Experimental Physics

Experiment C & D:

Pulsed Laser & Dye Laser

Course: FY12

Project: The Pulsed Laser

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Introduction:

In this experiment we are going to work with Nd:YAG pulsed lasers. We are going to divide this report to small parts as follows:

Part 1) Radiation measurements by Nd:YAG laser

Part 2) Using the Second Harmonic Generator, SHG

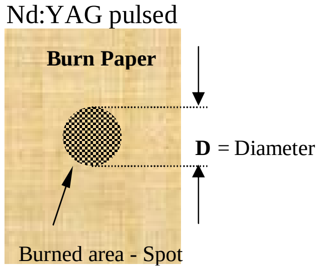
Part 3) Dye Laser

Part 4) Tunable dye laser & Grazing Incident grating

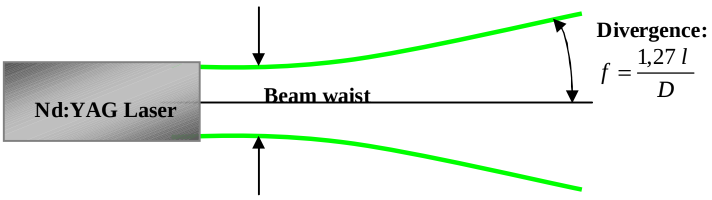
Part 1) Radiation measurements by Nd:YAG laser

What kind of laser are we using in this experiment? In this experiment we use Nd:YAG pulsed laser with a wavelength λ=1064 nm - IR range. By using a burn paper we measure the transverse structure of the beam of the Nd:YAG pulsed laser. That means we can see the cross section shape of it on this special kind of paper. In other words we can measure directly the diameter at the beam waist of the laser beam by measuring the spot size of he burned area of the paper.

After measuring the diameter, D, and focal length, f, we got the following data: D=3,0 mm and f=50,0 mm. The best possible divergence of the beam can be found as follows:



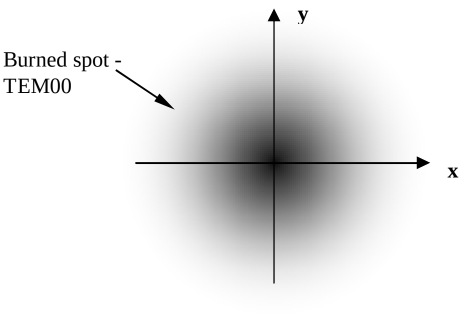
Figur 1 Burned Spot.



Figur 2 The divergence of the laser beam.

$$f = \frac{1{,}27\, l}{D} = \frac{1{,}27 \cdot 1064 \cdot 10^{-9}}{3{,}0 \cdot 10^{3}} = 450.10^{-6}\, rad$$

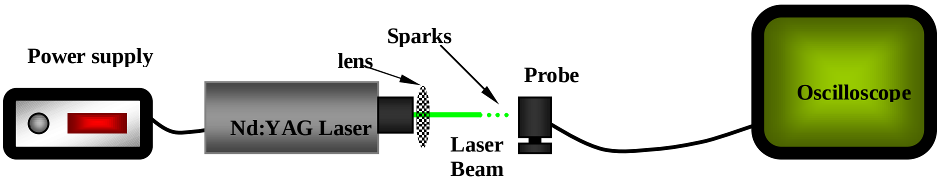
This transverse mode is a TEM_{00} which means that if we plot our spot in a x,y- coordinate system, will the centre of the spot be at coordinates (x,y) = (0,0). At this coordinate we have the maximum burned area of the spot – where the laser beam has the maximum intensity.



Figur 3 TEM_{00}

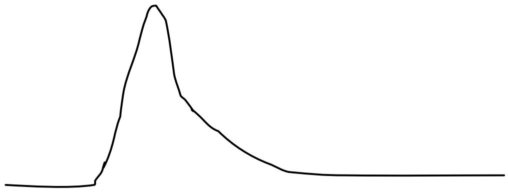
The next step in the experiment was to ionise the air by focussing the laser beam with a lens. This could be observed as sparks in the focus point of the lens. But what is the electric field needed to ionise the air? To know that we observed ionisation by observing the sparks in air, so we could measure the intensity of the laser beam. The intensity is proportional to the energy in the laser pulse. Therefore we measured the energy by using a probe (detector), which was connected to an oscilloscope. We increased the intensity of the laser until we could observe some sparks. From the oscilloscope we could measure the converted energy to voltage with a factor 8,0 V/J. The measured voltage was 0,4 V. From this, the energy will be:

$$E = \frac{V}{8,0} = \frac{0,4}{8,0} = 50mJ$$



Figur 4 Energy measurement.

The pulse width is found by using the speed of light, the length of the path of the light and the number of passes made, the time was given to be about 10ns. Depletion of inversion in active media required is about 3 passes of light in the resonator.



Pulse Shape

The output power can be calculated as follows:

$$P = \frac{E}{\Delta t} = \frac{50x10^{-3}}{10 \cdot 10^{-9}} = 5MW$$

Where Δt is the pulse duration.

The intensity can now be found as follows:

$$I = \frac{P}{A} \Rightarrow \frac{P}{(p\ /\ 4)d^2}$$

Where A is the area of the laser beam from the aperture and d is the diameter of the focussed beam. So to calculate the intensity we first need to calculate d, which gives the following:

$$d = ff = \frac{1{,}27\, fl}{D} = \frac{1{,}27 \cdot 5 \cdot 10^{-2} \cdot 1064 \cdot 10^{-9}}{4{,}0 \cdot 10^{-3}} = 16.891x10^{-6}\, m$$

Where D and f are the diameter and focal length, which we measured in the beginning of the experiment.

Now it is possible to calculate the intensity:

$$I = \frac{P}{(d\ /\ 2)^2 p} = 22.313x10^{15}\ \mathrm{W/m}^2$$

Our goal was to calculate the electric field which can be done as follows:

$$I = \frac{c \cdot e_0}{2} \cdot E^2$$

$$\Downarrow$$

$$E = \sqrt{\frac{2 \cdot I}{c \cdot e_0}}$$

$$\Downarrow$$

$$E = \sqrt{\frac{22.313x10^{15}}{3{,}0 \cdot 10^8 \cdot 8{,}85 \cdot 10^{-12}}} = 2.899x10^9 \,\mathrm{V/m}$$

Conclusion:

To ionise the air the alternating electric field strength must reach a certain value. In our case the electric field must reach the above value to make it possible to get sparks when the electric field is discharged – the air is then ionised.

Part 2) Using the Second Harmonic Generator, SHG

In this part of the experiment we use a KDP crystal to get a second harmonic generation. With a wavelength λ = 1064 nm the crystal produces a wavelength of 532nm. One of our goals here was to calculate the divergence of the radiation. This result is later used in making comparisons of the half width angles.

By using a lens to focus the laser beam, we measured the spot size of the beam so we could calculate the divergence of the radiation. The problem is that, due to diffraction the light can not be focused to a single point. But a spot size from the beam that depends on the divergence makes it possible to find out how much the divergence is. We used a lens with a refraction index, n_{lens} = 1,46, and a radius curvature, R_0= 1,0 m, at one surface and, $R_\infty = \infty$ m, at the other surface. We assume that the surrounding medium has the refraction index, n_0 = 1,0, because the laser is propagating in air. That gives the following focal length, f, of the lens:

$$\frac{1}{f} = \frac{n_{lens} - n_0}{n_0} \cdot \left(\frac{1}{R_0} - \frac{1}{R_\infty} \right)$$
$$\Downarrow$$
$$f = \left(\frac{n_{lens} - n_0}{n_0} \left(\frac{1}{R_0} - \frac{1}{R_\infty} \right) \right)^{-1}$$
$$\Downarrow$$
$$f = \left(\frac{1{,}46 - 1{,}0}{1{,}0} \left(\frac{1}{1{,}0} - \frac{1}{\infty} \right) \right)^{-1} = 2{,}2 \ \text{[m]}$$

We placed a burn paper in the laser beam at the focal point. The diameter of the spot was measured and found to be 0.9mm at the beam waist. Now it is possible to calculate the divergence with the measured diameter as follows:

$$d = ff \Rightarrow f = \frac{d}{f} = \frac{0{,}9 \cdot 10^{-3}}{2{,}2} = 4{,}09x10^{-4} \ [rad]$$

Let us compare with the optimum divergence angle of a diffraction spot. The wavelength of the second harmonic of the Nd:YAG laser in this experiment is λ=530 nm. The diameter of the aperture we were using was D=3,0 mm. The divergence in this case will be:

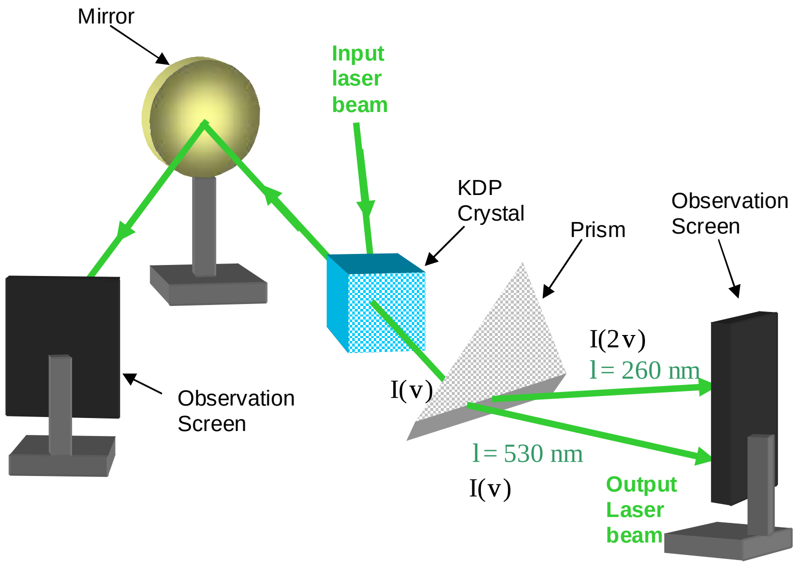
$$f = \frac{1{,}27 \cdot l}{D} = \frac{1{,}27 \cdot 530 \cdot 10^{-9}}{3 \cdot 10^{-3}} = 2{,}24 \cdot 10^{-4} \ \text{[rad]}$$

Consideration all the possible sources of error, this is pretty close to the calculated value.The next step was to do an experiment with an angular half width of the phase matching curve. We used an other KDP crystal to create second harmonic generation. Here in this case the second harmonic generator creates the wavelength of the Nd:YAG laser. From the output we get two different wavelengths:

- The original wavelength, l= 532 nm
- New wavelength, l = 266 nm

We used a prism to separate those two different lights at the different wavelengths (and frequencies).
The second wavelength, l = 260 nm, corresponds (should) to a wavelength twice the original frequency, with a spectrum in the UV region, so it was difficult to observe it while we were doing the experiment. Using a light piece of paper solved this. In this experiment we were turning the crystal and observing the intensity at the same time. We did that until we could find the optimum angle, which corresponds to index matching of the original and the generated wave from the crystal. So now it is possible to calculate the half width of the phase matching curve, which was our goal

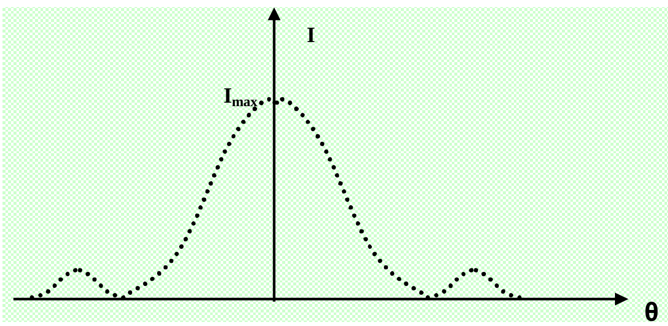
from the beginning. Therefore we observed the spot of the reflected light from the KDP crystal, which was directed by a mirror to a screen. By turning the KDP crystal, the spot will move from its position and the intensity of the frequency doubled light will change. The reason for that is that the second harmonic generation occurs when the refractive indices for the original and the second harmonic wave are matched, $n_{original} = n_{SH\text{-}wave}$. This is illustrated in the following figure:



Figur 5 Experiment for the angular half width of the phase matching curve.

From previous optics courses we know that the output intensity is proportional to a sinc^2-function:

$$I(\Delta n) = I^2(w)\frac{2v^2 |c_{eff}^{(2)}|^2 L^2}{n^3 c^3 e_0} \cdot \mathrm{sinc}^2\left(\frac{2w}{c}\Delta n L\right)$$

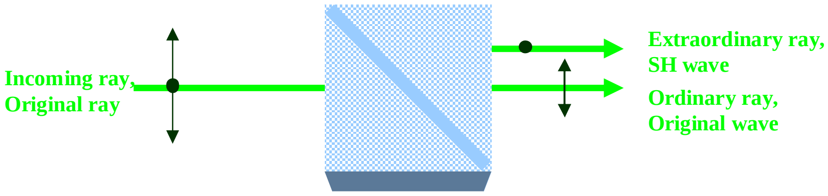


Figur 6 The Intensity as function of the angle, sinc^2-function.

Generally the refractive indices for the original and second harmonic are different:

$n_{original} \neq n_{SH\text{-}wave} \Rightarrow \Delta n = n_{original} - n_{SH\text{-}wave} \neq 0$

But for a specific θ, $n_{original} = n_{SH\text{-}wave}$ when the second harmonic travels as an extraordinary ray, while the original travels as the ordinary ray, which we know from birefringence technique as showed in the following figure:



Figur 7 Second Harmonic wave and the Original wave propagation.

This will give the following refractive indices:

$$\Delta n = \mathrm{n}_{\text{Original}} - \mathrm{n}_{\text{SH-wave}}(q)$$

Where $\dfrac{1}{\mathrm{n}^2_{\text{SH-wave}}(q)} = \dfrac{\cos^2 q}{n^2_{\text{Original}}} + \dfrac{\sin^2 q}{\mathrm{n}^2_{\text{SH-wave}\ q=\frac{p}{2}}}$

We can now use the reflected light to calculate how much the angular half width will be to get 50% of I_{max}. We turned the crystal to one direction until we could observe the second harmonic output at its minima. After that we turned the crystal to the other direction until we could observe the second minima on the other side. In that way we can determine the angle, which the crystal has been turned. The distance from the reflected beam movement was X_1 = 22 cm. The distance from the mirror to the screen where we were observing was X_2= 2,6 m. We can use small angle approximation to calculate the angle as follows:

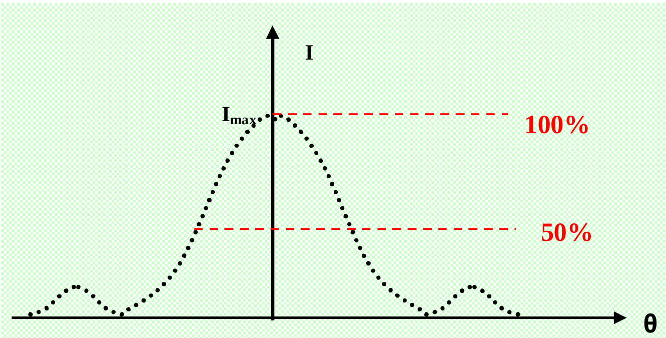
$$\Delta q = \frac{X_1}{X_2} \Rightarrow \frac{0.22}{2.6} = 0{,}0086\ [\text{rad}]$$

This angle is twice as big as the angle that the crystal is turned, this can be shown as follows:

$$\Delta q_{crystal} = \frac{\Delta q}{2} = \frac{0{,}0086}{2} \Rightarrow \Delta q_{crystal} = 0{,}0043\,[\text{rad}]$$

This shows that the crystal has been turned with the angle $\theta_{Crystal}$ = 0,019 [rad]. The angular half width can be measured between the two points, where the output intensity has dropped to 50 %. But this can be approximated with the angle between I_{max} and the first I_{min}, which can be found as a fourth of the measured angle turning. The angular half width will be:

$$\Delta q_{halfwidth} = \frac{\Delta q_{crystal}}{4} = 0{,}00107\,[rad]$$



Figur 8 The output intensity has dropped to 50 %.

The formula for refractive indices is:

$$\frac{1}{n^2(q,2w)} = \frac{\sin^2(q)}{n_e^2(2w)} + \frac{\cos^2(q)}{n_o^2(2w)} = \frac{1}{n_o^2(w)}$$

By using the values of n found in the document http://www.clevelandcrystals.com/KDP.shtl:

Using the RHS: θ = 76.97^0.

Differentiating the LHS:

$$\frac{dn}{dq} = -\frac{\sin q \cos q \left(n_o^2 - n_e^2\right)}{n_o^2 + n_e^2} n_0^3(v)$$

On inserting the value of θ:

$$\frac{dn}{dq} = -0.0245$$

The distance to the first minimum is a wavelength and from:

$\Delta nL = \lambda$, where $\lambda = 0.266\mu m$ and L = 0 1cm => $\Delta n = 26.6 \times 10^{-6}$.

At very low values we assume linearity therefore:

$$\Delta q = \frac{\Delta n}{\frac{dn}{dq}} = \frac{26.6x10^{-6}}{-0.0245} = -0.00109$$

We can see than the theoretical and measured values almost match.

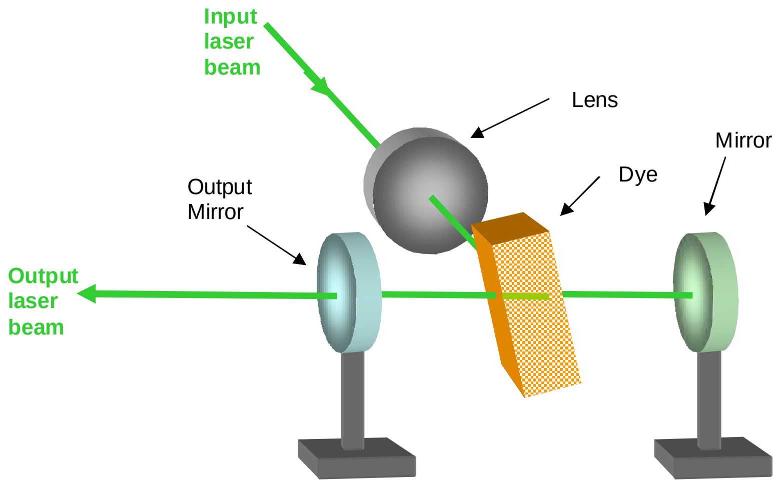
Part 3) Dye Laser

Our goal now is to construct a simple dye laser so we can see how it works. A dye laser includes the same 3 common and most important components as all other lasers, which are:

- **Pump:** In our experiment we used a Nd:YAG laser as a pump. But the output wavelength couldn't be used directly. Therefore we used the "Frequency Doubling" method. We got a wavelength l=530 for pumping in the dye.

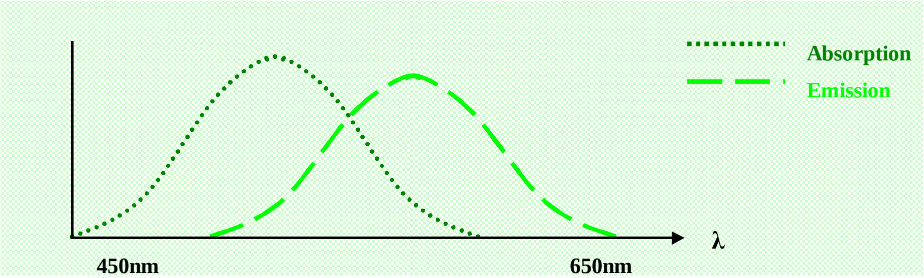
- **Active medium:** In our case the active medium includes an "optical component", which is filled with the organic dye "Rhodamine 6G" dissolved in a solvent like methanol

- **Resonator:** We used two mirrors. One of them was 100 % reflective and the other one at the output was almost 100 % reflective. That means that the output mirror allowed small percentage of the laser beam to be transmitted. We used also a cylindrical lens to focus the output of the frequency doubled Nd:YAG laser. This is required to get a fine light line into the Dye medium to make the lasing possible. We observe a channel, which emitted light at both directions due to amplified spontaneous emission. So we aligned the mirrors until we got a bright output beam of the dye laser.



Figur 9 A simple way to make a dye laser.

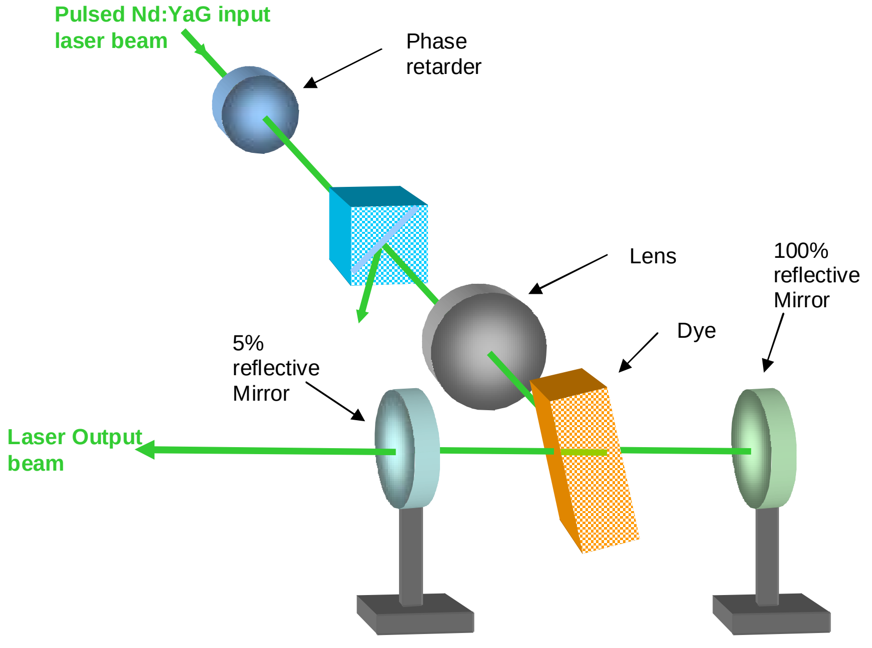
But Dyes can absorb light at a certain spectrum (wavelength) so they can get excited and emit light at longer wavelengths. That means the absorption and emission spectrums are different, which can be seen in the following figure.



Figur 10 Absorption and Emission as function of the wavelength.

Part 4) Tunable dye laser & Grazing Incident grating

We have to design a tuneable dye laser with a big bandwidth which is pumped by a frequency-doubling Q switched Nd:YaG laser. The light from the pulsed Nd:YaG laser has a wavelength, λ = 1064 nm. This wavelength is actually out of the visible light spectrum. By using a second harmonic generator aperture we get generated the second harmonic wavelength, λ = 532 nm. This wavelength is in the visible green light spectrum. In the figure below one can see how we sat up the experiment. The second harmonic beam is send to a phase retarder, a so-called λ/2-plate retarder. From there we can control the polarisation which is filtered through the polarisation prism.



Figur 11 Dye Laser Experiment.

The second harmonic beam is passed through a λ/2-plate retarder. From there we can control the polarisation which is filtered through the polarisation prism.

Now the vertical polarised beam is sent through a cylindrical lens that focuses the beam onto a dye media. The media is pumped so we can get a spontaneous emission of the light in a ray. With a help of two mirrors which we put perpendicular to the dye, one gets a lasing ray as an output. Now it is possible to see the dye lasers wide spectrum.

To get a more narrower spectrum, one can use different methods. The most simple method is to send a ray through several prisms to gain a narrow lasing spectrum. In principle the secret behind this method is that one “filters” the unwanted wavelengths.

A more used method is to use a grating. One can use a grating in a certain angle to reflect the first order diffraction. In our case we tried to adjust the grating with different angles and tried to experiment a little bit with the optical apertures in the lab.
At the end we found out that when the angle of our grating was around 48˚, we got then the most clear light spot. This light spot was yellow and after measuring the wavelength of it, we got a wavelength of λ = 585 nm.
On using a 16 cm^{-1} Free Spectral Range Fabry-Perot interferometer, we could see that the systems, was around 1,5 cm^{-1}. Our goal was to get it down to 1,0 cm^{-1}.
To optimise that, we used a Grazing Incident Grating.
We use it so the beam hits the Grazing Incident Grating from the side like it is shown in the picture. This will allow the beam to hit many roules. At the end we get lazing between the two mirrors. This can be seen in Fig. 2. After some adjustments we could observe some interference fringes in 1 cm^{-1} FSR Fabry-Perot interferometer.

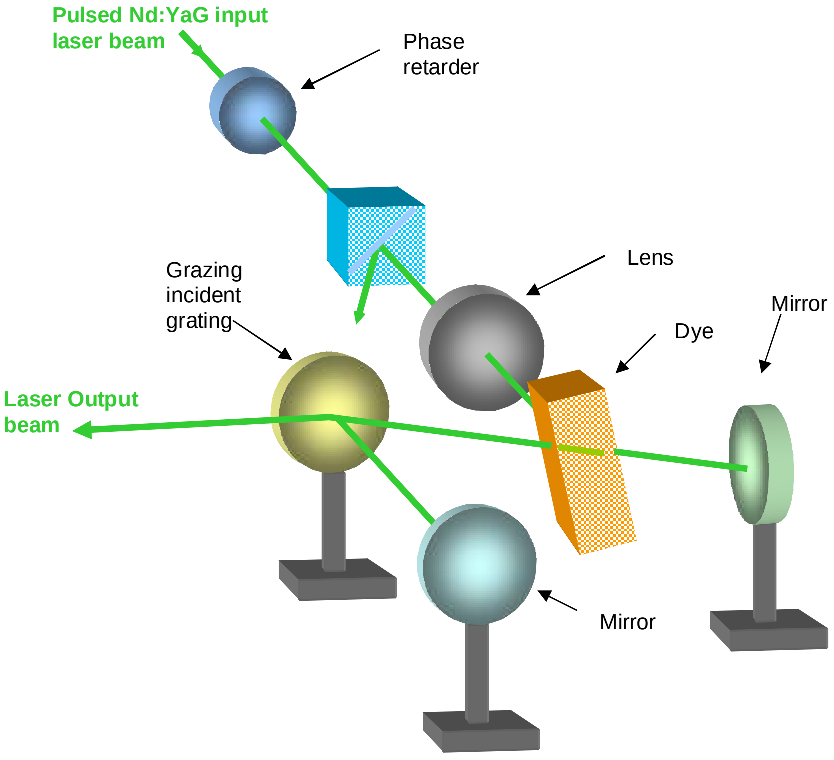


Figure 12 Grazing Incident grating Experiment

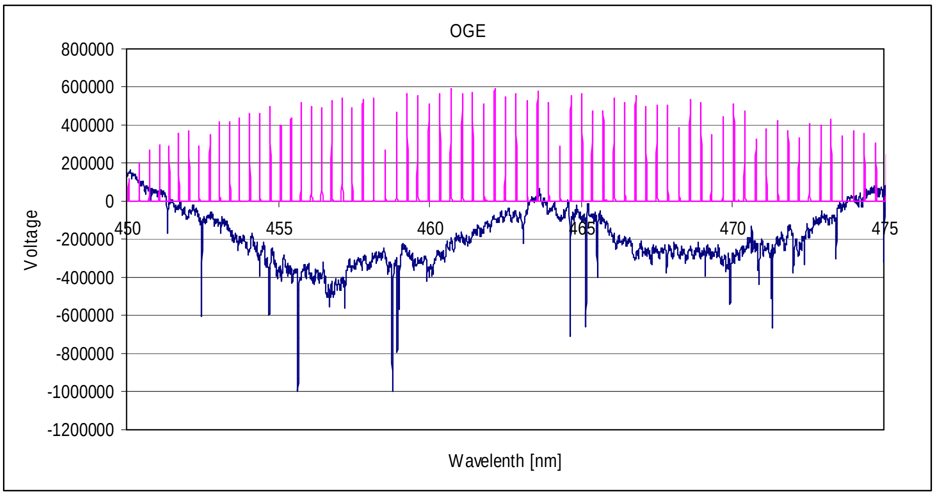


Figure 13 : Results from OGE measurement

The positive peaks that one can see going up and down are the finesse of the F.P, which we measured with a Fabry-Perot interferometer. The distance between these peaks can lead us to calculate the wavelength. If we look at the first 3 peaks, we get the following data: $\Delta\lambda_1$ = 0,34 nm, $\Delta\lambda_2$ = 0,34 nm, $\Delta\lambda_3$ = 0,33 nm. The average distance will be λ = 0,337 nm.

The following relationship is valid

$$\Delta\lambda_{FSR} = \frac{l}{2d}$$

$$l = \sqrt{\Delta l \cdot 2d} = \sqrt{0{,}337nm \cdot 2 \cdot 0{,}0003} = 449{,}667\text{nm (with a large uncertainty)}$$

Where d is the distance between the interferometer mirrors

The distance between the last three peaks at λ = 475 nm are:

$\Delta\lambda_1$ = 0,36 nm
$\Delta\lambda_2$ = 0,37 nm
$\Delta\lambda_3$ = 0,36 nm

These give the wavelength: λ = 467 nm. If we look at this wavelength. It is different from what we were expecting which might cause an uncertainty in the measurements.

The lower peaks in Figure 13 show the result of the so-called OGE. These can be used to calibrate the laser. Between λ = 458 nm and λ = 459 nm we get 3 consecutive downward pointing peaks. Therefore we scanned with a speed of 0,002 nm per step over the range λ = 458 nm to λ = 459 nm to get a more detailed plot. The fringes (with Fabry-Perot Interferometer) can now be used to find the wavelength. All in all there are 158 steps between the 2 first tops which give the following wavelength.

$$l = \sqrt{\Delta l \cdot 2d} = \sqrt{158 step \cdot 0.0023 nm / step \cdot 2 \cdot 0{,}0003} = 467 nm$$

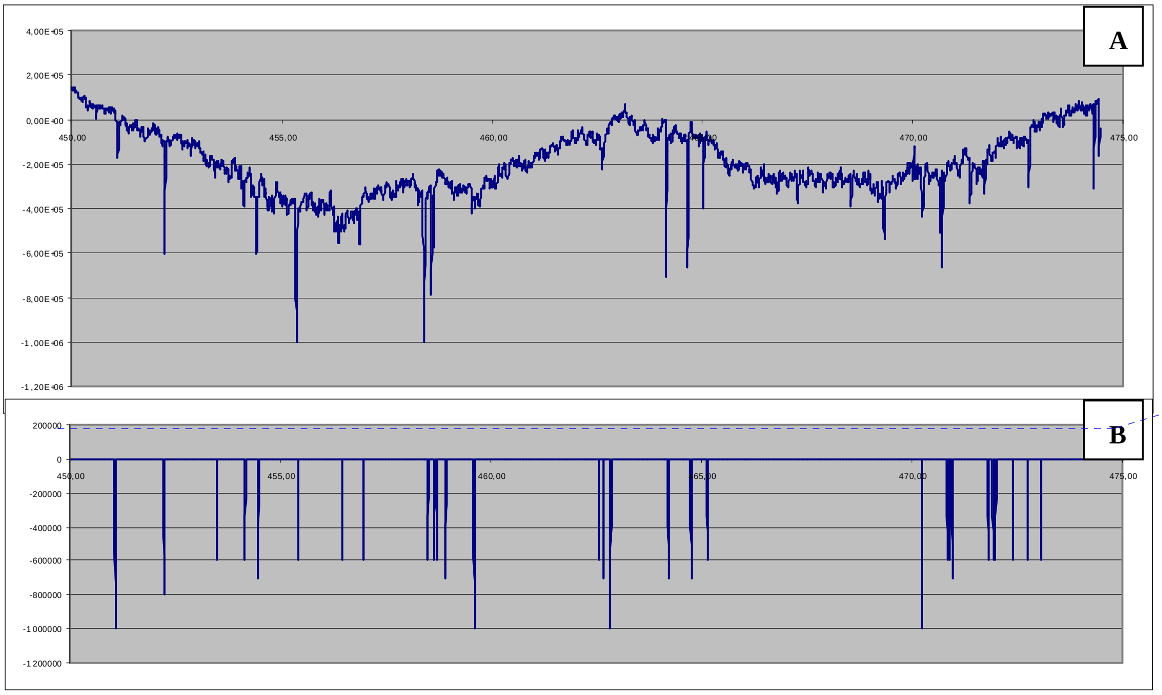
This is different from the λ = 458 nm that our measurement shows. The three OGE tops was observed to lie on

λ = 458.68 nm
λ = 458.85 nm
λ = 458.91 nm

It gives the distance between 0.17 nm between the two first peaks and 0,06 nm between the last two peaks. If we compare this with Nestor's table it will show that there are three peaks at

λ = 458.49 nm
λ = 458.66 nm
λ = 458.72 nm

These also have a distances 0,17 nm and 0,06 nm. This means that our measurements is 0,19 nm over the Nestor's table. To calibtate we introduce an offset of 0,19 nm and divide each step by 0,0098 nm. This will give a graph where the peaks will lie similar to those from Nestor's Table.



Kommentar:

Figure 14 Calibration results according to Nestor's table: A-Our results. B-Peaks from Nestor's table.