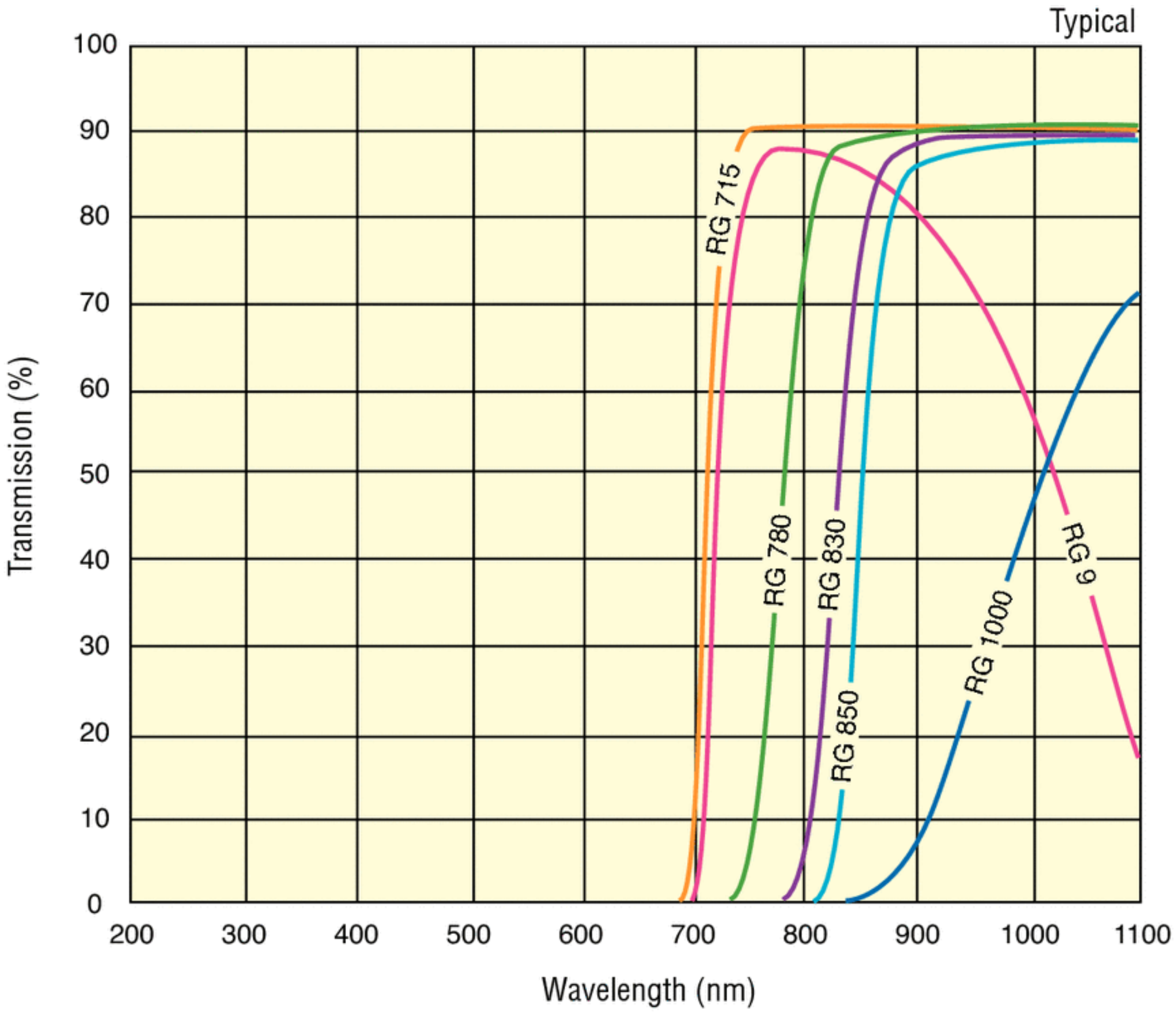

Figure 6: Transmission curves RG-filter

References

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[5] Thomas Feurer: Experimentelle Optik, Skript Unibe SS07 (chapter 4 to 4.1.3: Ausbreitung lokalisierter Wellenpakete)

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