Protokoll
Praktikum Quantenphysik

Helium-Neon Laser

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1 Introduction

1.1 Theory of He-Ne Lasing

1.1.1 Population Inversion

Usually, in thermal equilibrium, the number of particles per state (say N_1 and N_2, with N_2 for the higher-energy state) are Boltzmann distributed.

$$\frac{N_2}{N_1} = \exp\left(\frac{-(E_2 - E_1)}{k\,T}\right)$$

If the temperature is high enough, $N_2 = N_1$. If it is lower, $N_2 < N_1$.

For Lasers, we want to have $N_2 > N_1$. This is only possible if the system is not in thermal equilibrium.

Helium has metastable states, for example 2^1S_0, 2^3S_0. Because of the selection rules for optical transitions, from there, to the ground state.

These states can be populated by electron collisions (of the second type - the one where the collision causes a transition to take place) via gas discharge.

Such a Helium atom can collide with a Neon atom (atomic collision of the second type), the Helium atom reaches the ground state because its energy has been used to excite the Neon atom. The Neon atom reaches the $3s$ state (for example).

The Neon atom can tranfer to $2p$ via an optical transition.

Eventually, the Neon atom will end up in $1s$ via spontaneous emission.

Because the lifetimes of the $3s$ states of Neon are 10 times longer than those of the $2p$ states, the necessary population inversion is achieved.

This enables Light Amplification by Stimulated Emission of Radiation.

Other Helium and Neon states are possible and cause different wavelengths of light to be emitted.

1.2 Experimental Setup

We use a rail in order to affix devices we require for the particular experiment. Usually the laser tube is placed in the middle of the rail. Other devices are placed further outside along the rail, constructing our experimental setup.

If necessary, we have a pilot laser and iris in order to make a coarse alignment of the devices possible.

After alignment, we power the laser tube and adjust the devices in order to get the laser to operate.

We then optimize the laser output power by adjusting the devices and record a spectrum of the outgoing light using our spectrograph.

1.2.1 Laser tube with Brewster Window

The Laser tube contains the Helium-Neon gas, a capillary, and a cathode and anode at opposite ends of the tube.

The windows at the ends of the tube are tilted by Brewster's angle, reducing the gain of the σ-polarized light and minimizing reflections. However, the π-polarized light will pass through without loss.

Ingniting the laser takes about 8 kV (applied between anode and cathode), continuous operation takes about 2 kV.

The voltage will cause a gas discharge and lasing will commence.

The tube we used has optimal output in the fundamental mode with a purely Gaussian beam.

1.2.2 Mirrors

The gain is proportional to $(N_2 - N_1)$. If the gain compensates for the losses, a standing wave (mode) will be built up in the resonator.

The mode must fulfil the condition

$$L = n\,\frac{\lambda}{2} = n\,\frac{c}{2\,\nu}$$

where L is the length of the resonator, λ the wavelength of the mode, c the speed of light, ν the frequency of the generated light and n an integer.

Thus a mode has frequency

$$\nu(n) = n\,\frac{c}{2\,L}$$

The spectral distance between neighbouring modes is:

$$\Delta\nu = \frac{c}{2\,L}$$

The mirrors are tilted using adjustment screws until the laser ignites.

1.2.3 Littrow Prism

For wavelength selection, it's possible to use a Littrow prism. This is a special type of dispersive prism, usually triangular. A Littrow prism has a reflective coating on its back side, causing only one wavelength (selection by the angle of incidence) to be reflected back into the resonator.

1.2.4 Birefringent Crystal

In a Birefringent Crystal, the refractive index depends on the direction of propagation, causing an extraordinary beam (which seems to be violating Snell's law) to be emitted in addition to the ordinary beam.

It is an anisotropic crystal. It causes a phase shift of $\pi/2$ (i.e. $\lambda/4$) in the extraordinary beam with respect to the ordinary beam, slowing the component down compared to the other.

Also, the incoming beam's polarization is changed in such a way that if the orginary and extraordinary beam were to be superposed, an elliptically polarized beam would result (how exactly depends on the orientation of the birefringent crystal with respect to the optical axis).

In our laser setup, the birefringent crystal is used for wavelength selection.

The birefringent plate is placed under Brewster's angle into the resonator (Brewster's angle to minimize reflection losses).

The laser can only oscillate in a direction of polarisation given by the Brewster window.

The birefringent plate only doesn't change the polarisation if a phase shift of 2π occurs between the ordinary and extraordinary beam (after passing through it twice).

For all other phase shifts, the polarisation will change and there will be reflection losses at the Brewster window, stopping the oscillation there.

In this way, we can select for a specific wavelength because all the beam contributions for other wavelengths will be attenuated very much.

1.2.5 Etalon

An Etalon can be used for mode (frequency) selection. It's a small glass plate acting as an additional resonator.

$$d := 1\,\mathrm{cm}$$
$$\lambda_m = \frac{2\,d}{m}\sqrt{n^2 - \sin(\alpha)}$$

where λ_m is the wavelength with maximal transmission, m is the order of the mode, d the thickness of the etalon, α the angle the etalon is tilted against the incoming beam, n is the refractive index.

We calculate the number of modes that can oscillate in our laser with an emission wavelength of $\lambda_0 = 632.8\,\mathrm{nm}$:

$$L := 60\,\mathrm{cm}$$
$$\lambda_0 := 632.8\,\mathrm{nm}$$
$$c := 299792458\frac{\mathrm{m}}{\mathrm{s}}$$
$$k := 1.38 \cdot 10^{-23}\frac{\mathrm{m}^2\,\mathrm{kg}}{\mathrm{s}^2\,\mathrm{K}}$$
$$T := 293.15\mathrm{K}$$
$$m_{Ne} := 20.10\,\mathrm{u} = 3.34988 \cdot 10^{-26}\mathrm{kg}$$
$$v_w := \sqrt{\frac{2\,k\,T}{m_{Ne}}} \approx 491\,\frac{\mathrm{m}}{\mathrm{s}}$$
$$\lambda_0 \nu_0 = c$$
$$\Delta\nu_{Doppler} := 2\,\sqrt{\ln(2)}\,\frac{v_w}{c}\,\nu_0$$
$$\Delta\nu_{Doppler} = 2\,\sqrt{\ln(2)}\,\frac{v_w}{\lambda_0} \approx 1.29\,\mathrm{THz}$$
$$\Delta\nu = \frac{c}{2\,L} \approx 250\,\mathrm{MHz}$$
$$N_{modes} := \frac{\Delta\nu_{Doppler}}{\Delta\nu} \approx 5$$

2 Results

2.1 Mirror-Mirror

We set up the rail with a mirror, the laser tube and a mirror, in that order.

Then we adjusted the mirrors using a pilot laser and an iris.

Then we enabled power to the laser tube, fine-tuned the mirrors until we accomplished lasing.

After further tuning to maximize laser output power, we got 12.80 V on the photodetector and the following spectrum (mind the clipping because of saturation):

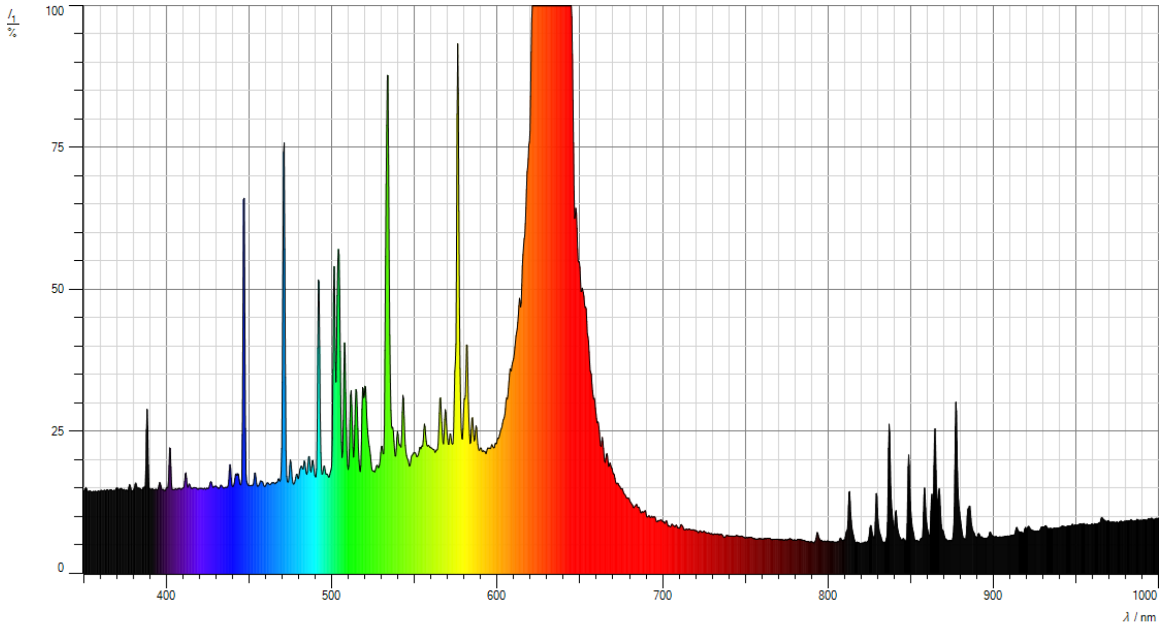

Figure 1: Spectrum when using Mirror-Mirror; integration time: 100 ms

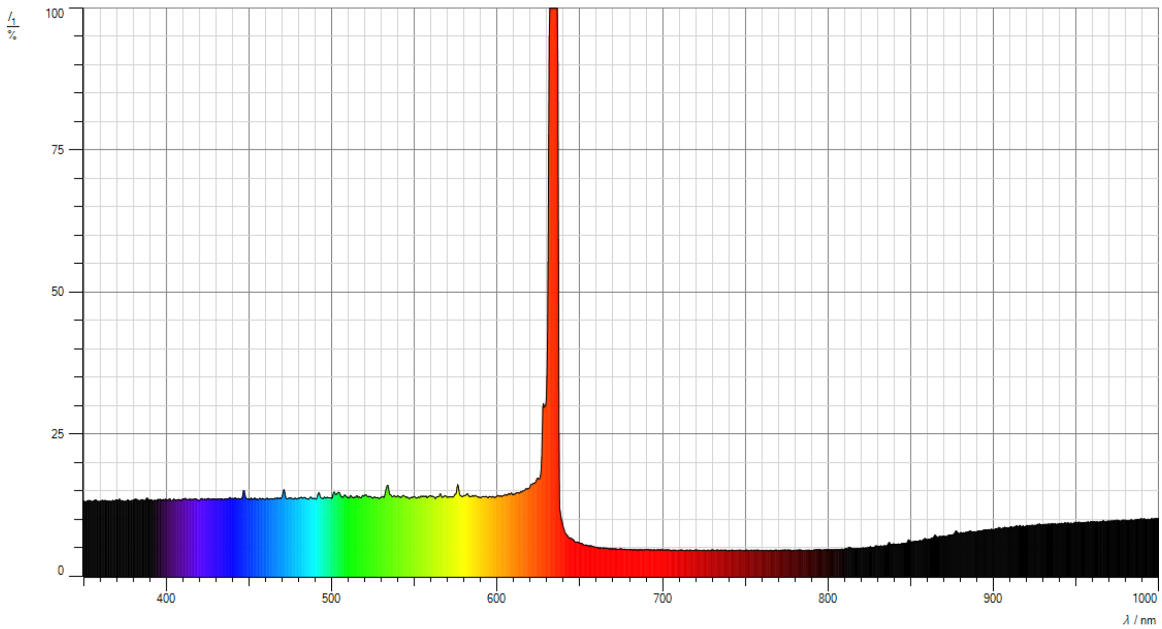

Figure 2: Spectrum when using Mirror-Mirror; integration time: 3 ms

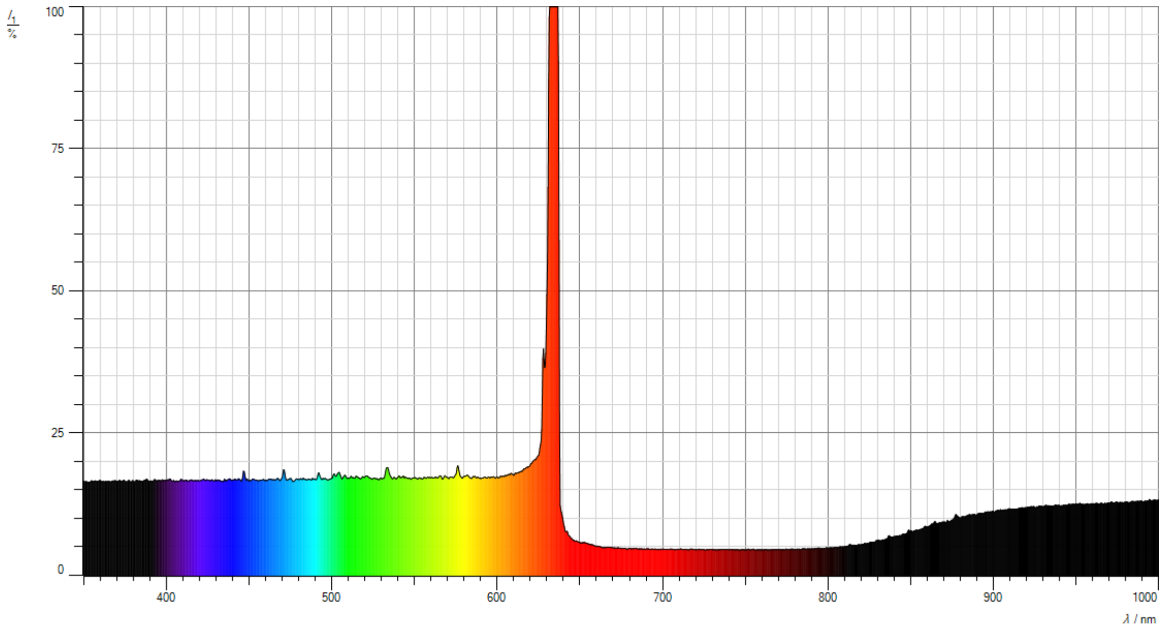

Figure 3: Spectrum when using Mirror-Mirror; integration time: 3 ms

Subtracting the noise floor we get:

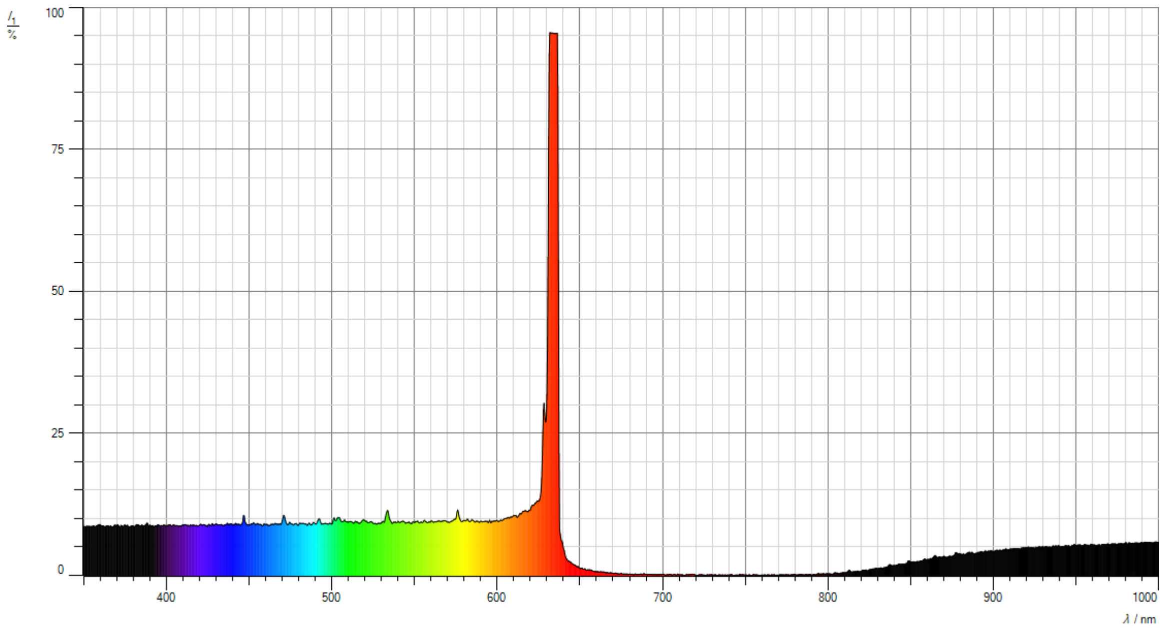

Figure 4: Spectrum when using Mirror-Mirror; integration time: 3 ms

2.2 Littrow Prism

Note that from this point on, we subtracted the background light intensity in the graphs.

We then set up the laser using the Littrow Prism as described above and maximized the power.

Maximizing the output power gave us 12.84 V at the photodiode (on the left side).

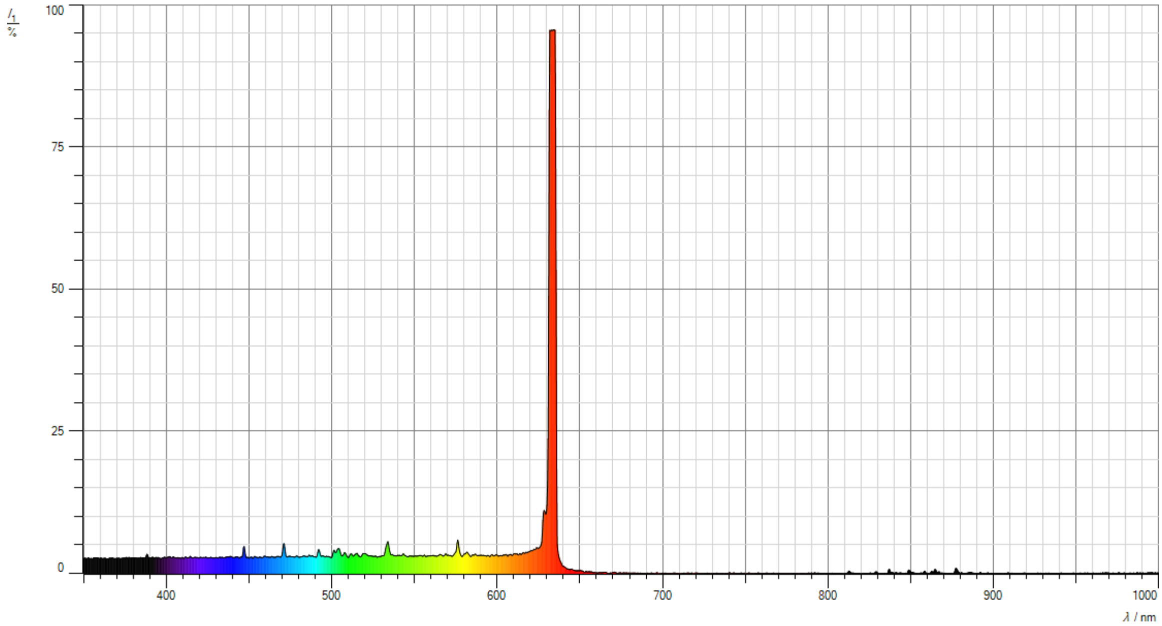

Figure 5: Spectrum when using Littrow Prism; integration time: 3 ms

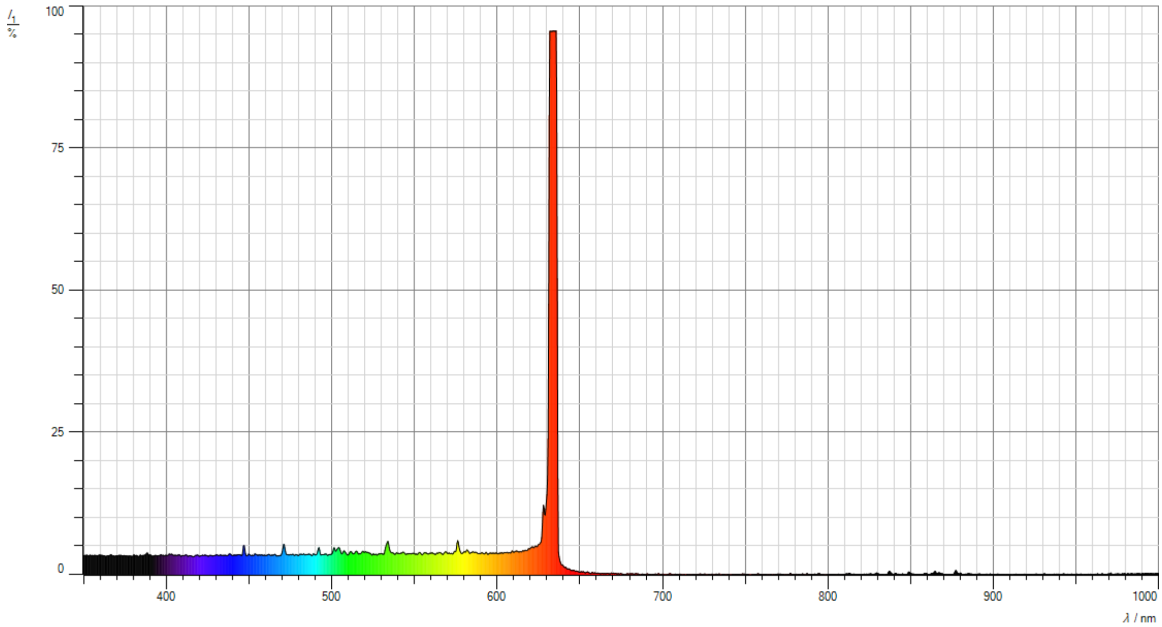

Figure 6: Spectrum when using Littrow Prism; integration time: 3 ms

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We couldn't find the orange line at $\lambda = 611.8\,\text{nm}$.

2.3 Birefringent Crystal

We set up the laser using the birefringent crystal as described above and maximized the power.

The strongest lines are at 632.8 nm (and 640.1 nm - spectra not shown) wavelength, the photodiode voltage was 12.7 V.

The other lines are now strongly attenuated.

Tuning the birefringent crystal, we saw the same spectrum repeated seven times. Three of them follow:

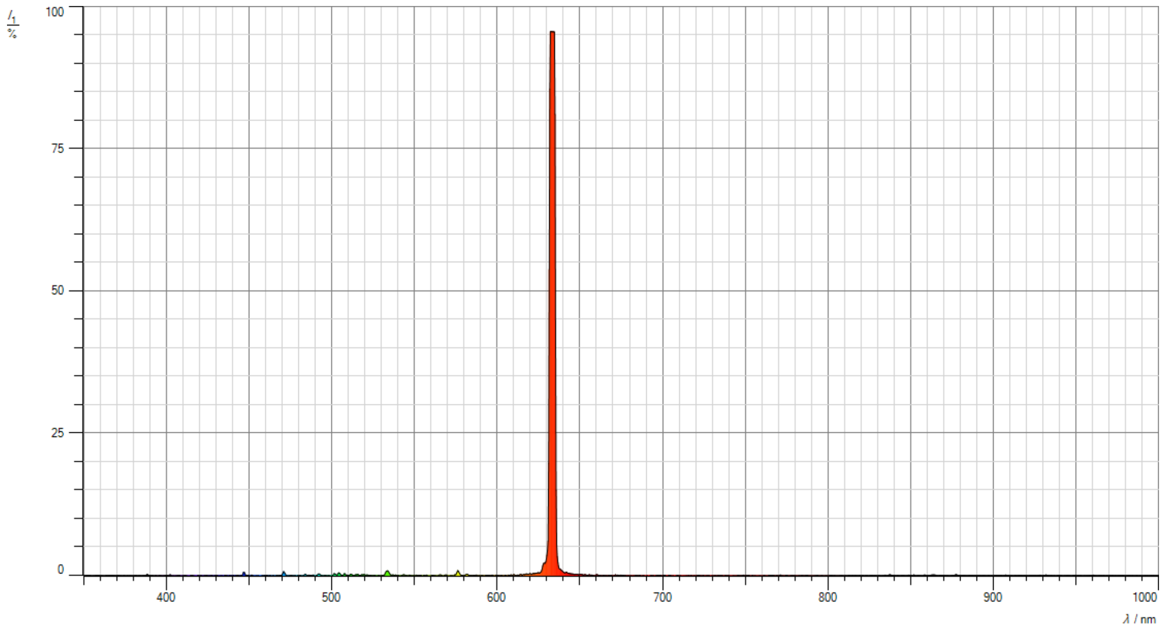


Figure 7: Spectrum when using Birefringent Crystal; integration time: 10 ms

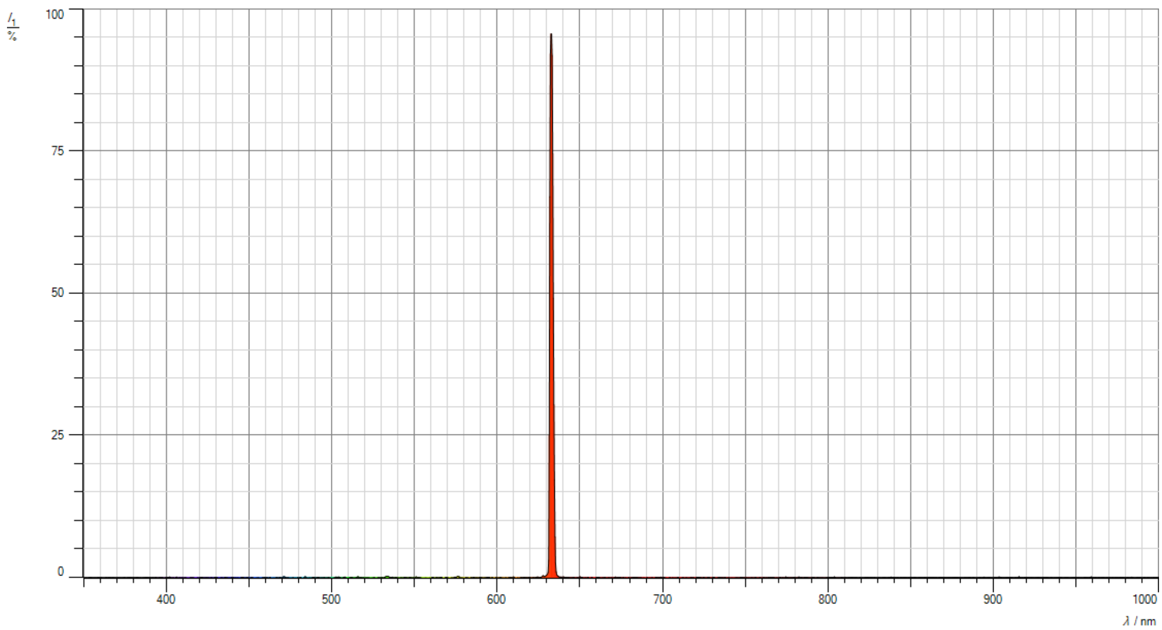
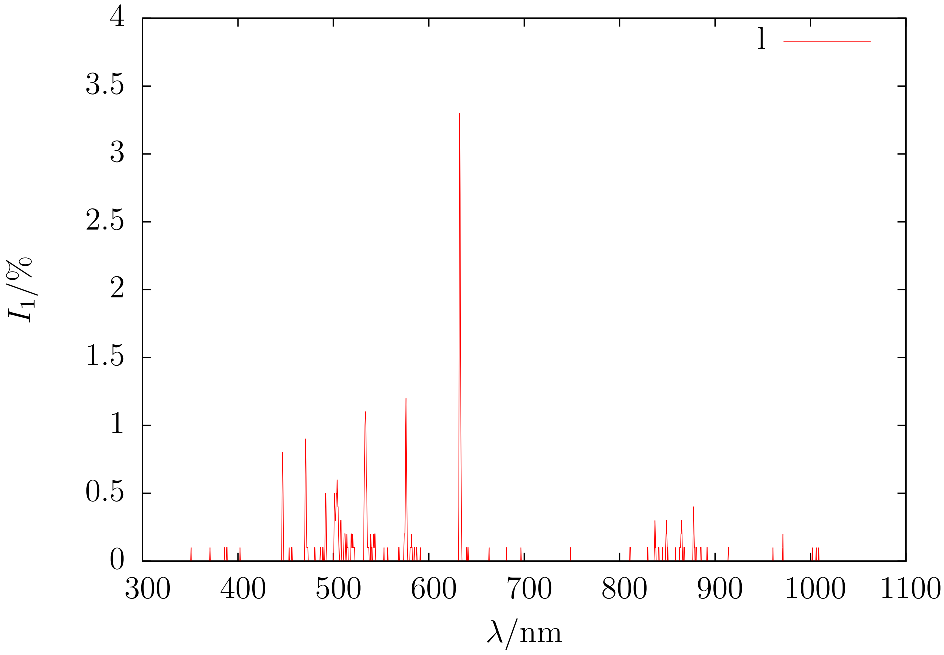


Figure 8: Spectrum when using Birefringent Crystal; integration time: 3 ms

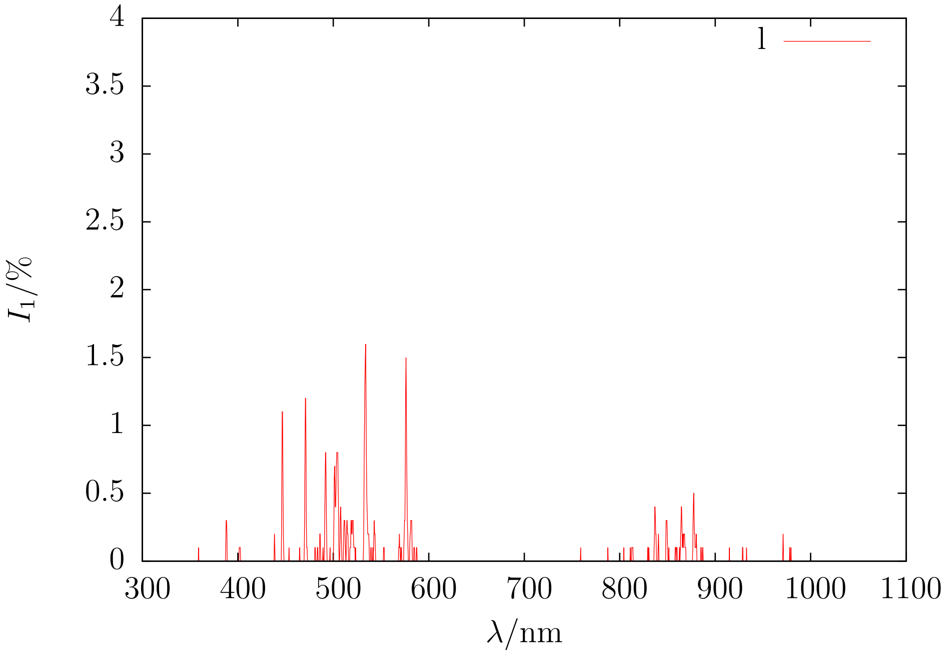
2.4 Etalon

We used the Etalon as described above. We found multiple modes around the maximum intensity (12.79 V) at $\lambda = 632.5$ nm. The linewidth is now very narrow.

After some seeking, we found the zero order mode:



After very minimal tilting (i.e. can happen by the air without anyone touching it) it looks like this:



Spectra of the other orders are very weak (for example the following spectrum was taken when the photodiode voltage was $1.4\,V$):

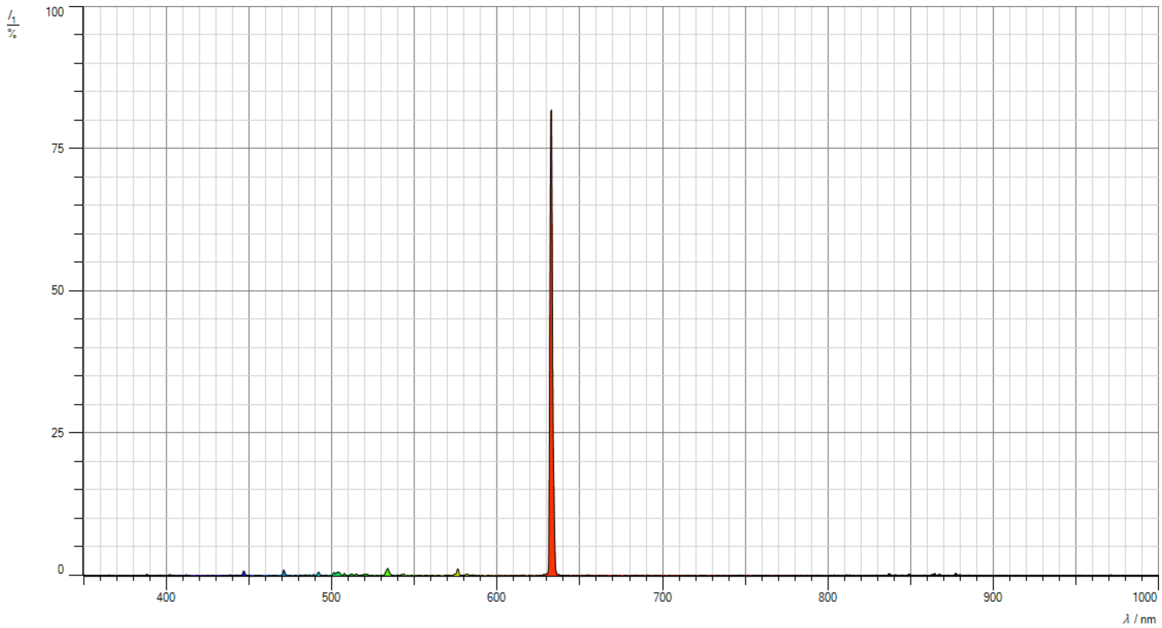


Figure 9: Spectrum when using Etalon; integration time: 3 ms

Putting the Etalon straight, we got:

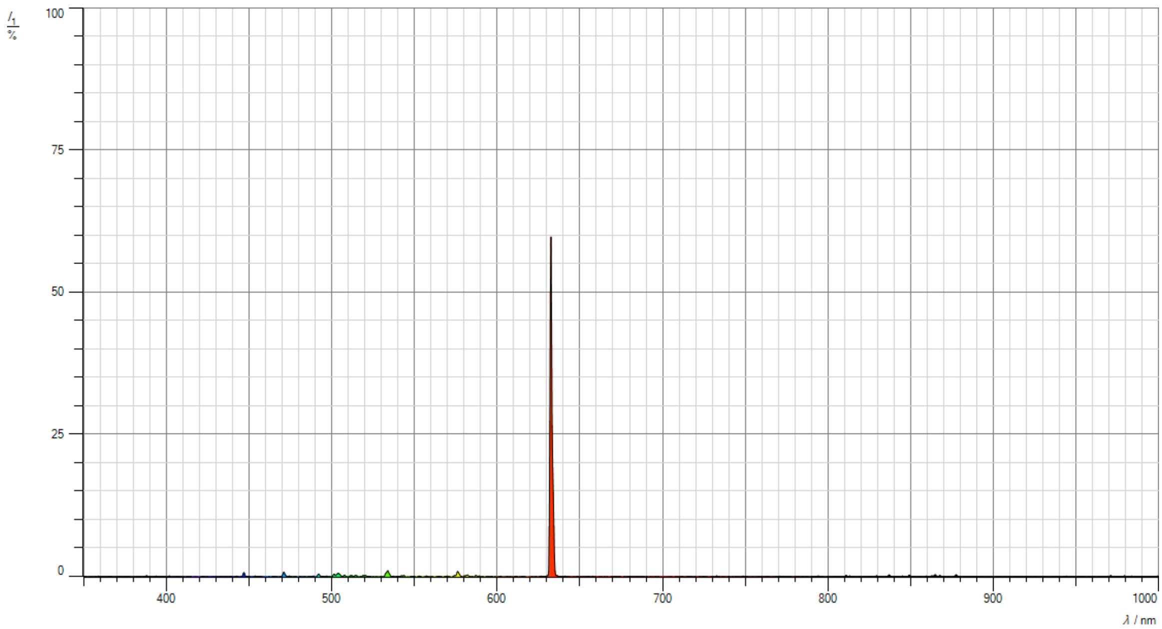


Figure 10: Spectrum when using Etalon; integration time: 3 ms

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Tilting the Etalon, we got:

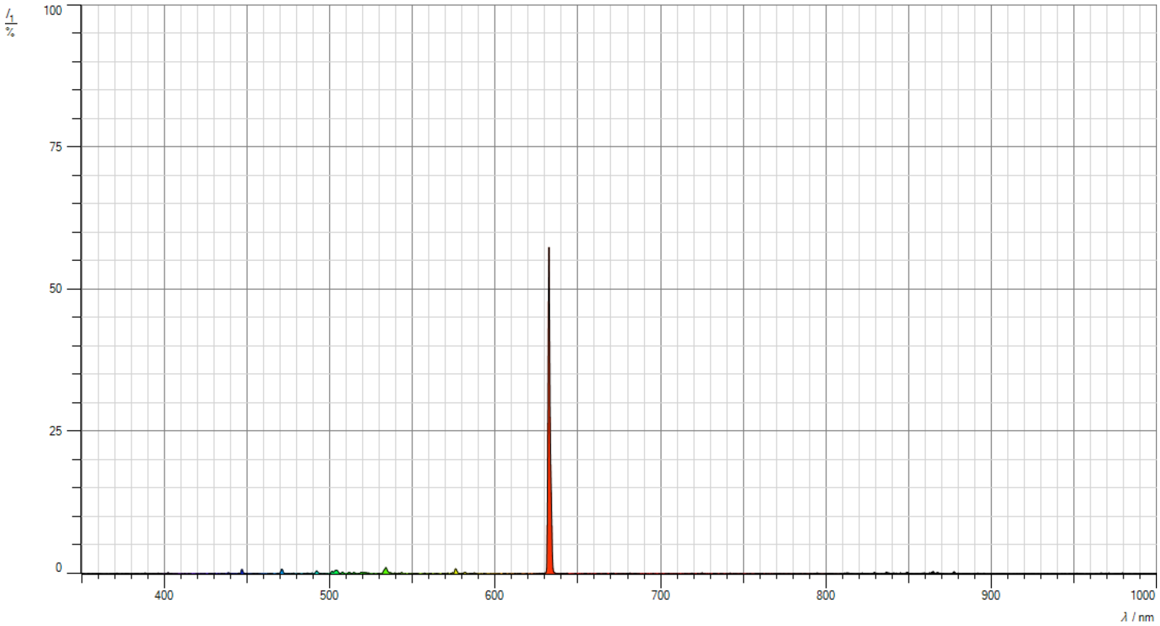

Figure 11: Spectrum when using Etalon; integration time: 3 ms